Fifteenth International Symposium

on Capture Gamma-Ray Spectroscopy

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CGS15

Dresden, August 25 to August 29, 2014

Book of Abstracts

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Testing CVC and CKM unitarity via superallowed nuclear beta decay

J.C. Hardy and I.S. Towner

Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA

Currently, the most restrictive test of the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix is anchored by nuclear beta decay. Precise measurements of the *ft*-values for superallowed beta transitions between analog 0^+ states are used to determine G_V, the vector coupling constant; this, in turn, yields V_{ud}, the up-down quark-mixing element of the CKM matrix. The determination of a transition's *ft*-value requires the measurement of three quantities: its *Q*-value, branching ratio and parent half-life. To achieve 0.1% precision on the final result, each of these quantities must be measured to substantially better precision, for which special techniques have had to be developed.

A new survey and analysis of world data [1] reveals that there are now fourteen such transitions with *ft*-values known to ~0.1% precision or better, and that they span a wide range of nuclear masses, from ^{10}C, the lightest parent, to ^{74}Rb, the heaviest. Of particular interest is the recent completion [2] of the first mirror pair of $0^+ \rightarrow 0^+$ transitions, ^{38}Ca $\rightarrow$ ^{38}K^m and ^{38}K^m $\rightarrow$ ^{38}Ar, which provides a valuable constraint on the calculated isospin-symmetry-breaking corrections needed to derive G_V from the experimental data.

As anticipated by the Conserved Vector Current hypothesis, CVC, all fourteen transitions yield consistent values for G_V. The value of V_{ud} derived from their average makes it by far the most precisely known element of the CKM matrix, which, when combined with the other top-row elements, V_{us} and V_{ub}, leads to the most demanding test available of the unitarity of that matrix. Since CKM unitarity is a key pillar of the Electroweak Standard Model, this test is of fundamental significance.

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Inelastic Neutron Scattering Studies of ^{76}Ge and ^{76}Se: Relevance to Neutrinoless Double-β Decay

B.P. Crider[1], J.M. Allmond[2], M.T. McEllistrem[1], E.E. Peters[3], F.M. Prados-Estévez[1,3], T.J. Ross[1,3], J.R. Vanhoy[4], and S.W. Yates[1,3]

[1]*Department of Physics & Astronomy, University of Kentucky, Lexington, KY 40506, USA*
[2]*Joint Institute of Nuclear Physics and Applications, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
[3]*Department of Chemistry, University of Kentucky, Lexington, Kentucky 40506, USA*
[4]*Department of Physics, United States Naval Academy, Annapolis, Maryland 21402, USA*

With inelastic neutron scattering, nuclear levels can be non-selectively populated up to the incident neutron energy, and lifetimes in the femtosecond regime can be determined [1]; most low-spin excited states can be observed and transition probabilities can be extracted. These measurements permit the characterization of the low-lying level scheme particularly well and can also supply structural information relevant to the calculation of the nuclear matrix elements for the neutrinoless double-β decay ($0\nu\beta\beta$) rate.

In recent years, the (n,n'γ) reaction has been identified as an important potential source of background interference in the observation of $0\nu\beta\beta$ [2]. A favorable case in the search for $0\nu\beta\beta$ is ^{76}Ge, for which the experimental signature is a sharp peak at the Q-value of the reaction, ~2039 keV. Given the rarity with which $0\nu\beta\beta$ is predicted to occur, knowledge of all interferences in the region of interest is critical. Of particular concern is the known 3952-keV level in ^{76}Ge [4], which has a weak (~4%) 2041-keV γ-ray branch that is unlikely to be completely resolved from the $0\nu\beta\beta$ experimental signature. Recent studies to measure the cross section of this γ ray resulted in an upper limit of 3 mb, but the 2041-keV γ ray was not directly observed [3].

INS experiments were performed at the University of Kentucky Accelerator Laboratory on enriched ^{76}Ge and ^{76}Se scattering samples at incident neutron energies from 2.0 to 4.0 MeV. Many new levels were identified and characterized in both nuclei; level lifetimes, transition probabilities, multipole mixing ratios, and other properties were determined. In addition, γ-ray cross sections for the ^{76}Ge(n,n'γ) reaction were measured at neutron energies ranging from 4.0 to 5.0 MeV, with the goal of determining the cross section of the aforementioned 2041-keV γ ray. Gamma rays corresponding to the three strongest branches from the 3952-keV level were observed, but the 2041-keV γ ray was obscured by other, more intense γ rays. Population cross sections of 4 to 7 mb across the range of incident neutron energies were assigned to the 3952-keV level, resulting in a cross section of ~0.2 mb for the 2041-keV branch using the previously determined branching ratios [4]. Beyond this, the data from these experiments indicates that there are previously unreported γ rays that can be found near the 2039-keV region.

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New Information on the Occurrence of O(6) Symmetry in Nuclei

N. Pietralla[1], T. Möller[1], C. Kremer[1], G. Rainovski[2], S. Aslanidou[1], C. Bauer[1], J. Beller[1], M.P. Carpenter[3], R.V.F. Janssens[3], A. Krugmann[1], D. Seweryniak[3], and S. Zhu[3]

[1]*Institut für Kernphysik, TU Darmstadt, D-64289 Darmstadt, Germany*
[2]*Faculty of Physics, St. Kliment Ohridski University of Sofia, 1164 Sofia, Bulgaria*
[3]*Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA*

Understanding the structure and dynamics of complex many-body systems can often be obtained from the observation and analysis of symmetries. Symmetry considerations are particularly significant for addressing a key question in such systems, namely, how do simple features emerge within a complicated environment. Notable examples are the dynamical symmetries of the Interacting Boson Model (IBM) for the description of collective valence shell excitations of heavy nuclei [1]. Several nuclides have been identified over the last four decades whose low-energy excitation spectra would closely correspond to the predictions of dynamical symmetries.

Some Pt isotopes [2] and nuclides of the A≈130 mass region [3] have been claimed to be good realizations of the O(6) symmetry which corresponds to the structure of a deformed rotovibrator with fluctuating triaxiality in terms of the geometrical model. Recent data from ultra-high statistics γ-ray spectroscopy in projectile-Coulomb excitation of Xenon isotopes [4,5] have questioned the previous claims for the A≈130 mass region. In particular, the absolute E2 decay strengths of the excited states with claimed O(6) quantum number $\sigma = N-2$ were found to be incompatible with that assignment.

It was obvious that a similar investigation of the Pt isotopes was necessary. We have performed ultra-high statistics γ-ray spectroscopy experiments in projectile-Coulomb excitation reactions of ^{194,196}Pt isotopes using the gammasphere detector array at ANL. Comprehensive information on absolute E2 transition rates has been obtained and will be presented. Electron scattering experiments at the Superconducting Darmstadt Linear electron Accelerator (S-DALINAC) on ^{196}Pt yield complementary information. While realizations of the O(6) dynamical symmetry are very rare, the occurrence of O(6) partial dynamical symmetries are more frequent [6] and are recently found [6] to occasionally coincide with an SU(3) quasi-dynamical symmetry.

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Measurements of neutron-induced capture cross-sections at the n_TOF facility at CERN

M.Barbagallo[1] on behalf of the n_TOF Collaboration[2]

Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Bari, 70125, Italy
[2]*www.cern.ch/nTOF*

Neutron-induced capture cross-sections are of particular interest in the field of Nuclear Astrophysics, as well as for advanced Nuclear Technologies, namely Generation IV Reactors, Accelerator Driven Systems (ADS) and reactors based on the Th/U fuel cycle.
Some of the needs of accurate new data on neutron-induced reaction for Astrophysics and Applications can be addressed at the the Neutron Time-Of-Flight (n_TOF) facility operative at CERN since more than a decade. Indeed high quality results on capture and on fission cross sections have been obtained up to date for a very wide range of isotopes, many of which radioactive, ranging from light elements to U, Pu and Minor Actinides
The well suited features of the facility, namely the high instantaneous neutron flux [1], high resolution and wide energy range are complemented by high performance detection systems for capture reactions: a pair of low neutron sensitivity C_6D_6 detectors and a 4π BaF_2 Total Absorption Calorimeter. Data on a given isotope are often collected with both systems, in order to reduce systematic uncertainties and to reach accuracy as low as few percent. This approach has been followed, as an example, on the measurement of the ^{197}Au(n,γ) [2] and, more recently, on the ^{236}U(n,γ) reaction, whose results will be also presented in this talk.

Recently a second experimental area, at a shorter flight path distance (20 m vs 185 m), has been proposed and is now under construction. The shorter flight-path ensures a 25 times higher flux, relative to the first beam line, resulting also in a very strong reduction of the background related to the natural radioactivity of the sample. Taking advantage of both experimental areas, it will be possible to further increase the measurement capabilities of the facility, allowing to extend the experimental program performed so far.

After a brief description of the facility, the most significant results obtained so far on capture cross section measurements will be reported, together with the program foreseen in the next future in both experimental areas.

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Impact of neutron capture reactions on s-process nucleosynthesis

M. Pignatari[1,2], U. Battino[1,2], A. Koloczek[3,2], B. Thomas[3,2], C. Ritter[4,2], R. Reifarth[3,2], F. Herwig[4,2]

[1]*Department of Physics, University of Basel, Klingelbergstr. 82, CH-4056 Basel, Switzerland*
[2]*NuGrid collaboration, http://www.nugridstars.org*
[3]*Goethe University, 60438 Frankfurt am Main, Germany*
[4]*Department of Physics & Astronomy, University of Victoria, Victoria, BC, V8P5C2 Canada*

The slow neutron capture process (s process) in stars is responsible for the production of a relevant part of elements heavier than iron observed today in the Solar System. For instance, most of the solar abundances of copper, gallium and germanium are made by the s process in massive stars (M > 10Msun), while most of the solar barium, lanthanum and lead are made by the s process in low-mass and intermediate-mass stars, during the Asymptotic Giant Branch (AGB) phase. The nucleosynthesis abundance yields from theoretical stellar models are a fundamental tool to analyze and understand the observation of these elements, in our Sun or in other stars in the Milky Way and further away, e.g., in globular clusters or in dwarf spheroidal galaxies. The predictive power of these theoretical predictions are also affected by the uncertanty of the nuclear reaction rates. For instance, it is well-known the impact of the ^{22}Ne(α,n)^{25}Mg reaction on the s process in massive stars and in AGB stars.

In this presentation we will consider the impact of neutron capture reaction rates uncertainty on the s-process stellar yields. Charged particle reactions directly affect the production of neutrons. On the other hand, the neutron capture rates of light species (e.g., ^{20}Ne and ^{25}Mg) defines the neutron economy in the stellar environment, and how much of these neutrons are captured by the iron seeds to make heavy elements. The detailed distribution of s-process isotopes beyond iron depends on the neutron capture reaction rates of heavy species. In particular, the branching points between neutron capture and β-decay for a number of unstable isotopes (e.g., ^{63}Ni, ^{78}Se and ^{85}Kr) become of great astrophysical interest if the relevant nuclear reaction rates are known and constrained from experiments. Indeed, the relative abundances of stable isotopes located near the branching points can provide fundamental insights about stellar interiors where the s process is activated.

Session 3 – Room 120: Nuclear Structure

Quantum Phase Transitions in many-body systems

F. Iachello[1]

[1]*Center for Theoretical Physics, Yale University,*
New Haven, Connecticut 06520-8120, USA

Quantum Phase Transitions (QPT) are phase transitions that occur as a function of a coupling constant in the Hamiltonian describing the system. Originally introduced in nuclear physics [1], they have been in recent years applied to all fields of physics [2]. In nuclear physics, they have been mostly discussed within the context of the interacting boson model (IBM) (shape phase transitions). In this talk, the phase diagram of IBM will be shown and experimental evidence for QPTs presented [3, 4].

QPTs are phase transitions between different symmetries of many-body systems. In recent years it has been suggested [5] that in addition to the symmetries of the different phases of the system, there are symmetries which occur at the critical point of the phase transition, called "critical" symmetries. This surprising result has been verified experimentally in a series of nuclei, ^{150}Nd, ^{152}Sm, ^{154}Gd. The experimental evidence for critical symmetry in ^{152}Sm [6] will be presented.

Finally QPTs in mixed Bose-Fermi systems (odd-A nuclei) will be discussed and the experimental evidence in $_{61}$Pm, $_{63}$Eu and $_{65}$Tb presented [7]. It will be shown that the odd particle acts as a retarder or as a catalyst of the phase transition, depending on the sign of the interaction between the bosons and the odd-particle [8]. Critical Bose-Fermi symmetries will be also briefly discussed [9].

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Nuclear Forces and Exotic Oxygen and Calcium Isotopes

Jason D. Holt[1,2]

[1]*Technische Universität Darmstadt / 64289, Darmstadt / Germany*
[2]*TRIUMF / V6T 2A3, Vancouver / Canada*

With the advent of next-generation rare-isotope beam facilities worldwide, thousands of undiscovered nuclei, often existing at the limits of stability, will be created and studied in the laboratory. The quest to understand from first principle the properties of these exotic nuclei, many critical for understanding the origin of heavy elements in the universe, represents a cornerstone of modern nuclear science. At the heart of these efforts are three-nucleon (3N) forces. Within the context of valence-space Hamiltonians derived from different ab initio many-body methods, I will discuss the importance of 3N forces in understanding and making new discoveries in two of the most exciting regions of the nuclear chart: exotic oxygen and calcium isotopes.

Beginning in oxygen, we find that the effects of 3N forces are decisive in explaining why ^{24}O is the last bound oxygen isotope [1,2]. Furthermore, 3N forces play a key role in reproducing spectra, including signatures of doubly magic ^{22,24}O, as well as properties of isotopes beyond the dripline [2,3,4]. The calcium isotopes, with potentially three new magic numbers beyond the standard N=20,28, present a unique laboratory to study the evolution of shell structure in medium-mass nuclei. From the viewpoint of two-neutron separation energies and spectroscopic signatures of doubly-magic systems, we emphasize the impact of 3N forces in reproducing the N=28 magic number in ^{48}Ca [5] and in predicting properties of $^{50-56}$Ca, which indicate new N=32,34 magic numbers. Finally, I will highlight the close connection of this work with recent and future experimental efforts in these regions [4,7-9].

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Disentangling the nuclear shape coexistence in even-even Hg isotopes using the interacting boson model

José-Enrique García-Ramos[1], Kris Heyde[2]

[1]Departamento de Física Aplicada, Universidad de Huelva, 21071 Huelva, Spain
[2] Depart. of Physics and Astronomy, Ghent Univ., Proeftuinstraat, 86 B-9000 Gent, Belgium

Shape coexistence has been observed in many mass regions throughout the nuclear chart and turns out to be realized in more nuclei than anticipated a few decades ago [1]. A particularly well-documented example of shape coexistence is the Pb region where ample experimental evidence for shape coexisting bands has been accumulated for the Pt (Z=78), Hg (Z=80), Pb (Z=82), and Po (Z=84) nuclei. In the case of the Hg and Pb nuclei the existence of intruder configurations is self-evident after a careful inspection of the energy level systematics, where the intruder energies show a parabolic behavior. However, in the case of the Pt and Po nuclei, the presence of intruder configurations is somehow hidden [2,3] and not fully evident only considering excitation energies and transition probabilities.

In this contribution, we study the long chain of even-even Hg isotopes, $^{172-200}$Hg, using a symmetry dictated model, i.e., the Interacting Boson Model including configuration mixing (IBM-CM in short). This work has been triggered by the ample experimental evidence in this mass region of shape coexistence, in particular, by the very recent Coulomb excitation experiments in the neutron deficient Hg isotopes, $^{182-188}$Hg, providing unique evidence for the presence of two competing structures with quite different deformation [4].

To carry out our analysis we start considering all the available experimental data, regarding excitation energies and transition probabilities. That allows us to extract the parameters of the IBM-CM Hamiltonian and therefore a consistent description of spectra and electromagnetic transition rates for the whole Hg chain. Moreover, we obtain, in the framework of the IBM-CM, a precise description of the wave functions of the collective states for the whole chain of isotopes and therefore the capability of calculating other observables.

We have proven the coexistence of two types of configurations: a slightly deformed oblate (regular) configuration and a more deformed prolate (intruder) configuration. It turns out that the 0^+ ground state is characterized by the oblate configuration with the prolate configuration admixture never exceeding 20%. The situation is different for the 2^+ states, where a much larger mixing results. We also explored the influence of shape coexistence on several observables, such as the quadrupole moment and the nuclear radius (or the isotopic shift). Both observables agree very well with the experimental data and independently confirm the presence of two coexisting configurations.

Calculations of the mean-field energy surfaces in the framework of the IBM-CM also give rise to the presence of two coexisting minima (near the N=104 mid-shell) very close in energy. Surprisingly, our calculations are fully equivalent with Hartree-Fock-Bogoliubov (HFB) calculations using Skyrme interactions [5].

Finally we have calculated quadrupole shapes invariants which can be directly compared with experiment [4], confirming the presence of two coexisting structures around mid-shell: a slightly oblate one, which turns to describe the ground state, and a prolate one very close in energy to the ground state.

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Collectivity in Gadolinium

S. R. Lesher[1,2], A. Aprahamian[2], C. Casarella[2], B.P. Crider[3], I. Marsh[1], E. E. Peters[3], M. Smith[2], S. W. Yates[3]

[1]*Univ. of Wisconsin – La Crosse, La Crosse, WI 54601 / USA*
[2]University of Notre Dame, Notre Dame, IN 46556 / USA
[3]*University of Kentucky, Lexington, KY 40506 / USA*

The nature of low-lying excitations, $K^{\pi}=0^+$ bands in deformed nuclei remain enigmatic in the field, especially in relationship to quadrupole vibrations. One method of characterizing these states is by reduced transition probabilities, B(E2) values, a measure of the collectivity. These values can be measured directly by Coulomb excitation or calculated from measured lifetime values. Within the deformed region, there are five stable Gd isotopes, three of which have been studied to obtain B(E2) values, a fourth, ^{160}Gd is the focus of this work. We have examined ^{160}Gd with the (n,n'γ) reaction and neutron energies up to 3.0 MeV to confirm known 0^+ states. Angular distributions at three different neutron energies were performed to determine their lifetimes through DSAM measurements. Gamma-ray excitation functions, angular distribution, and lifetime measurements will be presented and compared with the other Gd isotopes.

Partial dynamical symmetry and odd-even staggering in deformed nuclei

A. Leviatan

Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel

The concept of dynamical symmetry (DS) is now widely accepted to be of central importance in our understanding of many-body systems, such as nuclei. Its hallmarks are the solvability of the complete spectrum, and the existence of exact quantum numbers for all eigenstates. However, in most applications to realistic systems, the predictions of an exact DS are rarely fulfilled and one is compelled to break it. More often one finds that the assumed symmetry is not obeyed uniformly, i.e., is fulfilled by only some states but not by others. The need to address such situations has led to the introduction of partial dynamical symmetries (PDSs). The essential idea is to relax the stringent conditions of complete solvability, so that the DS is broken, but part of the eigenspectrum remains solvable with good symmetry. Various types of bosonic and fermionic PDSs have been shown to be relevant to nuclear spectroscopy [1]. In the present contribution we extend the PDS notion to encompass Hamiltonians with higher-order terms. We present a systematic procedure for constructing such PDS Hamiltonians [2], and demonstrate their relevance to the odd-even staggering found in the γ-band of the axially-deformed nucleus ^{156}Gd [3].

The SU(3)-DS limit of the interacting boson model (IBM), exhibits a rotor-like spectrum and E2 rates for all bands. Such a pattern is suitable for the ground and β bands in ^{156}Gd, but is in marked disagreement with the pronounced odd-even staggering observed in the γ-band. An improved description of such signature splitting, necessitates the inclusion of at least cubic terms in the Hamiltonian. In the IBM there are 17 possible three-body interactions. One is thus confronted with the need to select suitable higher-order terms that can break the DS in the γ-band but preserve it in the ground and β bands. As will be shown, this can be accomplished by the PDS construction mentioned above. The analysis serves to highlight the merits gained by using the notion of PDS as a criterion for selecting higher-order terms in situations when a prescribed symmetry is not obeyed uniformly. On one hand, the PDS approach allows more flexibility by relaxing the constraints of an exact DS. On the other hand, the PDS picks particular symmetry-breaking terms which do not destroy results previously obtained with a DS for a segment of the spectrum. The PDS construction is implemented order by order, yet the scheme is non-perturbative in the sense that the non-solvable states experience strong symmetry-breaking. These virtues can be exploited in attempts to extend the ab-initio and beyond-mean-field methods to heavy nuclei.

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Session 4 – Room 028: Nuclear Reactions

Combined study of the gamma-ray strength function of [114]Cd with (n,γ) and (γ,γ') reactions

T. Belgya[1], R. Massarczyk[2], L. Szentmiklósi[1], G. Schramm[2], R. Schwengner[2], A.R. Junghans[2], A.Wagner[2] and E. Grosse[2]

[1]_Nuclear Analysis and Radiography Department, Institute for Energy Security and Environmental Safety, Centre for Energy Research H-1525 POB 49, Budapest, Hungary_
[2]_Helmholtz-Zentrum Dresden-Rossendorf, Institute of Radiation Physics, D-01328 Dresden, Germany_

Collaboration on strength function measurements and evaluations has been started between the Budapest Prompt Gamma Neutron Activation Analysis and the ELBE Nuclear Physics group within the framework of EU FP6 EFNUDAT project. The idea was to prove that theoretical descriptions of measured gamma-ray spectra collected in the (n,γ) and (γ,γ') reactions can be described using same gamma-ray strength functions in a wide energy range from 1 to 10 MeV for the same residual nucleus. For this reason, we have selected pairs of isotopes for which the neutron capture state has the same spin and parity to the favoured 1^- that are most probably excited in the (γ,γ') reactions. We found only two stable pairs of nuclei, namely the [77,78]Se and [195,196]Pt for these studies and showed that indeed the same gamma strength function can be applied for each residual nucleus in describing the observed spectra independent of the applied reactions [1,2].

For the third pair of isotopes [113,114]Cd the capture state has 1^+ spin and parity. Never the less, the combined study can underline whether the parity plays an important rule or not. Preliminary results fro the combined study and development in the data analysis of the Budapest group will be presented in the paper.

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^{89,90}Zr(n,γ) and ^{87}Y(n,γ) from surrogate reaction approach

Shuya Ota[1], J.T. Burke[1], R.J. Casperson[1],
J.E. Escher[1], R.O. Hughes[1], J.J. Ressler[1], N.D. Scielzo[1], I. Thompson[1],
R.A.E. Austin[2], E. McCleskey[3], M. McCleskey[3],
A. Saastamoinen[3], J. Benstead[4], T, Ross[5]

[1]Lawrence Livermore National Laboratory, CA/USA
[2]St. Mary's University, TX/USA
[3]Texas A&M University, TX/USA
[4]University of Surrey, UK
[5]University of Kentucky, KY/USA

The surrogate nuclear reaction approach is an indirect method for determining nuclear reaction cross sections which cannot be measured directly or predicted reliably [1]. While recent studies proved validity of the surrogate reaction approach for studying fission cross sections of short-lived actinides [2], its applicability for radiative neutron-capture reactions ((n,γ)) is still under investigation [3]. We studied the γ-decay of ^{90,91}Zr and ^{88}Y produced by ^{91}Zr(p,d), ^{92}Zr(p,d) and ^{89}Y(p,d), respectively, in order to infer the ^{89,90}Zr(n,γ) and ^{87}Y(n,γ) cross sections. The experiments were carried out at the H150 Cyclotron facility at Texas A&M University with a 28.5 MeV proton beam. The reaction deuterons were measured at forward angles of 30-60∘ with the STARS (Silicon Telescope Array for Reaction Studies) array of three segmented Micron S2 silicon detectors. The compound nuclei with energies up to a few MeV above the neutron separation thresholds were populated. The coincident γ-rays were measured with the LiTeR (Livermore Texas Richmond) array of five Compton-suppressed HPGe clovers. We will present results of γemission probabilities of ^{89,90}Zr(n,γ) and nuclear structure studies of ^{88}Y and some theoretical discussions.

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Studies of ^{54,56}Fe neutron scattering cross sections[‡]

<u>S. F. Hicks</u>[1], J. R. Vanhoy[2], A. J. French[1], S. L. Henderson[1], T. J. Howard[1], R. L. Pecha[1], Z. C. Santonil[1], B.P. Crider[3], S. Liu[3], M.T. McEllistrem[3], E.E. Peters[3], F.M. Prados-Estévez[3], T. J. Ross[3], S.W. Yates[3]

[1]University of Dallas, 75062 Irving, TX USA
[2]United States Naval Academy, 21402 Annapolis, MD USA
[3]University of Kentucky, 40506-0055 Lexington, KY USA

Elastic and inelastic neutron scattering differential cross sections and γ-ray production cross sections have been measured on ^{54,56}Fe at several incident energies in the fast neutron region between 1.5 and 5.0 MeV. All measurements were completed at the University of Kentucky Accelerator Laboratory (UKAL) using a 7-MV Model CN Van de Graaff accelerator, along with the neutron production and neutron and γ-ray detection systems located there. The facilities at UKAL allow the investigation of both elastic and inelastic scattering with nearly monoenergetic incident neutrons. Time-of-flight techniques were used to detect the scattered neutrons for the differential cross section measurements. The measured cross sections are important for fission reactor applications and also for testing global model calculations such as those found at ENDF[1], since describing both the elastic and inelastic scattering is important for determining the direct and compound components of the scattering mechanism. The γ-ray production cross sections are used to determine cross sections to unresolved levels in the neutron scattering experiments. Results from our measurements and comparisons to model calculations will be presented.

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^{124}Xe(n,γ)^{125}Xe and ^{124}Xe(n,2n)^{123}Xe measurements for National Ignition Facility

Megha Bhike[1,2], Matthew Gooden[2,3], Nurin Ludin[4], and Werner Tornow[1,2]

[1]Department of Physics, Duke University, Durham, NC 27708, USA
[2]Triangle Universities Nuclear Laboratory, Durham, NC 27708, USA
[3]Department of Physics, North Carolina State University, Raleigh, NC 27695, USA
[4]University of Denver, CO, 80208, USA

Nuclear reactions play an important role in understanding the complicated physics governing the Inertial Confinement Fusion (ICF) plasma. Currently, a consistent theory of stopping powers of charged-particles in ICF plasmas does not exist. However, the neutron energy distribution created in Deuterium-Tritium(DT) ICF plasmas strongly depends on the stopping power of deuterons and tritons in the plasma. Therefore, efforts are underway at the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory to accurately measure the neutron energy distribution obtained in DT shots. NIF employs 192 powerful lasers which are designed to deposit up to 500 TW of peak power – 1000 times more than the United States uses at any one moment – and up to 1.85 MJ of UV light on a small DT capsule.

The radius of a DT capsule is typically between 200 and 400 μm. The outer ablator consists of plastic or beryllium which almost completely burns away when hit by the lasers. For diagnostic purposes about 10^{15} atoms of ^{124}Xe are loaded into the inner-most layer of the ablator shell, which in turn surrounds a layer of DT ice and a sphere of DT gas pressurized to about 20 atm. In the presence of DT neutrons the isotope ^{124}Xe undergoes (n,γ) and (n,2n) reactions, leading to ^{125}Xe and ^{123}Xe, respectively. The threshold for the ^{124}Xe(n,2n)^{123}Xe reaction is 10.569 MeV, and its cross section increases with energy in the neutron energy range of interest. Therefore, this reaction probes the primary 14 MeV DT neutrons and a small portion of the down-scattered neutrons (small-angle scattering). In contrast, the energy threshold of the ^{124}Xe(n,γ)^{125}Xe reaction is zero, and its cross section increases with decreasing neutron energy. With increasing areal density ρR of the DT fuel with radius R, more neutrons will down-scatter to lower energies, thereby increasing the ^{125}Xe activity at the expense of the ^{123}Xe activity, which to a large extent depends on the primary DT neutron yield produced in the capsule. Therefore, the ^{125}Xe/^{123}Xe intensity ratio provides a measure for ρR of the ICF plasma.

Following a NIF shot, the isotopes are collected and analyzed using gamma-ray spectroscopy to determine the ^{125}Xe/^{123}Xe ratio. Therefore, the capsule performance can be benchmarked according to the ^{125}Xe/^{123}Xe ratio. However, until now the interpretation of the data relied completely on evaluations and model calculations for the ^{124}Xe(n,γ)^{125}Xe capture cross section.

Therefore, measurements of the neutron radiative-capture cross section of ^{124}Xe have been performed for the first time for neutron energies above 100 keV. In addition, data for the ^{124}Xe(n,2n)^{123}Xe reaction cross section have been obtained from threshold to 14.8 MeV to cover the entire energy range of interest, while previous data existed only at around 14 MeV. The results of our ^{124}Xe(n,γ)^{125}Xe measurements between 0.4 and 7.5 MeV and our ^{124}Xe(n,2n)^{123}Xe measurements will be presented and compared to results from evaluations and model calculations.

Neutron Capture Cross Section Measurement on ^{91}Zr at J-PARC/MLF/ANNRI

J. Hori[1], H. Yashima[1], S. Nakamura[2], K. Furutaka[2], K. Y. Hara[3], H. Harada[2], K. Hirose[2], M. Igashira[3], T. Katabuchi[3], A. Kimura[2], K. Kino[4], F. Kitatani[2], Y. Kiyanagi[5], M. Koizumi[2], M. Mizumoto[3], T. Sano[1], Y. Takahashi[1], and Y. Toh[2]

[1]*Research Reactor Institute, Kyoto University, Kumatori-cho, Sennan-gun, Osaka 590-0494, Japan*
[2]*Japan Atomic Energy Agency, Tokai-mura, Naka-gun, Ibaraki 319-1195, Japan*
[3]*Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology, O-okayama, Meguro-ku, Tokyo 152-8550, Japan*
[4]*Graduate School of Engineering, Hokkaido University, Sapporo, Hokkaido 060-8628, Japan*
[5]*Graduate School of Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, 464-8603, Japan*

The neutron capture measurement on ^{91}Zr was performed using the Accurate Neutron-Nucleus Reaction measurement Instrument (ANNRI) [1, 2] installed at the Materials and Life-science experimental Facility (MLF) in J-PARC. Prompt capture gamma rays from the sample were detected with a 4π Ge spectrometer [3] at a distance of 21.5 m from the spallation neutron source by the neutron Time-of-Flight (TOF) method. A metal disk with a weight of 78 mg and with an isotopic purity of 88.7 % was used as the ^{91}Zr sample.

The net gamma-ray pulse-height spectra corresponding to the 182-eV p-wave resonance and the 292-eV s-wave resonance were obtained by gating on the TOF regions, respectively. Though the decay patterns of primary transitions from the capture state were quite different between the resonances, the prominent characteristic common to both resonances was the very strong ground-state transition from the 935-keV state. Therefore, a ground-state transition method was applied to obtain the capture yield, so that the background components due to impurities such as Hf and W contained in the sample were successfully extracted. The energy dependence of the incident neutron flux was determined by measuring the 478-keV gamma ray from the ^{10}B(n,$\alpha\gamma$) reaction.

The neutron capture cross sections of ^{91}Zr were obtained in the energy range from 0.01 eV to 5 keV. The present cross section results were compared with previous experimental and evaluated data.

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Session 5 – Room 120: Nuclear Structure

Complementarity in nuclear structure studies

Paul E. Garrett

Dept. of Physics, University of Guelph, Guelph, ON Canada N1G2W1

The atomic nucleus enjoys a rather unique place in physics. A many-body fermionic system with two basic building blocks, it exhibits incredibly complex excitations. Compared with molecular systems, for example, where rotational, vibrational, and electronic excitation energy scales differ by one to two orders of magnitude, in the nuclear system the energy scales are approximately equal. Because of this, very detailed spectroscopy is required to determine the nature of the excitation; the excitation energy alone is insufficient. Fortunately, we have at our disposal a wide variety of probes that can be used, some of which are highly selective and directly probe the components in the wave function, such single- and two-nucleon-transfer reactions, high-energy inelastic hadronic scattering, etc., and others that are insensitive to the details of the nuclear wave functions, such as fusion-evaporation reactions, low-energy inelastic scattering.

Nuclei lying on or near the valley of stability can typically be studied by the variety of techniques mentioned above so that a large complementary data set can be obtained. The complementary data can shed light on both collective, pairing, and single-particle aspects of the excitations, sometimes in a contradictory way. While the contradictions can appear at first to be puzzling, the full scope of information ultimately leads to a deeper understanding of excited states in nuclei. Further, the correct interpretation of excited states in nuclei near stability is vital to serve as benchmarks when attempting to elucidate structure in nuclei far from stability. Examples of the information gleaned from complementary studies [1,2], such as in the Cd isotopes, will be given. In addition, the need to repeat experiments with modern facilities and spectrometers will be stressed through examples of recent work β-decay work [3,4,5,6] performed at the TRIUMF-ISAC facility, and transfer reactions with the Q3D [7,8,9] spectrometer at Munich, that challenge accepted interpretations of the structure.

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Microscopic analysis of quadrupole-octupole shape evolution

Kosuke Nomura

Grand Accélérateur National d'Ions Lourds (GANIL), CEA/DSM-CNRS/IN2P3,
F-14076 Caen Cedex 5, France

The evolution of nuclear equilibrium shapes and the corresponding collective excitations present one of the most intriguing aspects of nuclear many-body problems. Most deformed medium-heavy and heavy nuclei are quadrupole (reflection symmetric) shaped, but in particular regions of mass table octupole deformations (reflection asymmetric, or pear-like shapes) occur, which is characterized by the low-lying negative-parity band and by the enhanced E1 and E3 transitions [1]. The renewed interest in the studies of reflection asymmetric nuclear shapes using accelerated radioactive ion beams [2] point to the significance of a timely systematic theoretical analysis of quadrupole-octupole collective states of nuclei.

In this work we analyse the quadrupole-octupole collective states in characteristic sets of deformed medium-heavy and heavy nuclei based on the microscopic energy density functional (EDF) theory. The analysis starts by the constrained self-consistent mean-field calculation using a given EDF to generate the potential energy surface with quadrupole and octupole degrees of freedom. A quantitative study of nuclear collective excitation must include symmetries (spin, parity, particle number, … etc) and fluctuations that are missing in the mean-field approximation. The excitation spectra for both positive- and negative-parity states and the transition rates are computed by using the Hamiltonian of the appropriate version of the interacting boson model, whose parameters are determined by mapping the microscopic potential energy surface onto the expectation value of the Hamiltonian in the boson condensate state [3].

In this talk, I will discuss the outcome of our recent studies [4,5] on the quadrupole-octupole collective states in two characteristic mass regions of octupole deformations, that is, rare-earth and light actinide nuclei. Consistently with the empirical trend, the microscopic calculation based on the systematics of the \beta2-\beta3 energy surfaces, the resulting low-lying negative-parity states and the transition rates show the evidence for a shape transition between stable octupole deformation and octupole vibrations characteristic for \beta3-soft potentials. In particular, our result suggests that 226Th and 224Ra nuclei present the best cases exhibiting the pronounced octupole collectivity, the latter being a manifest octupole deformed nucleus in the recent Coulomb excitation measurement [2].

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Shell model estimate of electric dipole moment in medium and heavy nuclei

E. Teruya[1], N. Yoshinaga[1], and K. Higashiyama[2]

[1]*Department of Physics, Saitama University, Saitama City 338-8570, Japan*
[2]*Department of Physics, Chiba Institute of Technology, Narashino, Chiba 275-0023, Japan*

The existence of a finite permanent electric dipole moment (EDM) of a particle or an atom indicates violation of time-reversal symmetry (*T*). It implies simultaneous violations of charge conjugation (*C*) and parity symmetry (*P*) through the *CPT* invariance. The Standard Model predicts tiny EDMs, which are too small to be detected in present experimental accuracy. However, many extensions of the standard model, such as a supersymmetric theory, naturally produce much larger EDMs. Thus, an experimental measurement of the EDM is one of the best probes for the physics beyond the Standard Model. The EDM of a neutral atom with closed electron subshells is mainly induced by the nuclear Schiff moment, since the electron EDM is very small and the nuclear EDM is shielded by outside electrons owing to the Schiff theorem [1]. Nuclear Schiff moments for various nuclei were calculated in terms of the nuclear mean field theories [2,3] and some collective models [4,5]. However, no study has yet been made from the nuclear shell model point of view.

The nuclear Schiff moment is induced mainly by two different sources of mechanism. One comes from the nucleon intrinsic EDM. The other comes from the two-body nuclear interaction which violates *P* and *T* invariance. In this work, we estimate the Schiff moments of Xe isotopes assuming the both sources. In order to describe the nuclear structure of these nuclei, we have used the full shell model [6]. The effective Hamiltonian employed in the present shell model calculations consists of the single particle energies and the monopole and quadrupole pairing plus quadrupole-quadrupole interactions. As for single-particle levels, the four orbitals, $0g_{7/2}$, $1d_{5/2}$, $1d_{3/2}$, $0h_{11/2}$ and $2s_{1/2}$, in the major shell between the magic numbers 50 and 82 are considered for both neutrons and protons. The shell model calculations reproduce well the experimental energy levels and electromagnetic transition rates for the low lying and high-spin states.

Using the theoretical results of the shell model, we predict the Schiff moments for Xe isotopes by making use of the neutron intrinsic EDM and the two-body interaction violating *P* and *T* invariance. The theoretical results will be presented and discussed in this conference.

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Octupole Correlations in Positive-Parity States of the Rare-Earth and Actinide Nuclei

Mark Spieker[1], Dorel Bucurescu[2], Janis Endres[1], Thomas Faestermann[3], Ralf Hertenberger[4], Sorin Pascu[1,2], Hans-Friedrich Wirth[4], Nicolae-Victor Zamfir[2], and Andreas Zilges[1]

[1]*Institute for Nuclear Physics, University of Cologne, 50937 Cologne, Germany*
[2]*Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania*
[3]*Physik Department, Technische Universität München, Germany*
[4]*Fakultät für Physik, Ludwig-Maximilians-Universität München, Germany*

Very recently, experimental data for ^{220}Rn and ^{224}Ra [1] have triggered new interest in the octupole degree of freedom in the actinides and rare earths [2-4]. While these studies discussed the possibility of a first-order phase transition to octupole-deformed shapes to be observed already in the ground state, also second-order phase transitions to octupole-deformed shapes at higher spins have been studied in the actinides [5]. Furthermore, the possibility of octupole-phonon condensation [6] has been discussed to describe the experimental results in the actinides [7] and rare earths [8]. As a common feature, Refs. [5-7] have pointed out the importance of including double-octupole phonon excitations.

In this contribution, we will present further evidence of the importance of multiphonon-octupole excitations to describe new and existing experimental data. First, we will present new results of a (p,t) experiment at the Q3D magnetic spectrograph in Munich, which we performed to selectively excite $J^\pi=0^+$ states in ^{240}Pu. Especially for the second $J^\pi=0^+$ states of the actinides, a pairing isomeric character has been previously discussed because of their uniformly strong (p,t) population. In our recent publication we have shown that the *spdf* interacting boson model (IBM) is able to describe the observed strong (p,t) population, while predicting a double-octupole structure of the second $J^\pi=0^+$ state in ^{240}Pu [9]. It will also be shown that the inclusion of the negative-parity bosons is important to describe the enhanced *E1* transitions observed for the second $K^\pi=0^+$ rotational band members [9]. Second, we have adopted the framework of the IBM for the description of experimental observables related to octupole excitations in the rare earths. Here, we could show that the IBM is able to describe the signature splitting and the *E1/E2* ratios between positive- and negative-parity states when multi-dipole and multi-octupole bosons are included. The present study might support the idea of octupole-phonon condensation at intermediate spin ($J^\pi=10^+$) to describe the change in Yrast structure observed in the rare earths.

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"No-spin" states and low-lying structures in ^{130}Xe and ^{136}Xe

T.J. Ross[1], E.E. Peters[1], A. Chakraborty[1], B.P. Crider[1], A. Kumar[1], S.H. Liu[1], M.T. McEllistrem[1], F.M. Prados-Estévez[1], J.R. Vanhoy[2], and S.W. Yates[1]

[1]*Departments of Chemistry and Physics & Astronomy, University of Kentucky, Lexington, KY 40506, USA*
[2]*Department of Physics, United States Naval Academy, Annapolis, MD 21402, USA*

The xenon isotopes have recently become the focus of experimental studies with interests including the location of mixed-symmetry states, the transition from gamma-soft to vibrational character, and pairing correlations [1]. Studies of ^{130}Xe and ^{136}Xe are also timely due to their relevance to neutrinoless double-beta decay ($0\nu\beta\beta$) searches. ^{136}Xe is seen as a good candidate for observation of the $0\nu\beta\beta$ process and is utilized as both the source *and* detection medium for the EXO project. ^{130}Xe is the daughter nucleus following the decay of ^{130}Te. The low-lying level structure of the nuclei involved (parent, intermediate and daughter) can play a role in nuclear matrix element calculations, which are of vital importance if one is to extract a neutrino mass should the ultra-rare process be observed.

Aside from tin, xenon exhibits the longest chain of stable isotopes on the nuclear chart. In spite of this fact, the gaseous nature of the element makes studying these nuclei difficult and requires gas targets or studies in inverse kinematics. At the University of Kentucky Accelerator Laboratory (UKAL), a campaign is in progress to probe these nuclei utilizing the inelastic neutron scattering technique and *solid* xenon difluoride targets. With the (n,n'γ) reaction at UKAL, lifetimes in the femto-second regime can be measured utilizing the Doppler-shift attenuation method [2]. In addition, multipole mixing ratios can be measured and B(E2) values extracted. Complementary excitation function measurements allow gamma-ray threshold and level spin determinations.

Comprehensive spectroscopy of the low-lying structures of ^{130}Xe and ^{136}Xe has been carried out and level schemes have been established. In both cases, clarity is brought to the level schemes with several new J^{π} assignments and numerous new levels. In ^{130}Xe, the Nuclear Data Sheets currently adopt three states as having $J^{\pi} = 0^+$. We comment on the nature of these levels, and observe that the level at 2017 keV could, in fact, be a 0^+ and 2^+ doublet. We assign two new 0^+ levels. Reasonable agreement with the previously accepted level scheme of ^{136}Xe is found up to ~ 3 MeV. However, for the lowest-lying adopted 0^+ state at 2582 keV (erroneously assigned?) we do not observe any depopulating gamma rays. We suggest a new candidate level for the lowest-lying excited 0^+ state in ^{136}Xe. Systematics of the N = 82 nuclei will be discussed.

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The structure of rotational bands in alpha-cluster nuclei

Roelof Bijker

ICN-UNAM, AP 70-543, 04510 Mexico, MEXICO

In this contribution, I discuss an algebraic treatment of alpha-cluster nuclei based on the introduction of a spectrum generating algebra for the relative motion of the alpha-clusters. Particular attention is paid to the discrete symmetry of the geometric arrangement of the alpha-particles, and the consequences for the structure of the rotational bands in the C12 and O16 nuclei. In C12 the alpha-particles are located at the vertices of an equilateral triangle with D(3h) symmetry) [1,2], and in O16 at the vertices of a regular tetrahedron with T(d) symmetry [3,4]. The rotational sequences consist of both positive and negative parity states, just as observed experimentally in C12 [2] and O16 [4], and can be considered as fingerprints of the underlying discrete symmetry of the geometric configuration of the alpha-particles. Of special interest is the geometric structure of the Hoyle band, whether it is a bent-arm configuration [5], or rather an equilateral triangular configuration just as the ground state [2]. It is suggested that a measurement of the rotational excitations of the Hoyle state is crucial [6] to understand the structure of the Hoyle band and to elucidate the geometric arrangement of the three alpha-particles.

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Session 6 – Room 028: Nuclear Reactions

Measurement of neutron capture cross-sections of ^{89}Y at average neutron energies of 15-36 MeV

M. Zaman[1], <u>G.N. Kim</u>[1][1], K. Kim[1], M. Shahid[1], S.C. Yang[1,2], T. Song[2], H. Naik[1,3]

[1]_Department of Physics, Kyungpook National University, Daegu 702-701, Republic of Korea_
[2]_Nuclear Data Center, Korea Atomic Energy Research Institute, Dajeon 305-353, Republic of Korea_
[3]_Radiochemistry Division, Bhabha Atomic Research Center, Mumbai 400085, India_

Corresponding author. Tel.: +82 53 950 5320; fax: +82 53 939 3972.
E-mail address: gnkim@knu.ac.kr (G. N. Kim).

We measured neutron-induced reaction cross-sections for ^{89}Y(n,2n)^{88}Y, ^{89}Y(n,3n)^{87}Y, and ^{89}Y(n,4n)^{86}Y reactions with the average neutron energy region from 15 to 36 MeV by an activation and an off-line γ-ray spectrometric technique. High energy neutrons were produced from the ^{9}Be(p,n) reaction with 25-, 35- and 45-MeV proton beam from the MC-50 Cyclotron at Korea Institute of Radiological and Medical Sciences (KIRAMS). The neutron-induced reaction cross-sections of ^{89}Y as a function of neutron energy were calculated using the TALYS 1.4 with the mono-energetic neutron. The flux-weighted average (n, 2n), (n, 3n) and (n, 4n) reaction cross-sections of ^{89}Y were determined by using the neutron spectrum estimated from the MCNPX code and the reaction cross-sections for mono-energetic neutron. The present flux-weighted average cross-sections for ^{89}Y(n, xn; x=2-4) reactions are compared with the literature data and those from the TALYS 1.4. We observed that the individual reaction cross-section increases sharply from its reaction threshold to the energy where other reaction channel is opened. Then it remains constant for a while until the next reaction channel reaches its maximum.

Photoneutron cross section measurements on Sm isotopes

D. Filipescu[1,2], H. Utsunomiya[3], I. Gheorghe[2], T. Glodariu[2], O. Tesileanu[1], H.T. Nyhus[4], T. Renstrøm[4], T. Shima[5], K. Takahisa[5], Y.-W. Lui[6],S. Miyamoto[7]

[1] *Extreme Light Infrastructure – Nuclear Physics, str. Atomistilor nr. 407, Bucharest-Magurele, P.O.BOX MG6, Romania,*

[2] *National Institute for Physics and Nuclear Engineering Horia Hulubei, str. Atomistilor nr. 407, Bucharest-Magurele, P.O.BOX MG6, Romania,*

[3] *Department of Physics, Konan University, Okamoto 8-9-1, Higashinada, Kobe 658-8501, Japan,*

[4] *Department of Physics, University of Oslo, N-0316 Oslo, Norway,*

[5] *Research Center for Nuclear Physics, Osaka University, Suita, Osaka 567-0047, Japan*

[6] *Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA,*

[7] *Laboratory of Advanced Science and Technology for Industry, University of Hyogo, 3-1-2 Kouto, Kamigori, Hyogo 678-1205, Japan.*

Photoneutron cross section measurements were performed for all the stable Sm isotopes in the γ-ray beam line GACKO (Gamma Collaboration Hutch of Konan University) of the synchrotron radiation facility NewSUBARU[1]. The incident γ rays were produced by the inverse Compton scattering of laser photons on relativistic electrons. Due to the high energy resolution of this new gamma ray source, we investigated the cross sections of (g,n) reactions with a lower degree of uncertainty and also at energies much closer to the neutron emission threshold compared to the previous experiments[2-3]. Using Geant4, the simulations previously used to reproduce the LaBr3 detector response were improved by generating the interaction between the laser photons and the relativistic electrons considering the electron beam size and emittance. The results are important for nuclear astrophysics calculations and also for probing γ-ray strength functions in the vicinity of neutron threshold.

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γ-ray production cross sections of inelastic neutron scattering on natural molybdenum

M. Nyman[1], A. Plompen[1], C. Rouki[1]

[1]*European Commission, Joint Research Centre, Institute for Reference Materials and Measurements, Retieseweg 111, B-2440 Geel, Belgium*

γ-ray production cross sections of inelastic neutron scattering have been measured for molybdenum using the (n,n'γ)-technique. The experiment was performed at the GELINA facility at the Institute for Reference Materials and Measurements (IRMM) with the Gamma Array for Inelastic Neutron Scattering (GAINS) setup. GAINS consisted of eight high purity germanium detectors at the time of this experiment. The sample was made of natural molybdenum, which includes seven isotopes (A = 92, 94, 95, 96, 97, 98, 100). The presence of so many isotopes in the sample leads to overlapping peaks in the spectra, which limits the amount of data that can be extracted from the analysis. Nevertheless, a total of 31 γ rays from the seven isotopes were analysed and γ-ray production cross sections were determined. Comparisons to other experimental results were made when such data was available. Also comparisons with model calculations made with the TALYS code will be shown. In a publication by Garrett *et al.* [1] a normalization of experimental data was done using a calculated gamma-production cross section for the 1510 keV $2^+ \rightarrow 0^+$ transition in ^{92}Mo. A difference of about 40% between the present data for the 1510 keV γ ray and that reported in [1] was found.

[1] P. E. Garrett *et al.*, Phys. Rev. C 62, 054608 (2000).

Neutron capture cross section and capture gamma-ray spectra of ^{138}Ba in the keV-neutron energy region

Tatsuya Katabuchi[1], Shotaro Yanagida[1], Kazushi Terada[1,2],
Nobuyuki Iwamoto[2], Masayuki Igashira[1],

[1]*Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology, Meguro-ku, 152-8550, Tokyo, Japan*
[2]*Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan*

Barium isotopes are important in modelling s-process nucleosynthesis. The neutron capture cross sections of these isotopes are important inputs for the nucleosynthesis model. ^{138}Ba has the smallest neutron capture cross section among the stable Ba isotopes because of the closed neutron shell structure. The neutron capture reaction of ^{138}Ba is dominated by resolved resonances in the astrophysically relevant energy region. The statistical nuclear reaction model does not work well in the resolved resonance region. Thus, reliable experimental data of the ^{138}Ba(n,γ)^{139}Ba cross section are necessary. In the present work, we measured the neutron capture cross section of ^{138}Ba in the energy region from 15 keV to 100 keV by the time-of-flight method. Experiments were performed at the Research Laboratory for Nuclear Reactors at the Tokyo Institute of Technology. Incident neutrons were generated through the ^{7}Li(p,n)^{7}Be reaction by a pulsed proton beam from a Pelletron accelerator bombarding a lithium target. Capture gamma rays from the sample were detected with an anti-Compton NaI(Tl) spectrometer. The (n,γ) cross sections were obtained from the pulse height spectra by the pulse-height weighting technique. A comparison of the present results with previous experimental data and evaluated data as JENDL-4.0 and ENDF/B-VII.1 was made. We also derived gamma-ray spectra by unfolding the pulse height spectra with the detector response function. It was revealed that the shape of the gamma-ray spectra strongly depends on neutron energy.

Experimental neutron capture data of ^{58}Ni from the CERN n_TOF facility

Petar Žugec[1] for the n_TOF collaboration

[1]*Department of Physics, Faculty of Science, University of Zagreb, 10000 Zagreb, Croatia*

The (n,γ) cross section of ^{58}Ni – of importance for the nuclear astrophysics, as well as nuclear technologies – was measured at the neutron time-of-flight facility n_TOF at CERN [1]. For the measurement, two C_6D_6 liquid scintillation detectors were used, specially optimized to provide as low neutron sensitivity as manageable [2].

At n_TOF, the highly luminous white neutron beam covers more than 9 orders of magnitude in energy – from thermal to 1 GeV. It is produced by a pulsed beam of 20 GeV protons irradiating a massive Pb spallation target. Before reaching the experimental area at a distance of approximately 185 m from a spallation target, the beam is shaped by two collimators and cleaned-up of charged particles by a sweeping magnet [3]. The measurement is performed by detecting the prompt capture γ-rays from ^{58}Ni(n,γ) reaction. In order to calculate a capture yield from a measured data, a well-established Pulse Height Weighting Technique was applied. The capture yield was analyzed in the energy range from 27 meV and 400 keV. The resolved resonance region was analyzed up to 122 keV by means of a multilevel R-matrix code SAMMY. Within the resolved resonance region 51 capture resonances were identified and their parameters reported. Complementing these results with the data from the unresolved resonance region – analyzed by the code SESH – the Maxwellian averaged cross sections (MACS) were calculated for the stellar temperatures of kT = 5–100 keV. The new results call for the revaluation of the cross section data presently available in libraries, while revealing a significant impact on ^{58}Ni abundance in the massive stars.

In calculating the capture yield a significant effort has been paid to the clear identification of the various background components. While the environmental and the so called empty-frame background are easily and regularly measured, the neutron background – caused by the neutrons elastically scattered off the sample itself – has been identified for the first time at n_TOF by means of the high-precision GEANT4 simulations [4]. The simulated results were extensively compared against the available experimental data, confirming that they may be used with high degree of confidence for reaching the new precision standards in analyzing the capture data from n_TOF.

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[2] R. Plag, M. Heil, F. Käppeler, et al., Nucl. Instr. and Meth. A 496, 425 (2003)
[3] C. Guerrero, A. Tsinganis, E. Berthoumieux, et al., Eur. Phys. J. A (2013) 49:27
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Measurement of the γ emission probability of ^{173}Yb using transfer reactions

Delaune O.[1], Blanc A.[1], Burke J.T.[2], Casperson R.[2], Chau P.[1], McCleskey M.[3], Meot V.[1], Roig O.[1], Simmons E.[3]

[1] CEA, DAM, DIF, F-91297 Arpajon, France
[2] Lawrence Livermore National Laboratory, Livermore, California 94550, USA
[3] Cyclotron Institute, Texas A&M University, 3366 TAMU, College Station, TX, USA

Radiative neutron capture cross sections measurements on stable nuclei are performed using a rather well mastered technique. However, it is much less straightforward when these cross-section measurements are extracted from radioactive nuclei. Such measurements being very challenging and even impossible to perform, the surrogate reaction method has been proposed and used to obtain some informations about these unstable nuclei. The principle is to use a different target (stable or less radioactive) coupled to a suitable beam in order to produce the same compound nucleus whose the decay is then studied. This surrogate reaction method is succesfully applied to study the fission of the actinides (see for example [1]). The validity of the method is also investigated in the rare earth region[2].

In this framework, a first experiment using the tranfer reaction ^{174}Yb(^{3}He,α)^{173}Yb has shown that the populated spin of the compound nucleus ^{173}Yb are quite high compared to the ones populated in the reaction ^{172}Yb(n, γ)[3]. It has been proposed to use a lighter beam, via the ^{174}Yb(p,d)^{173}Yb reaction, which should transfer fewer angular momentum to the compound nucleus. A second experiment, using the STARS/LiBerACE setup[4], has been performed at Texas A&M University in order to measure the γ emission probability of ^{173}Yb. A proton beam of 25 MeV impinged on a ^{174}Yb target. The ejectile nuclei are identified within a double-sided segmented silicon telescope. Thus, the deuterons tag the production of ^{173}Yb. Meanwhile, the γ-rays are detected using 6 Germanium detectors. The γ emission probability from this experiment is compared to the one extracted from the first experiment (^{174}Yb(^{3}He,α)^{173}Yb).

The validity of the surrogate reaction method in the rare earth region will be discussed and some outlooks will be proposed.

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[2] T.J. Ross et al., Phys. Rev. C 85, 051304(R) (2012)
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Session 7 – Room 120: Nuclear Structure

Gamma-Ray Spectroscopy of Fission Fragments in the EXILL Campaign

G. Simpson[1,2], A. Blanc[3], G. De France[4], M. Jentschel[3], U. Köster[3], P. Mutti[3], T Soldner[3], C. Ur[5], W. Urban[3,6], F. Drouet[2], A. Vancraeyenest[2], J. M. Regis[7], and the EXILL collaboration

[1]*University of the West of Scotland, High Street, Paisley, PA1 2BE UK*
[2]*LPSC, 53 rue des Martyrs, Grenoble, 38026, France*
[3]*ILL, 71 Avenue des Martyrs 38042 Grenoble CEDEX 9, France*
[4]*GANIL, BP 55027, 14076 Caen CEDEX 5, France*
[5]*INFN, Sezione di Padova, Via Marzolo 8, 35131 Padova, Italy*
[6]*Faculty of Physics, University of Warsaw, ul. Hoza 69, PL-00-681 Warsaw, Poland*
[7]*IKP, University of Cologne, Zülpicher str. 77, D-50937 Köln, Germany*

Gamma-ray spectroscopy of neutron-rich fission fragments in the mass range A=80-160 has been performed at the PF1B instrument of the Institut Laue-Langevin. Fission was induced by cold neutrons from the collimated PF1B beam [1, 2], impinging on ^{235}U and ^{241}Pu targets, with thick backings. Prompt gamma rays were detected using the EXOGAM array [3], further augmented with 6 GASP [4] and 2 Clover detectors. A trigger-less data acquisition system recorded all the detector signals, though triple-gamma coincidences were required to select the cascades of interest. The use of ^{235}U and ^{241}Pu targets allows the neutron-rich mass 80-95 and 125-135 regions to be better studied than in previous spontaneous and light-ion induced fission experiments, due to the higher fission yields. These regions lie close to the doubly magic nuclei ^{78}Ni and ^{132}Sn, allowing tests of the interactions used in shell-model calculations to be performed. The campaign will also provide data useful for fission-yield and reactor-heating studies.

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The Generalized Centroid Difference method for lifetime mesaurements via γ-γ coincidences using large fast-timing arrays

J.-M. Régis[1], J. Jolie[1], G. Pascovici[1], M. Pfeiffer[1], M. Rudigier[1], N. Saed-Samii[1], N. Warr[1], A. Blanc[2], A.M. Bruce[3], G. de France[4], L.M. Fraile[5], S. Illieva[6], M. Jentschel[2], U. Köester[2], W. Korten[7], T. Kröll[6], S. Lalkovki[8], H. Mach[5,9], N. Marginean[10], P. Mutti[2], V. Paziy[5], P.H. Regan[11], G.S. Simpson[12], T. Soldner[2], C.A. Ur[13], W. Urban[2,9]

[1]*IKP der Universität zu Köln, Zülpicher Str. 77, 50937 Köln, Germany*
[2]*Institut Laue-Langevin, 6, rue Jules Horowitz, 38042 Grenoble Cedex 9, France*
[3]*School of Computing, Engineering and Mathematics, University of Brighton, Lewes Road, Brighton, BN2 4GJ, United Kingdom*
[4]*GANIL, Bd Henri Becquerel, BP 55027, 14076 Caen Cedex 05, France*
[5]*Grupo de Fisica Nuclear, FAMN, Universidad Complutense, CEI Moncloa, 28040 Madrid, Spain*
[6]*IKP der Technische Universität zu Darmstadt, Schlossgartenstr. 2, 64289 Darmstadt, Germany*
[7]*CEA de Saclay, Route Nationale, 91400 Gif-sur-Yvette, France*
[8]*Faculty of Physics, University of Sofia "St. Kliment Ohridski", 1164 Sofia, Bulgaria*
[9]*National Centre for Nuclear Research, BP1, ul. Hoza 69, PL-00-681, Warsaw, Poland*
[10]*Horia Hulubei NIPNE, 77125 Bucharest, Romania*
[11]*Department of Physics, University of Surrey, Guildford, GU2 7XH, United Kingdom*
[12]*LPSC Grenoble, 53, rue des Martyrs, 38026 Grenoble Cedex, France*
[13]*INFN, Sezione di Padova, Via Marzolo 8, 35131 Padova, Italy*

A novel method for direct electronic ``fast-timing'' lifetime measurements of nuclear excited states via γ-γ coincidences using an array equipped with N very fast high-resolution $LaBr_3(Ce)$ scintillator detectors is presented. The generalized centroid difference method provides two independent ``start'' and ``stop'' time spectra obtained without any correction by a superposition of the N(N-1) calibrated γ-γ time difference spectra of the N detector fast-timing system. The two fast-timing array time spectra correspond to a forward and reverse gating of a specific γ-γ cascade and the centroid difference as the time shift between the centroids of the two time spectra provides a picosecond sensitive mirror symmetric observable of the set-up. The energy dependent mean prompt response difference between the start and stop events is calibrated and used as a single correction for lifetime determination. These combined fast-timing array mean γ-γ zero-time response can be determined for 40 keV < E_γ < 1.4 MeV with a precision better than 10 ps using a ^{152}Eu γ-ray source. The new method is described with examples of (n,γ) and (fission,γ) experiments performed at the intense cold-neutron beam facility of the Institut Laue-langevin in Grenoble, France, using 16 $LaBr_3(Ce)$ detectors within the EXILL&FATIMA campaign 2013. The results are discussed with respect to possible systematic errors induced by background contributions.

The (n,γ) campaigns at EXILL

J Jolie[1], J.-M. Régis[1], D. Wilmsen[1], S. Ahmed[1], M. Pfeiffer[1], N. Saed-Samii[1], N. Warr[1],
Blanc[2], M. Jentschel[2], U. Köster[2], P. Mutti[2], T Soldner[2] G. Simpson[3], G. De France[4],
W. Urban[5], F. Drouet[3], A. Vancraeyenest[3], P. Baczyk[5], M. Czerwinski[5], A. Korgul[5],
C. Mazzocchi[5], T. Rzaca-Urban[5], A. Bruce[6], O.J. Roberts[6], L.M. Fraile[7], V. Paziy[7],
A. Ignatov[8], S. Ilieva[8], Th. Kröll[8], M. Scheck[8,9], J. Stamm[8], M. Thürauf[8], D. Ivanova[10],
S. Kisyov[10], S. Lalkovski[6,10], Z. Podolyak[11], P.H. Regan[11], W. Korten[12], D. Habs[13],
P. Thirolf[13], C. A. Ur[14], C. Bernards[15], R.F. Casten[15], N. Cooper[15], F. Naqvi[15], V. Werner[15,8],
R.B. Cakirli[16], S. Leoni[17], G. Benzoni[17], G. Bocchi[17], S. Bottoni[17], F.C.L. Crespi[17],
B. Fornal[18], N. Cieplicka[18], B. Szpak[18], C.Petrache[19], R. Leguillon[19], R. John[20], C.Lorenz[20],
R. Massarczyk[20], R. Schwengner[20], D. Curien[21], L. Sengele[21]

[1]IKP, University of Cologne, Zülpicher str. 77, D-50937 Köln, Germany,
[2]ILL, 71 Avenue des Martyrs 38042 Grenoble CEDEX 9, France
[3]LPSC, 53 rue des Martyrs, Grenoble, 38026, France
[4]GANIL, BP 55027, 14076 Caen CEDEX 5, France
[5]Faculty of Physics, University of Warsaw, ul. Hoza 69, PL-00-681 Warsaw, Poland
[6]SCEM, University of Brighton, Lewes Road, Brighton BN2 4GJ, UK
[7]Departamento de Fisica Atomica y Nuclear, Universidad Complutese, 28040 Madrid Spain
[8]Institut für Kernphysik, TU Darmstadt, Germany
[9]University of the West of Scotland,Paisley, PA1 2BE, United Kingdom
[10]Faculty Physics, University of Sofia, Bulgaria
[11]Dep. Of Physics, Univ. of Surrey, Guildford GU2 7XH & Nat. Phys. Lab., Teddington, UK
[12]CEA, Centre de Saclay, IRFU, F-91191 Gif-sur-Yvette, France
[13]Fak. F. Physik, LMU, 85748 Garching, Germany
[14]INFN Sezione di Padova, 35131 Padova, Italy
[15]WNSL, Yale University, New Haven (CT), USA
[16]Istanbul University, Istanbul, Turkey
[17]University of Milano and INFN sez. Milano, Italy
[18]The Niewodniczanski Inst. of Nucl. Physics, Polish Academy of Sciences, Krakow, Poland
[19]CSNSM, Orsay, France
[20]Helmholtz-Zentrum Dresden-Rossendorf, 01328 Dresden, Germany
[21]Centre de Recherches Nucléaires, Strasbourg, France

At the PF1B cold neutron beam line at the Institut Laue Langevin the EXILL array consisting of EXOGAM [1], GASP [2] and LOHENGRIN detectors was used to perform (n,γ) measurements at very high coincidence rates. About ten different reactions were measured in autumn 2012 using a highly collimated cold neutron beam [3]. In spring 2013 the EXOGAM array was combined with 16 LaBr$_3$(Ce) scintillators in the FATIMA@EXILL campaign for the measurement of lifetimes using the generalised centroid difference method [4,5]. We report on the properties of the set-ups and present first results from both campaigns.

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From EXILL to FIPPS

M. Jentschel[1], A. Blanc[1], H. Faust[1], P. Mutti[1], U. Koester[1], A. Chebboubi[2], G. Kessedijan[2], C. Sage[2], W. Urban[3], T. Materna[4], S. Panebianco[4]

[1]Institut Laue-Langevin, Grenoble, France
[2]LPSC, Universite Joseph Fourier, Grenoble 1
[3]Insitute of Experimental Physics, Warsaw University
[4]CEA Sacley/DSM/IRFU/SPhN

Within the EXILL campaign a large and efficient cluster of Ge-detectors was installed around a very well collimated neutron beam. This has allowed to carry out rather complete spectroscopic studies close to the line of stability using the (n,gamma) reaction. Neutron rich isotopes were produced by neutron induced fission and prompt spectroscopy was carried out. The isotope selection in this setup was based on a partially known level scheme and the use of triple coincidences. The latter is limiting the statistical sensitivity in the case of weak production yields. Based on the experiences of these campaigns we are currently developing a new setup: FIPPS (FIssion Product Prompt Spectroscopy). This setup combines a collimated neutron beam, a highly efficient cluster of Ge detectors, a gas filled magnet and auxiliary detectors. The presence of the gas filled magnet will allow us to identify fission products directly. This should allow a new quality of studies if compared to the EXILL campaign. The talk discusses the physical case for such a setup, which on the one side is triggered by fission studies and on the other hand by spectroscopic aims. For fission studies the setup should have a maximum solid angle of the magnet to allow best measurements of fission yields. Further it should be combined with an ionization chamber to yield the total kinetic energy. For spectroscopic studies the solid angle of the germanium cluster needs to be large, while the gas filled magnet needs to be optimized for mass resolution and combined with a time of flight setup and/or a time projection chamber for fission fragment tracking. Further options like a low energy detector cluster, a plunger, a conversion electron spectrometer or neutron detectors and potentially possible experiments will be discussed.

Session 8 – Room 028: Nuclear Astrophysics

Heating and cooling in neutron star crusts and what rare isotope facilities can do about it

Hendrik Schatz[1]

[1]Dept. of Physics and Astronomy, NSCL, Joint Institute for Nuclear Astrophysics, Michigan State University, East Lansing, MI 48824, USA

Observations of accreting neutron stars in X-ray binaries provide a unique window into the structure of neutron stars and the properties of dense matter. Observables such as thermonuclear bursts and cooling behavior are strongly affected by nuclear processes in the crust that involve neutron captures and beta decays on extremely neutron rich rare isotopes. These nuclear processes control nuclear heating, neutrino cooling, and compositional changes that affect thermal transport and need to be understood to interpret X-ray observations. The challenges for nuclear physics are similar to understanding the extremely neutron rich nuclei in the r-process. I will discuss recent progress in delineating the nuclear processes in accreting neutron stars, including a novel neutrino cooling process based on electron-capture and beta decay Urca cycles on nuclei in the outer crust. I will also give an overview over astronomical observables and attempts to address the nuclear physics questions through laboratory measurements at rare isotope facilities. This includes the prospects of obtaining most of the nuclear data in the near future with the new FRIB accelerator

Underground cross section measurements of stellar reactions at astrophysically relevant energies

Alba Formicola

(for the LUNA collaboration)
INFN-Laboratori Nazionali del Gran Sasso
S.S.17bis km18+910 67010
Assergi (AQ) Italy

Accurate knowledge of thermonuclear reaction rates is important in understanding the generation of energy, the luminosity of neutrinos, and the synthesis of elements in stars.
The LUNA Collaboration has shown that, by going underground and by using the typical techniques of low background physics, it is possible to measure nuclear cross sections down to the energy of the nucleosynthesis inside stars.
This talk will give an overview of the experimental techniques adopted in underground nuclear astrophysics and will present a summary of the main recent results and achievements.

The future of Nuclear Astrophysics at LUNA

Matthias Junker

(for the LUNA collaboration)
INFN-Laboratori Nazionali del Gran Sasso
S.S.17bis km18+910 67010
Assergi (AQ) Italy

During the last decades the LUNA collaboration has been operating inside the underground laboratories of the Laboratori Nazionali del Gran Sasso (Italy) reaching an unprecedented sensitivity in cross section determination at or close to astrophysical energies. This talk will give an overview of the future actives at LUNA.

Nuclear masses and neutron stars

S. Kreim[1,2]

[1]*CERN, 1211 Geneva, Switzerland*
[2]*Max Planck Institute for Nuclear Physics, Saupfercheckweg 1, 69117 Heidelberg, Germany*

A large fraction of stars end their lives in dramatic explosions forming ultra-compact objects. These resulting neutron stars have an onion-like structure with a density exceeding that of the atomic nucleus. Their outer crust is considered as possible birthplace of the heavy elements through the rapid neutron-capture process of nucleosynthesis. Modeling the neutron star and its composition requires a wide range of physics to model and the knowledge of nuclear binding energies. Masses of exotic nuclides impose constraints on models for the nuclear interaction and thus affect the description of the equation of state of nuclear matter, which can be extended to describe neutron-star matter. With knowledge of the masses of nuclides near shell closures, one can also derive the neutron-star crustal composition.

The Penning-trap mass spectrometer ISOLTRAP at CERN-ISOLDE has recently achieved a breakthrough measuring the mass of 82Zn, which allowed constraining neutron-star crust composition to deeper layers [1]. A more detailed study on the sequence of nuclei in the outer crust of neutron stars with input from different nuclear models illustrates the sensitivity to masses and the robustness of neutron-star models. The dominant role of the N = 50 and N = 82 closed neutron shells for the crustal composition is confirmed [2]. This contribution will present the ISOLTRAP experiment [3] and recently produced mass data. The results will be explained in light of neutron-star models and their composition.

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Session 9 – Room 120: Nuclear Structure

Shapes of exotic nuclei and shell evolution

Takaharu Otsuka[1,2,3],

[1]Department of Physics, University of Tokyo, Hohgo, Bunkyo-ku, Tokyo 113-0033, Japan
[2]Center for Nuclear Study, University of Tokyo, Hohgo, Bunkyo-ku, Tokyo 113-0033, Japan
[3]National Superconducting Cyclotron Laboratoty, Michigan State University, East Lansing MI 48824, USA

Since the proposal by Mayer and Jensen in 1949, the shell structure and magic numbers of atomic nuclei have been considered to remain unchanged among nuclei except for a gradual change as a function of the mass number, A. However, this paradigm has been challenged recently particularly after the shell evolution mechanism due to the tensor force [1,2]. There have been many experiments showing the shell evolution, among which a recent example is the confirmation of neutron number N=34 magic number in ^{54}Ca by RIBF [3]. Here, the shell evolution occurs as a function of the proton number, Z : neutron $f_{5/2}$ goes up rapidly as Z is decreased from Z=28 to Z=20 [3]. Such changes can be called Type I Shell Evolution.

We have reported recently that there is Type II Shell Evolution, where spherical single particle energies, *i.e.*, shell structure, are changed significantly due to massive particle-hole excitations [4]. This produces prominent shape coexistence at low excitation energies. This can be described quantitatively in terms of Monte Carlo Shell Model (MCSM). We applied MCSM to exotic Ni isotopes. The nucleus ^{68}Ni shows a clear example of the coexistence of spherical, oblate and prolate shapes [4,5], mainly due to the reduction of proton $f_{7/2} - f_{5/2}$ splitting caused by neutron excitations from *pf*-shell to $g_{9/2}$. The prolate states come down to the 0^{+}_{2} and 2^{+}_{2} states in ^{70}Ni. Such intriguing phenomenon is gone in heavier Ni isotopes, where Type II Shell Evolution is suppressed due to Type I Shell Evolution. Instead, we show that gamma-softness shows up in ^{74,76}Ni. The double magicity arises in ^{78}Ni in different ways from doubly magic nuclei, ^{56,68}Ni. These points are visualized by a new method to analyze shell-model eigenstates in terms of intrinsic-shape contents and correlations/fluctuations. Thus, Type II Shell Evolution is shown to be an underlying robust mechanism for the shape coexistence in exotic nuclei with realistic nuclear forces including the tensor force.

We shall discuss how one can discuss Type II Shell Evolution from the viewpoint of Landau's quantum liquid theory, introducing a possibly new picture of *multiple quantum liquid*.

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A shell-model study of the light Cd isotopes

A. Blazhev[1], K. Heyde[2], J. Jolie[1], T. Schmidt[1]

[1]Institut für Kernphysik, Universität zu Köln, D-50937 Cologne, Germany
[2]Department of Physics and Astronomy, Ghent University, B-9000 Ghent, Belgium

The Cd isotopes (Z=48) are the two-proton-hole neighbours of the semi-magic Sn isotopes. Adding neutrons to the N=50 closed shell, the energy spectra in the Cd isotopes exhibit a changing character from seniority dominated (near N=50) towards collective spectra with relatively constant energies of the yrast 2+ and 4+ levels when approaching mid-shell. The measured B(E2) reduced transition probabilities along the yrast line increase with increasing neutron number, i.e. one notices an onset of collectivity. Several IBM and collective model studies have tried to describe the Cd isotopes, only with partial success as the experimental data show specific deviations, in particular for the B(E2) values, especially when approaching the middle of the N=50-82 shell.

In an attempt to address the structure in the light Cd isotopes, starting from a microscopic approach, we have performed large-scale shell-model calculations (LSSM) using a monopole corrected G-matrix interaction in the proton ($2p_{1/2}$, $1g_{9/2}$) and the neutron($2d_{5/2}$, $1g_{7/2}$, $2d_{3/2}$, $3s_{1/2}$, $1h_{11/2}$) model space. Results of non-truncated calculations for energy spectra, B(E2) and B(M1) reduced transition probabilities for isotopes up to ^{108}Cd will be presented and discussed. A possible extension of the calculations for the Cd isotopes above A=108 will also be discussed.

We concentrate in particular on the B(E2) values along the yrast band and their variation as a function of increasing neutron number outside of N=50, extensively comparing with the data and the appearance of side-bands as more and more neutrons become active. Moreover, we carry out a detailed study of the E2 decay from the lowest non-yrast states into the yrast band and study the relative B(E2) values intensity decay rates as a marker of collectivity. Particular attention is given in the discussion to the role played by the changing occupation numbers for the neutron orbitals filling between N=50 and N=82 as a function of spin and neutron number.

Recent development of projected shell model based on many-body techniques

Yang Sun[1]

[1]Department of Physics and Astronomy, Shanghai Jiaotong University, Shanghai 200240, China

The original version of the projected shell model [1] assumes a fixed deformation with restricted types of quasi-particle configuration in its model space. We have recently extended the model in the following two aspects. (1) The configuration space has been expanded to include 6-qp states for both positive and negative parities [2]. To avoid a combinatorial complexity in calculating rotated matrix elements of multi-qp states, the Pfaffian algorithm [3] is used to replace the generalized Wick's theorem. This development in many-body techniques enables us to study some interesting high-spin phenomena. As the first application of the Pfaffian algorithm in spectroscopy calculation, we take ^{166}Hf as an example and show that 6-qp states become the main configuration in the yrast band beyond spin $I \sim 34$, which explains the observed third back-bending in moment of inertia. Multi-qp high-K isomers in ^{176}Hf with different configurations are investigated as another example.

(2) To describe fluctuations about deformation equilibrium, we have improved nuclear many-body wave functions by superimposing angular-momentum and particle-number-projected states constructed with different quadrupole deformation and pairing gap parameters as two-dimensional generator coordinates. Using these as trial wave functions, we solve the Hill-Wheeler Equation and analyze obtained weight functions with help of the Gaussian overlap approximation. We take deformed rare-earth nuclei as examples and quantitatively compare the calculated low-lying 0^+ bands and associated electric monopole transition rates with experimental data. The analysis of the obtained results for the excited 0+ states indicates clear features of quantum oscillation, with large fluctuations in deformation found for soft nuclei and strong anharmonicities in oscillation for rigidly-deformed nuclei. We try to identify physical quantities that may help for understanding competitions between shape and pairing fluctuations.

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Session 10 – Room 028: Nuclear Astrophysics

Neutron radiative-capture reactions on nuclei of relevance to $0\nu\beta\beta$, dark matter and neutrino/antineutrino searches

W. Tornow[1,2]

[1]_Department of Physics, Duke University, Durham, NC 27708, USA_
[2]_Triangle Universities Nuclear Laboratory, Durham, NC 27708, USA_

A program is underway at the Triangle Universities Nuclear Laboratory (TUNL) to measure the neutron capture cross section in the 0.5 to 15 MeV energy range on nuclei which potentially could create backgrounds in searches for rare events, which are indistinguishable from the events of interest. Here, we refer to neutrino-less double-beta decay and dark-matter searches, and neutrino and/or antineutrino interactions. Although the associated experiments are mounted or will be mounted underground, cosmic-ray produced spallation neutrons and neutrons from (α,n) reactions are a major concern. So far, (n,γ) cross-section data have been obtained on ^{40}Ar, ^{74,76}Ge, ^{nat}Te, and ^{136}Xe [1]. Mono-energetic neutrons were produced via the reactions ^{7}Li(p,n)^{7}Be, ^{3}H(p,n)^{3}He, ^{2}H(d,n)^{3}He and ^{3}H(d,n)^{4}He using the tandem accelerator facility at TUNL. The neutron capture cross sections have been obtained using the activation technique. Indium and gold foils were used for neutron fluence determination. After irradiation, the de-excitation γ rays were detected off-line with HPGe detectors of well-known efficiency. The cross-section results are compared to evaluations and model calculations, providing in most cases for the first time stringent experimental constraints in the MeV neutron energy regime. To complement the (n,γ) measurements, (n,2n) cross-section data were also obtained. This reaction, with its very large cross section between 10 and 15 MeV, not only acts as a neutron multiplier during the slowing down process of the primary, high-energy spallation neutrons, but it also creates nuclei whose de-excitation γ rays could interfere with the events of interest.

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Neutrinos and the synthesis of heavy elements

O. L. Caballero[1]

[1]*University of Guelph, N1G 2W1 Guelph, Ontario/Canada*

The synthesis of heavy elements in the Universe presents several challenges. From one side the astrophysical site is still undetermined and on other hand the input from nuclear physics requires the knowledge of properties of exotic nuclei, some of them perhaps accessible in ion beam facilities. Black hole accretion disks have been proposed as possible r-process sites. Analogously to Supernovae these objects emit huge amounts of neutrinos. I will discuss the neutrino emission from black hole accretion disks. In particular I will show the influence that the black hole strong gravitational field has on the synthesis of elements [1, 2].

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Nuclear masses near closed shells and their impact on *r*-process abundances

M. R. Mumpower[1], D.-L. Fang[2], R. Surman[3], M. Beard[1], and A. Aprahamian[1]

[1]*University of Notre Dame, Notre Dame, IN 46556, USA*
[2]*Michigan State University, East Lansing, MI 48824, USA*
[3]*Union College, Schenectady, NY 12308, USA*

Nuclear masses are a key ingredient of nuclear physics that go into astrophysical simulations of the *r* process. Nuclear masses effect *r*-process abundances by entering into calculations of Q-values, neutron capture rates, photo-dissociation rates, beta-decay rates and the probability to emit neutrons. Most of the thousands of short-lived neutron-rich nuclei which are believed to participate in the *r* process lack any experimental verification, thus the identification of the most influential nuclei is of paramount importance. We have conducted mass sensitivity studies near the closed shells (N=82 and N=126) in the context of a main *r*-process. Our studies take into account how an uncertainty in a single nuclear mass propagates to influence the relevant quantities of neighboring nuclei and finally to *r*-process abundances. Using various nuclear models and astrophysical conditions we identify key nuclei in these studies whose mass has a substantial impact on final *r*-process abundances and discuss implications for measurements at radioactive beam facilities.

Session 11 – Room 120: Nuclear Structure

Dipole response in neutron rich nuclei within self-consistent approaches using realistic potentials

F. Knapp[1], N. Lo Iudice[2,3], P. Vesely[4], F. Andreozzi[2,3], G. De Gregorio[2,3], A.Porrino[2,3]

[1] *Institute of Particle and Nuclear Physics, Charles University, Prague, Czech Republic*
[2] *Dipartimento di Fisica, Università di Napoli Federico II, Napoli, Italy*
[3] *Istituto Nazionale di Fisica Nucleare (INFN), sezione di Napoli, Napoli, Italy*
[4] *Institute of Nuclear Physics, Academy of Sciences, Czech Republic*

The dipole response in neutron rich medium and heavy nuclei was investigated within self-consistent microscopic frameworks using a chiral potential (NNLO$_{opt}$), whose parameters were optimized up to-next-to-next leading order so as to minimize the effect of the three-body force [1]. Calculations carried out in Hartree-Fock-Bogoliubov plus quasi-particle Tamm-Dancoff (TDA) and random-phase (RPA) approximations have shown that the NNLO$_{opt}$ improves substantially the description of the dipole response as compared to other realistic potentials [2]. A corrective, density dependent, term is still to be added in order to shift the theoretical peaks in the observed regions of the giant (GDR) and pygmy (PDR) dipole resonances. Both TDA and RPA calculations reproduce the overall behaviour of the dipole response and, in particular, yield a low-energy strength comparable in magnitude and shape to the measured one. The analysis of the transition densities to the states in the GDR and PDR regions supports the geometrical pictures associated to these two modes.

For a more realistic study of the fine structure of the two resonances we performed a self-consistent calculation within an equations of motion phonon method (EMPM) [3] in a space spanned by one plus two TDA phonon states.

The two-phonon basis states induce a strong fragmentation of both GDR and PDR. At low energy, a large number of weakly excited levels coexist with few strong excitations around the neutron decay threshold. These levels are excited by both isoscalar and isovector probes and, therefore, seem to be the analogue of the levels detected in (γ,γ') and $(\alpha,\alpha'\gamma)$ in several neutron rich nuclei [4]. The EMPM confirms for several states the geometrical pictures associated to the GDR and PDR. On the other hand, about half of the EMPM states describing the low-lying weakly excited levels have dominant two-phonon components.

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Isospin transfer modes in exotic nuclei

Elena Litvinova[1,2]

[1]*Department of Physics, Western Michigan University, Kalamazoo, MI49008-5252, USA*
[2]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI48824-1321, USA*

The spin-isospin response associated with finite spin and isospin transfer is one of the most important properties of nuclei. This type of response provides information about a variety of weak interaction processes such as beta-decay, electron capture, neutrino capture and scattering in nuclei and stars. Lately the models which are commonly used to describe nuclear spin-isospin response, such as Quasiparticle Random Phase Approximation and Shell Model, have advanced considerably. However, a self-consistent model which can simultaneously reproduce data on the overall strength distribution up to high excitation energy, quenching and on the fine structure of the low-lying strength is still a challenge.

This work attempts to develop such a model based on the recent self-consistent extensions of the covariant energy density functional (CEDF) theory. The effective one-boson exchange interaction spans effective mesons and emerging collective modes. While heavy mesons are treated as classical fields, the low-lying collective phonons are included within non-perturbative quantum field theory schemes in the time-blocking approximation. Thus, the covariant spin-isospin response theory has been advanced to the inclusion of temporal and spatial non-localities [1,2] while pairing correlations of the superfluid type are included on the equal footing by means of the Gorkov's Green functions. The approach based on a few parameters of the CEDF provides a high-quality description of nuclear excitation spectra in both neutral and charge-exchange channels. Results of the recent calculations for spin-isospin response of exotic medium-mass nuclei studied at NSCL and RIKEN are presented and discussed.

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E1 "pygmy" strength: new remarkable features

V.O. Nesterenko[1], J. Kvasil[2], P.-G. Reinhard[3], A. Repko[2] , W. Kleinig [1,4], and N. Lo Iudice[5]

[1]BLTP, Joint Institute for Nuclear Research, Dubna,141980, Moscow region, Russia
[2]IPNP, Charles University, CZ-18000, Prague, Czech Republic
[3]Institute of Theoretical Physics II, University of Erlangen, D-91058, Erlangen, Germany
[4]TU Dresden, Institute of Analysis, D-01062, Dresden, Germany
[5]Istituto Nazionale di Fisica Nucleare, I-80126, Napoli, Italy

During the last decade there is an increasing interest in the E1 low-energy strength (LES), often called as the "pygmy dipole resonance" (PDR). The LES features, being related to the neutron skin and symmetry energy, can be used for building the isospin-dependent part of the nuclear equation of state and various astrophysical applications [1].

Despite of intensive studies, some important LES features (actual current flows, local interplay of various dipole modes, effect of nuclear deformation) are not yet well established [2,3]. Here we present analysis of these problems in the framework of the Skyrme random-phase-approximation method. The calculations use a representative set of Skyrme forces, various characteristics (strength functions, transition densities, current and velocity fields, form-factors) are scrutinized, both spherical and deformed nuclei in different mass regions (from ^{208}Pb [3-5] to Sn [6], Sm [7], and Yb [8] isotopes) are involved.

The analysis shows that a naive PDR-like view of LES, as an oscillation of a neutron excess against the nuclear core, should be revised [3,4]. Instead the calculated current fields show that the lower part of LES is about a pure isoscalar vortical toroidal motion while the higher part is a mixed isoscalar/isovector toroidal/compression flow [3]. The tail of the giant dipole resonance (GDR) is also involved. What is remarkable, the LES involves both irotational and vortical nuclear flows. Moreover, the LES energy region seems to host most of the dipole vortical nuclear strength realized through the toroidal giant resonance [4]. Here we get one more interesting LES feature in addition to many others. Note that irrotational and vortical flows occur at the nuclear surface and interior, respectively. As a result, the vortical motion does not affect much the correlations relevant for the symmetry energy [2].

The low energy E1 toroidal resonance dominates (after extraction of the spurious admixture) in the isoscalar channel. We discuss possible ways of its identification in various reactions. Further, we consider strong deformation effects in LES and corresponding E1 toroidal strength [7,8], in particular, an anomalous (opposite to GDR) order of K=0 and 1 dipole branches [8].

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Pygmy resonances and nucleosynthesis

Nadia Tsoneva[1,2], Horst Lenske[1]

[1]*Insitut für Theoretische Physik, Heinrich-Buff-Ring 16, 35392 Gießen, Germany*
[2]*INRNE, 1784 Sofia, Bulgaria*

Recently, new low-energy modes called pygmy resonances which reveal new aspects on the isospin dynamics of the nucleus have been observed. Their distinct feature is the close connection to nuclear skin oscillations which become visible in nuclear transition densities and currents. A successful description of the pygmy resonances could be achieved in a microscopic theoretical approach [1-6]. The model incorporates the density functional theory and QRPA formalism extended with multi-phonon degrees of freedom. The latter are found of crucial importance for the understanding of the fine structure of nuclear electric [1-5] and magnetic excitations [6] at low-energies. The precise knowledge of nuclear response functions below the neutron threshold plays a key role in the determination of nuclear reaction rates of importance for the s- and r-process of the nucleosynthesis. In this connection microscopically calculated theoretical response functions are implemented in the studies of s-process of neutron capture [7] and other nuclear reaction rates of astrophysical importance.

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The multipolarity of the low-energy γ-strength from a radiative proton capture experiment

A.V. Voinov, S.M. Grimes, C.R. Brune, T. N. Massey

[1]Physics and Astronomy Department, Ohio University, Athens, OH 45701

The γ-strength function measured in Oslo experiments with (a,b-γ) type of reactions includes all multipolarities of γ-transitions. The remarkable feature of measured functions is their low-energy enhancement [1]. It has been found recently that this enhancement is due to dipole transitions [2]. However, whether it is due to electric E1 or magnetic M1 transitions remains unclear. The enhancement of magnetic dipole transitions is supported by recent theoretical work of Ref. [3]. In order to understand this feature further, the experimental information on individual E1, M1 and E2 components is needed.

We measured two-step γ-cascades from the ^{55}Mn(p,2γ)^{56}Fe reaction at the proton energy of 1.65 MeV. Cascades populating the ground 0+ state of ^{56}Fe were identified and their intensities were determined. Experimental intensities were compared with theoretical calculations based on the concept of the statistical decay where E1, M1 and E2 strength functions are involved. In ^{56}Fe, because of the dominance of positive parity levels up to about 4.5 MeV, M1 transitions are dominant. The intensity of two-step cascades is very sensitive to the M1 γ-strength function in this energy region. We present experimental intensities of two-step γ-cascades along with calculations taking into account the total γ-strength for ^{56}Fe from Ref. [2] but with different assumptions on individual E1, M1 and E2 components. This comparison allows us to make conclusions on multipolaritty of the low energy part of the γ-strength function for ^{56}Fe.

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Session 12 – Room 028: Nuclear Astrophysics

Beta-delayed neutron emission and its role in the r-process

Iris Dillmann[1]

[1]TRIUMF, 4004 Wesbrook Mall, Vancouver BC, V6T 2A3, Canada

Beta-delayed neutron- (βn-) emitters play an important, two-fold role in the stellar nucleosynthesis of heavy elements in the "rapid neutron-capture process" (r process). On one hand they lead to a detour of the material beta-decaying back to stability. On the other hand, the released neutrons increase the neutron-to-seed ratio, and are re-captured during the freeze-out phase and thus influence the final solar r-abundance curve.

A large fraction of the isotopes for r-process nucleosynthesis are not yet experimentally accessible and are located in the "terra incognita". With the next generation of fragmentation and ISOL facilities presently being built or already in operation, one of the main motivation of all projects is the investigation of very neutron-rich isotopes at and beyond the border of presently known nuclei. However, reaching more neutron-rich isotopes means also that multiple neutron-emission becomes the dominant decay mechanism.

The investigation of βn-emitters has recently experienced a renaissance. I will show some recent results from a GSI campaign with the BELEN detector, and introduce the program planned for 2015/16 at RIKEN with the "BRIKEN" detector [1]. "BRIKEN" *("Beta-delayed neutron measurements at RIKEN for nuclear structure, astrophysics, and applications"*) is a worldwide effort which combines ^{3}He-neutron counters from groups in Germany, Japan, Russia, Spain, and the USA and the implantation detector AIDA from the UK to the presently largest and most efficient neutron detection setup. Planned first experiments comprise the first-time measurements of 48 β-delayed one-neutron and 24 β-delayed two-neutron emitters in the regions around doubly-magic ^{78}Ni and ^{132}Sn. Even some β-delayed three-neutron emitters in the heavier mass region will be tackled for the first time.

In parallel to these activities, the International Atomic Energy Agency (IAEA) has recently approved a Coordinated Research Project about "Beta-Delayed Neutron Emission Evaluation" [2,3] to create a solid basis for the vast amount of new neutron-rich isotopes being discovered with the new generation of RIB-facilities in the next decades.

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Constraining nucleosynthesis in stellar explosions through nuclear physics experiments"

Anuj Parikh[1]

[1]Escola Universitària d'Enginyeria Tècnica Industrial de Barcelona,
Consorci Escola Industrial de Barcelona,
Universitat Politècnica de Catalunya, Barcelona, Spain

Classical nova explosions, Type I X-ray bursts and Type Ia supernovae are astrophysical phenomena characterized by explosive burning. Reliable thermonuclear reaction rates are required to constrain predicted observable properties of these explosions. We discuss studies that have been performed to identify those rates that most significantly affect model predictions. Moderately provocative suggestions for future experimental and theoretical studies will be presented.

Low-energy resonances in the ^{22}Ne(p,γ)^{23}Na reaction directly observed at LUNA

F.Cavanna[1], R.Depalo[2] for the LUNA collaboration

[1]Dipartimento di Fisica Università degli studi di Genova and INFN Genova, 16146 Genova, Italy
[2]Dipartimento di Fisica Università degli studi di Padova and INFN Padova, 35131 Padova, Italy

The neon-sodium cycle of hydrogen burning influences the synthesis of the elements between ^{20}Ne and ^{27}Al in red giant stars and novae explosions [1,2]. In order to reproduce the observed elemental abundances, the cross sections of the reactions involved in the nucleosynthesis process should be accurately known.

The ^{22}Ne(p,γ)^{23}Na reaction rate is very uncertain because of a large number of unobserved resonances lying in the Gamow window [3]. For proton energies below 400 keV, in the literature there are only upper limits for the resonance strengths.

A new direct study of ^{22}Ne(p,γ)^{23}Na has been performed at the Laboratory for Underground Nuclear Astrophysics (LUNA) [4] in Gran Sasso using a windowless gas target and two high-purity germanium detectors. Several resonances have been observed for the first time in a direct experiment.

The experimental setup and preliminary strengths for the newly observed resonances will be shown.

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Direct measurement of ^{4}He(^{12}C,^{16}O)γ total cross section near stellar energy

K. Fujita[1], H. Yamaguchi[1], T. Ban[1], K. Hamamoto[1], Y. Narikiyo[1], H. Tao[1], K. Sagara[1]

[1]*Department of Physics, Kyushu University, 812-8581 Fukuoka, Fukuoka/Japan*

In heavy stars, the ^{4}He(^{12}C,^{16}O)γ cross section at E_{cm}= 0.3 MeV is very important to study the evolution after the helium burning process. The cross section is, however, still unknown in spite of many experiments in the world for more than 45 years, because the cross section is very small due to Coulomb repulsion and varies largely due to ^{16}O resonances near 0.3 MeV. We have a plan to measure the ^{4}He(^{12}C,^{16}O)γ total cross section from E_{cm}= 2.4 MeV down to 0.7 MeV, and to estimate the value at 0.3 MeV by extrapolation. We have already made the measurements at 2.4 and 1.5 MeV, and succeeded in a test measurement at 1.2 MeV. The measurements at 1.2 MeV and 1.0 MeV will be made in 2014.

We are making a direct measurement of the ^{12}C+^{4}He$\rightarrow$^{16}O+γ total cross section, using a ^{12}C beam from Kyushu University tandem accelerator and a ^{4}He windowless gas target, and detecting all the ^{16}O recoils in a selected charge state. The ^{16}O recoils are emitted along the ^{12}C beam direction within +-2 degree in the laboratory frame. To separate the ^{16}O recoils from the ^{12}C beam, we use a recoil mass separator (RMS) composed of electric and magnetic deflectors. At the focal plane of RMS, the ^{16}O recoils are detected by a gas counter and a Si-SSD.
We also measure the charge-state distribution of ^{16}O recoils in a separate experiment to estimate the total cross section. Detection of ^{16}O recoils is the only method to measure the ^{4}He(^{12}C,^{16}O)γ total cross section. The method has been adopted at Bochum[1] and Kyushu.

Since the ^{12}C+^{4}He$\rightarrow$^{16}O+γ total cross section is very small as about 0.1nb at 1.0MeV and about 1pb at 0.7MeV, we need a high intensity beam, a thick target and a high efficiency detector. Also extreme reduction of backgrounds (BG) is necessary, because the number of ^{16}O recoils at 0.7 MeV is about 10^{-18} of the number of ^{12}C beam particles. To reduce BG, we developed RMS, a beam pulsation system to use the time-of–flight technique, an RF deflector to select ^{16}O recoils, and an ionization chamber to identify ^{16}O from ^{12}C BG.

Our new data at 1.2 MeV and our preparation for the experiment at 1.0 MeV will be presented together with our original instruments and methods.

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Measurement of the [92,93,94,100]Mo(γ,n) reactions by Coulomb Dissociation and simulations for p-process nucleosynthesis

Kathrin Göbel[1], Olga Ershova[1,2], Jan Glorius[1], Alexander Koloczek[1], Marco Pignatari[3], René Reifarth[1], René Schach[1], Kerstin Sonnabend[1], Claudia Travaglio[4], the s295 collaboration, the NuGrid collaboration[5]

[1]*Goethe University Frankfurt am Main, Germany*
[2]*GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany*
[3]*University Basel, Switzerland*
[4]*INAF - Astrophysical Observatory Turin, Italy*
[5]*http://www.nugridstars.org*

Sequences of photo dissociations and β-decays during explosive conditions produce most of the p-nuclei between [74]Se and [196]Hg (γ-process) [1]. Some of the light p-nuclei, e.g. the neutron magic isotope [92]Mo, may also be synthesized by proton capture reactions [2].

Reliable studies of the production of the light p-nuclei require the experimental validation of the involved reaction rates predicted by statistical model calculations. Most nuclei involved in photo dissociation reactions in stellar nucleosynthesis networks are unstable and cannot be prepared as a sample for experiments using real photons. One solution is to study the (γ,n) reaction in inverse kinematics: The nucleus under investigation hits a high-Z target, where it interacts with the time-varying Coulomb field.

The reactions [92,93,94,100]Mo(γ,n) were measured by Coulomb Dissociation at the LAND/R[3]B setup at GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany [3]. The isotope [94]Mo is mainly synthesized via the (γ,n) photo disintegration chain starting from the more neutron-rich, stable Mo isotopes [4]. [94]Mo(γ,n) is the most important reaction determining the production ratio of [92]Mo to [94]Mo [2]. The analysis of [94]Mo(γ,n)[93]Mo will complete the analysis of this series of measurements, hence complete the experimental data base for the (γ,n) production chain of the p-isotopes of Mo.

The production and destruction of the light p-nuclei was studied with post-processing nucleosynthesis routines provided by the NuGrid collaboration [5]. The nucleosynthesis is calculated with temperature and density profiles derived from stellar models. Seed distributions serve as input parameters to the simulations.

We show the influence of rate variations on the abundances of the light p-nuclei in a 25 solar mass Supernova Type II model and the effect of different seed distributions. Furthermore, we present the current status of our nucleosynthesis studies of the p-process in thermonuclear supernovae.

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Session 13 – Room 120: Nuclear Structure/Reactions

The Facility for Rare Isotope Beams

C. Wrede[1]

[1]*Department of Physics and Astronomy and National Superconducting Cyclotron Laboratory, East Lansing, MI 48824, USA*

The Facility for Rare Isotope Beams (FRIB) is a United States Department of Energy user facility currently under construction on the campus of Michigan State University. Based on a 400 kW, 200 MeV/u heavy-ion driver linac, FRIB will deliver high-quality fast, thermalized, and re-accelerated beams of rare isotopes with unprecedented intensities to a variety of experimental areas and equipment. New science opportunities at the frontiers of nuclear structure, nuclear astrophysics, fundamental symmetries, and societal applications will be enabled by this future world-leading rare-isotope beam facility.

Gamow-Teller decays of beta delayed neutron emitters

R. Grzywacz[1,2], M. Madurga[1], S.V. Paulauskas[1], W.A. Peters[3], C.J. Gross[2], D. Miller[1], M. Al-Shudifat[1], D.W. Bardayan[2], J.C. Batchelder[3], J. Blackmon4, N.T. Brewer[1,5], L. Cartegni[1], J.A. Cizewski[6], P.A. Copp[7], A. Fijałkowska[1,8], M.E. Howard[6], S. Ilyushkin[9], C.U. Jost[1], S. Liu[3], B. Manning[6], C. Matei[3], M. Matos[4], A.J. Mendez II[2], K. Miernik[2,8], P.D. O'Malley[6], S. Padgett[1], F. Raiola[9], C. Rasco[4], A. Ratkiewicz[6], K. Rykaczewski[2], F. Sarazin[9], K.T. Schmitt[1], I. Spassova[3], D.W. Stracener[2], D. Walter[6], E.H. Wang[5], M. Wolińska-Cichocka[2,3], E.F. Zganjar[4]

[1]Dept. of Phys. and Astr., University of Tennessee, Knoxville,TN , USA
[2]Phys. Div., Oak Ridge National Laboratory, Oak Ridge,TN, USA
[3]Oak Ridge Associated Universities, Oak Ridge, TN, USA
[4]Dept. of Phys. and Astr., Louisiana State University, Baton Rouge,LA, USA
[5]Dept. of Phys. and Astr., Vanderbilt University, Nashville,TN, USA
[6] Dept. of Phys. and Astr., Rutgers University, Piscataway, NJ, USA
[7]Phys. Dept., University of Wisconsin-La Crosse, La Crosse, WI, USA
[8]Faculty of Phys., University of Warsaw, Warsaw, Poland
[9]Dept. of Phys., Colorado School of Mines, Golden, CO, USA

Beta-delayed neutron emission (βn) is a significant or even dominant decay channel for the majority of very neutron-rich nuclei. It appears that this particular decay mode probes the Gamow-Teller transitions, which compete with the so called "forbidden decays". Energy-resolved measurements of the beta-decay strength distribution constitute a strong test of nuclear models because they provide direct information on the strength distribution, in this case, to neutron unbound states. A new detector system called the Versatile Array of Neutron Detectors at Low Energy (VANDLE) [1,2] was constructed in order to study decays of very neutron-rich fission fragments produced at present-day facilities. The first experimental campaign at the Holifield Radioactive Ion Beam Facility investigated neutron energy spectra, in key regions of the nuclear chart: near the shell closures at ^{78}Ni and ^{132}Sn, and for the deformed nuclei near ^{100}Rb. In several cases, high-energy neutron structures were observed, which were interpreted to be due to large amplitude Gamow-Teller transformations.

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Failure of the Gross Theory of Beta Decay in Neutron Deficient Nuclei

Richard B. Firestone

Lawrence Berkeley National Laboratory, 1 Cyclotron Rd, Berkeley, CA 94720 USA

Neutron deficient Xe, Cs, and Ba isotopes were produced by a beam of ^{28}Si from the LBNL SuperHILAC on targets of ^{92,95,96,98,100}Mo in 1990 shortly before that facility closed. These isotopes were mass separated using the OASIS mass separator system [1], collected on a tape transport system, and deposited inside the LBNL Total Absorption Spectrometer (TAS) [2]. The atomic identification of isotopes populated by EC decay was measured by coincidences of TAS with a planar germanium x-ray detector. The TAS spectrum is a direct measurement of the EC feeding to excited states of the daughter nuclei. I have determined the experimental beta strengths for the EC/β+ decays of $^{117-121}$Xe, $^{117-124}$Cs, and $^{121-124}$Ba from the TAS data. The Gross Theory of beta decay assumes that the beta strength should increase with daughter level excitation due to both an exponential growth in the final state level density and proximity to the Giant Gamow-Teller resonance. These experiments indicated that the beta strength falls off rapidly near 4-5 MeV for the odd-Z, even-N isotopes, 3-4 MeV for the even-Z, odd-N isotopes, and 7-8 MeV for the odd-Z, odd-N isotopes. This is inconsistent with the prediction of Gross Theory. The total integrated beta strength for these for these nuclei gives effective *ft* values as low as 5000, comparable to the *ft*=4000-6000 range observed in mirror beta decays [3]. This suggests that the beta strength for these neutron deficient nuclei can be explained by single particle, mirror p→n transitions where the strength is distributed over many, low-lying levels due to configuration mixing. I have tested this hypothesis by calculating the half-lives of 110 nuclei with Z=51-64 near the proton drip line using the experimental beta strengths of ^{117}Xe for even-Z parents, ^{117}Cs for odd-Z, even-N parents, and ^{118}Cs for odd-Z, odd-N parents. These calculations are then compared with experimental half-lives from the literature [4] where excellent agreement was found assuming a 25% uncertainty in the calculation, part of which is due to the decay Q-value uncertainty.

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Study of isomer and proton decays in N ≈ Z nuclei below ^{100}Sn

K. Moschner[1], A. Blazhev[1], P. Boutachkov[2], P. Davies[3], R. Wadsworth[3], F. Ameil[2], H. Baba[4], T. Bäck[5], M. Dewald[1], P. Doornenbal[4], T. Faestermann[6], A. Gengelbach[7], J. Gerl[2], R. Gernhaeuser[6], S. Go[8], M. Górska[2], H. Grawe[2], E. Gregor[9], H. Hotaka[10], T. Isobe[4], D. G. Jenkins[3], J. Jolie[1], H. S. Jung[11], I. Kojouharov[2], N. Kurz[2], M. Lewitowicz[12], G. Lorusso[4], L. Maier[6], E. Merchan[9], F. Naqvi[13], H. Nishibata[14], D. Nishimura[10], S. Nishimura[4], N. Pietralla[9], H. Schaffner[2], P.-A. Söderström[4], K. Steiger[6], T. Sumikama[15], J. Taprogge[16], P. Thöle[1], N. Warr[1], H. Watanabe[17], V. Werner[13], Z. Xu[8], A. Yagi[14], K. Yoshinaga[10] and Y. Zhu[10]

[1]University of Cologne, Germany
[2]GSI, Darmstadt, Germany
[3]University of York, UK
[4]RIKEN, Japan
[5]KTH, Stockholm, Sweden
[6]Technische Universität München, Germany
[7]Uppsala University, Sweden
[8]University of Tokyo, Japan
[9]Technische Universität Darmstadt, Germany
[10]Tokyo University of Science, Japan
[11]Chung-Ang University, Republic of Korea
[12]GANIL, France
[13]Yale University, USA
[14]Osaka University, Japan
[15]Tohoku University, Japan
[16]IEM, CSIC, Madrid, Spain
[17]Beihang University, China

The N ≈ Z nuclei in the vicinity of the doubly magic nucleus ^{100}Sn exhibit a large abundance of isomeric nuclear states and are of particular importance for astrophysical element synthesis. The systematic study of these nuclei and their decay modes gives important insights for the understanding of the astrophysical rp-process and provides a sensitive probe of the residual proton-neutron interaction and the role of excitations of the ^{100}Sn core. The aim of the experiment RIBF83 performed within the EURICA project at the Radioactive Isotope Beam Facility (RIBF) at RIKEN, Japan was to advance our understanding of beta-decays from the self conjugate Ag, Cd, and In isotopes.

To create the nuclei of interest projectile fragmentation of a 345 MeV/u ^{124}Xe beam on a ^{9}Be target was used. The fragments were then separated and identified on an event by event basis in the BigRIPS spectrometer.

The EURICA setup utilizes the γ-ray efficiency of 12 EUROBALL HPGe cluster detectors in the RISING Stopped Beam configuration and the active stopper SIMBA composed of a segmented Si-array allowing for β-calorimetry measurements of positrons emitted in decays up to $Q_\beta \approx 10$ MeV. This contribution will report on the results from decay studies of ground and exited states in the implanted N ≈ Z nuclei.

Focussing on the most exotic silver isotopes, more precise lifetimes for ^{94}Ag and the very neutron deficient nucleus ^{93}Ag will be presented. Preliminary results for the β-calorimetry of positron decays of ^{94}Ag will be given. To extract the final Fermi and Gamov-Teller decay strengths from the experimental data, a detailed GEANT4 simulation of SIMBA is needed. The results of a new simulation code will be given and compared to the experimental data.

In ^{96}Cd the decay of the 16^+ spin-gap isomer has been studied and evidence was found for the presence of beta-delayed proton decay. In addition, a more precise measurement of the half-life of this state will be presented. Further results of the experiment RIBF83, including the half life of the extreme neutron deficient nucleus ^{95}Cd and the observation of a newly identified state in ^{98}Cd, populated through the GT decay of ^{98}In, will be reported.

Excited State Transitions in Double Beta Decay: A brief Review

Björn Lehnert[1]

[1]*Institut für Kern- und Teilchenphysik, Technische Universität Dresden, 01069 Dresden, Germany*

Double beta decays provide an important probe for physics beyond the Standard Model. Two neutrino double beta decay (2nbb) transitions have the longest half-lives observed in nature between 1e18 and 1e21 yr. Neutrinoless double beta decay (0nbb) transitions are expected to have even longer half-lives >1e25 yr. If they exist, they would violate lepton number, imply the Majorana nature of neutrinos and provide information on the neutrino mass. Nuclear matrix elements (NME) are needed to connect the half-life of the decay with the neutrino mass. The calculation of the NME depends on nuclear models and is subject to large uncertainties.

The 2nbb and the 0nbb can also occur into excited states of the daughter nucleus which provides important experimental information for the NME calculation. Excited state transitions have a reduced phase space and an even longer half-live compared to the ground state transitions; however, they offer an enhanced experimental signature including de-excitation gammas. So far 2nbb excited state transitions have been observed in Mo-100 and Nd-150.

This talk will present the current experimental status of excited state transitions in double beta decay isotopes. The focus will be on two different analysis methods for searches in Ge-76 with the GERmanium Detector Array (GERDA) and in Pd-110 with gamma ray spectroscopy.

Neutron-cross-section measurements on germanium with fast quasi-monoenergetic neutrons

A. Buffler[1], A. R. Domula[2], D. Geduld[1], P. Maleka[3], R. T. Newman[4], R. Nolte[5],
F. D. Smit[3], C. Vermeulen[3], A. Wallner[6], K. Zuber[2]

[1]*Department of Physics, University of Cape Town, Private Bag, Rondebosch 7701,
South Africa*
[2]*Technische Universität Dresden, Institut für Kern- und Teilchenphysik, Zellescher Weg 19,
D-01069 Dresden, Germany*
[3]*iThemba LABS, P O Box 722, Somerset West, 7129, South Africa*
[4]*Department of Physics, University of Stellenbosch, Matieland 7602, South Africa*
[5]*Physikalisch-Technische Bundesanstalt, Bundesallee 100, D-38116 Braunschweig,
Germany*
[6]*Department of Nuclear Physics, Research School of Physics and Engineering,
The Australian National University, Canberra, ACT 0200, Australia*

The process of neutrinoless double beta decay (0νββ) plays a key role in modern neutrino physics. The experiments on the ^{76}Ge-0νββ-decay using germanium-semiconductors are at the forefront in this field. Due to the extremely low count rates expected for this rare decay, any kind of background event in the detector, especially at energies close to $Q_{\beta\beta} = 2039\ \mathrm{keV}$ has to be avoided. Therefore a careful investigation on the neutron-induced background was carried out.

The decay of ^{68}Ge causes one of the major backgrounds for low-level-germanium-detectors. The relatively long living radionuclide is an intrinsic background nuclide in germanium-crystals themselves. This nuclide is produced from other germanium isotopes in ^{x}Ge(n,jn)^{68}Ge reactions induced by cosmogenic neutrons. For estimations of the intrinsic activation on the earth-surface cross-section data from model-calculations is available only.

Due to a lack of the necessary experimental neutron-cross-section data in the energy region above 20 MeV first measurements were performed at *iThemba LABS* (South Africa). The sector-cyclotron-facility provides a proton beam, which is used to generate quasi-monoenergetic neutrons deploying i.e. the ^{7}Li(p,n)^{7}Be-reaction. In the well characterised neutron-field the activation foil method was used to perform cross-section-measurements. First results are presented.

Session 14 – Room 028: Techniques/Reactions

VITO – Versatile Ion-polarized Techniques On-Line at ISOLDE-CERN

M. Stachura[1], A. Gottberg[1], M. L. Bissell[2], K. Johnston[3], M. Deicher[3], L. Hemmingsen[4],
G. Neyens[2], V. Amaral[5], J.G. Correia[6], A. Jancso[7], P. Finley[2], R. Kiefl[8], M. Kowalska[1],
A. MacFarlane[8], S. Pallada[1], L. M.C. Pereira[2], Z. Salman[9], N. Severijns[2], P.W. Thulstrup[4],
D. Zakoucky[10]

[1]*CERN – European Organization for Nuclear Research, CH-1211 Geneva 23, Switzerland*
[2]*Instituut voor Kern- en Stralingsfysics, KU Leuven, Belgium*
[3]*Universität des Saarlandes, Saarbrücken, Germany*
[4]*Kemisk Institut, København, København Denmark*
[5]*Departamento de Fisica, Universidade de Aveiro, Portugal*
[6]*Instituti Superior Tecnico, Universidade de Lisaboa, Pertugal*
[7]*Szervetlen es Analitikai Kemiai Tanszek, Szegedi Tudomanyegyetem, Szeged, Hungary*
[8]*Department of Chemistry, University of British Columbia, Vancouver, Canada*
[9]*Paul Scherrer Institut, laboratory for Muon Spin Spectroscopy, Switzerland*
[10]*Nuclear Physics Institute, ASCR, Prague, Czech Republic*

The Versatile Ion-polarized Techniques On-line (VITO) experiment at ISOLDE-CERN is a modification of the former UHV beam line hosting the Apparatus for Surface Physics and Interfaces at CERN (ASPIC) [1]. The major enhancement of the new line will be the introduction of laser-based nuclear spin polarization of the isotope beams, which will allow for establishing laser and β-NMR spectroscopies in addition to Perturbed Angular Correlation of γ-rays (PAC) spectroscopy in a wide range of sample environments. Being currently under construction, the line is planned to host three experimental end-stations:

1. The ASPIC apparatus, which achieves high resolution of local electronic and magnetic properties and high surface sensitivity at the same time. Therefore it combines nuclear PAC spectroscopy with state-of-the-art sample preparation and manipulation hosted in a common ultra-high vacuum system. In the second upgrade (planned for 2015), the ASPIC chamber will host in addition an UHV β-NMR spectrometer.

2. A β-NMR spectrometer with differential pumping for liquid samples or other applications, which do not require UHV environment. The prototype experimental chamber for measurements on liquid samples was successfully tested in August 2012, when the first β-NMR spectrum was recorded with ^{31}Mg implanted into a liquid drop [2].

3. An open-end station for movable experiments. If not occupied, the station will be used to monitor the achieved polarizations.

In the near future the line will allow for addressing various scientific phenomena ranging from laser spectroscopy through solid state physics and physics of fundamental interactions until biophysics.

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Measurements with the Multi-Reflection Time-of-Flight Mass Spectrometer of ISOLTRAP at ISOLDE/CERN

Frank Wienholtz[1]

for the ISOLTRAP* collaboration

[1]*Institute of Physics, University of Greifswald, 17489 Greifswald, Germany*

The masses of exotic nuclides are among the most important input parameters for modern nuclear theory and astrophysical models. At the high-precision Penning-trap mass spectrometer ISOLTRAP at ISOLDE/CERN, a multi-reflection time-of-flight mass spectrometer (MR-ToF-MS) in combination with a Bradbury-Nielsen gate (BNG) can be used to achieve high-resolution isobar purification with mass-resolving powers of 10^5 in a few tens of milliseconds [1, 2]. Furthermore, the MR-ToF device can be used as a spectrometer to determine the masses of nuclides with very low yields and short half-lives, where a Penning-trap mass measurement becomes impractical due to the lower transport efficiency and decay losses during the purification and measurement cycles. Recent cross-check experiments show that the MR-ToF MS allows mass measurements with uncertainties in the sub-ppm range. In a first application the mass measurements of the nuclides ^{53,54}Ca was performed [3], delivered with production rates as low as 10/s and half-lives of only 90(6) ms [4]. The nuclides serve as important benchmarks for testing modern chiral effective theory with realistic 3-body forces.

The contribution will present the on-line mass spectrometer ISOLTRAP focusing on the new applications, which became possible after the implementation of the MR-ToF MS into the current setup. In particular, the mass measurements of the neutron-rich calcium isotopes up to A=54 will be discussed. In addition, measurements of the isotonic potassium isotopes will be reported.

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* http://isoltrap.web.cern.ch/isoltrap/,

collaboration spokesperson:

Prof. Dr. Klaus Blaum, Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, sekretariat.blaum@mpi-hd.mpg.de

Search for anomalous elastic electron scattering from protons at keV energies

Raymond Moreh[1], Maarten Vos[2]

[1]*Physics Department, Ben-Gurion University of the Negev, Beer-Sheva, 84120, Israel*

[2]*Atomic and Molecular Physics Laboratories, Australian National University, Canberra, Australia*

In the literature several cases of large deviations of electron-proton scattering from the Rutherford formula were reported [1,2]. Such reports involving electron beams followed earlier claims (invloving neutron beams) of anomalous elastic neutron-proton scattering cross section in which a deficiency of ~ 30% were reported from the well-known documented values of elastic n-p scattering cross sections at neutron energies E_n ~ 10-200 eV. An outstanding case was obtained when the elastic n-p scattering intensities was compared to that from n-D in samples of H_2O and D_2O. More n-p scattering studies involved samples of polyethylene (CH_2), H_2O/D_2O, H_2, D_2 and HD.

Later on, similar claims for a shortfall of elastic *electron* scattering intensities from H-atoms were reported in the same and similar H-containing samples. In CH_2, the electron scattering intensity ratio from H:C was measured at E_e ~ 30 keV and reported to be lower by ~ 30% than the Rutherford Z^2 relation. Another case is that of electron scattering from H_2, D_2 and HD. It was noted that the scattering intensity from a 50:50 H_2-D_2 mixture, the integrated intensity of the H-peak is 31% lower than that from the D-peak [1]. This was compared with equal scattering intensities measured from the H- and D-atoms contained in a HD sample. Here, we carried out a critical review of those reported cases and show that in the light of a recent experiment in which a direct comparison of the electron scattering intensities [3] from the H:O in H_2O and the D:O in D_2O, that there are no deficiencies in the electron scattering intensities from the H-atom. Also no theoretical evidence was found supporting the above deficiencies. It appears that the source of all such deviations is instrumental and not due to any real effect.

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Probing the resonance structure in ^{12}C above the triple-alpha threshold

A. M. Howard[1], K. L. Laursen[1], H. O. U. Fynbo[1], O. S. Kirsebom[1], J. Refsgaard[1],
K. Riisager[1]

[1]*Institute for Physics and Astronomy, Aarhus University, 8000 Aarhus C, Denmark*

Carbon production in stellar environments is dominated by reactions proceeding through resonance states above the triple-alpha threshold. The lowest energy resonance is the well-known 0^+ Hoyle state at 7.65 MeV. The low-lying resonance structure, however, is relatively poorly known. Experimentally probing the region above the Hoyle state is complicated by J=0 and J=3 resonances, which mask much of the detailed structure. The 2^+ rotational excitation of the Hoyle state at ~10 MeV, whose properties are crucial to understanding ^{12}C production at elevated temperatures [1], is an excellent example. More than 50 years have passed between its proposed existence and recent discovery [2-5]. We describe a novel approach to selectively probing the structure above the Hoyle state via electromagnetic transitions from higher-lying resonances. Data have been collected at Aarhus University using the p+^{11}B reaction to populate the 16.11 MeV (2^+) and 17.78 MeV (0^+) resonances in ^{12}C. A large solid angle, high granularity silicon array was used to detect the resulting triple-alpha breakup. A complete kinematical reconstruction of the decay is then used to identify missing energy, corresponding to transitions to the region of interest. We will present the most recent results obtained using this technique.

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α induced reaction cross section measurements on ^{162}Er and the study of the α width at low energies

G. G. Kiss[1], T. Szücs[1,*], Gy. Gyürky[1], Zs. Fülöp[1] and T. Rauscher[2,3]

1 Institute for Nuclear Research (MTA ATOMKI), H-4001 Debrecen, Hungary
2 Centre for Astrophysics Research, School of Physics, Astronomy and Mathematics,
University of Hertfordshire, Hatfield AL10 9AB, United Kingdom
3 Department of Physics, University of Basel, 4052 Basel, Switzerland

The stable proton-rich nuclei with charge number Z<34 are the so called p-nuclei [1]. It is generally accepted that the main stellar mechanism synthesizing these nuclei – the so called γ-process – is initiated by (γ,n) photodisintegration reactions on preexisting neutron-rich seed nuclei [2]. As the neutron separation energy increases along this path towards more neutron deficient isotopes (γ,p) and (γ,α) reactions become stronger and process the material towards lower masses.

In order to understand the path of the γ-process in the region of the heavy p nuclei and to determine precisely the p-isotope abundances, experimental cross section data of the involved reactions are clearly needed. Stellar rates for (γ,α) photodisintegration reactions should always be derived from alpha-capture to maximize the experimental constraint on the rate [3,4]. Very few (α,γ) cross sections relevant for the γ-process are known experimentally, and owing to technical difficulties very few measurements are available in the heavy mass region above A = 150 [e.g. 5]. Despite several attempts, the data measured in this mass range cannot be described by any global α + nucleus potential.

Here I would like to present the measurement of the ^{162}Er(α,γ)^{166}Yb and ^{162}Er(α,n)^{165}Yb reactions which provided an another important milestone in the quest to test the predicted α strengths at low energies. For the first time in this mass region, the consistently measured (α,γ) and (α,n) data (with (α,γ) cross sections also below the (α,n) threshold) were found to be essential for an unambiguous study of the α width and its energy dependence [6]. The experimental details as well as the theoretical improvements are planned to be shown.

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* present address: Helmholtz-Zentrum Dresden-Rossendorf (HZDR), 01328 Dresden, Germany

Inelastic neutron scattering studies of ^{132,134}Xe: Elucidating structure in a transitional region and possible interferences for 0vββ searches

E.E. Peters[1], T.J. Ross[1,2], A. Chakraborty[1,2], B.P. Crider[2], A. Kumar[1,2], M.T. McEllistrem[2], F.M. Prados-Estévez[1,2], S.W. Yates[1,2]

[1]*Department of Chemistry, University of Kentucky, Lexington, KY 40506 USA*
[2]*Department of Physics & Astronomy, University of Kentucky, Lexington, KY 40506 USA*

In contrast to the transition from spherical vibrators to axially symmetric rotors, little is understood about the transition from spherical vibrators to gamma-soft nuclei. The stable isotopes of xenon span a region which exhibits such an evolution of nuclear structure and thus these nuclei may provide insight into the nature of this transition. As the xenon isotopes are gases under ambient conditions, the cumbersome high-pressure gas targets employed in the past introduce a host of difficulties to the measurements; consequently, these nuclei have not been well-characterized to date. For inelastic neutron scattering measurements at the University of Kentucky Accelerator Laboratory (UKAL), highly enriched (> 99.9%) ^{132}Xe and ^{134}Xe gases were converted to solid ^{132}XeF$_2$ and ^{134}XeF$_2$ and were used as scattering samples. Lifetimes of levels up to 3.5 MeV in excitation energy in each xenon isotope were measured using the Doppler-shift attenuation method. Gamma rays corresponding to new transitions and levels have been observed and reduced transition probabilities have also been determined. In the case of ^{134}Xe, significant revisions to the level scheme have been made, and in ^{132}Xe, new excited 0^+ states have been identified. This new information has been examined in an effort to elucidate the structure of these nuclei in a transitional region, and comparisons have been drawn with models which seek to describe such nuclei, *e.g.*, the E(5) critical-point symmetry of the IBM [1].

The nuclear structure of ^{134}Xe is also of relevance for neutrinoless double-beta decay (0vββ) experiments, specifically those searching for the decay of ^{136}Xe to ^{136}Ba. For example, the detector constructed by the EXO collaboration utilizes liquid xenon as the source and detector and is enriched to 80% in ^{136}Xe, while the remaining 20% is ^{134}Xe [2]. As neutrons may be produced by incident muons or natural radionuclides present in the surroundings, excited states in either isotope may be populated by inelastic neutron scattering. Therefore, γ rays emitted upon de-excitation of ^{134}Xe which have energies near the 0vββ end-point energy, 2458.7 keV, may obscure the observation of this rare decay. New γ rays corresponding to transitions in ^{134}Xe have been observed in this energy region, within the ~100-keV resolution of the EXO detector. Gamma-ray production cross sections have been measured for these newly identified potential interferences.

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Session 15 – Room 120: Nuclear Structure

The Pygmy Dipole Resonance – past, presence and future

A. Zilges[1] and D. Savran[2,3]

[1]*University of Cologne, Germany*
[2]*EMMI and Research Division, GSI Helmholtzzentrum, Germany*
[3]*Frankfurt Institute for Advanced Studies FIAS, Germany*

The advent of improved experimental and theoretical techniques has triggered a lot of attention to the electric dipole response of atomic nuclei in the last decade, see the review article [1] and references therein. This lead to the establishment of a concentration of E1 strength below the Giant Dipole Resonance in many nuclei. This phenomenon is commonly denoted as Pygmy Dipole Resonance (PDR). The talk will summarize the results obtained using different experimental probes, define the challenges to gain a deeper understanding of the excitations, and discuss the newest experimental developments.

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Electric dipole response from forward-angle polarized proton scattering, neutron skin and the neutron equation of state

Peter von Neumann-Cosel[1]

[1]Institut für Kernphysik, Technische Universität Darmstadt, 64289 Darmstadt, Germany

Polarized proton scattering at energies of a few 100 MeV and extreme forward angles including 0° has been established as a new tool to extract the complete E1 response in nuclei up to excitation energies of about 20 MeV [1]. In particular, this method provides information on the poorly determined B(E1) strength below and around neutron threshold in heavy nuclei. A case study of ^{208}Pb demonstrates excellent agreement with other electromagnetic probes [2,3]. From the information on the B(E1) strength one can derive the dipole polarizability of ^{208}Pb, which is strongly correlated to the neutron skin [4] and to parameters of the symmetry energy [5]. Recently, we have extracted the polarizability of ^{120}Sn with a comparable precision [6]. The combination of both results further constrains the symmetry energy parameters and presents a challenge for mean-field models, since many Skyrme as well as relativistic parameterizations cannot reproduce both experimental results simultaneously. A systematic study of the polarizability in heavy nuclei should thus allow to constrain the isovector interaction in mean-field models which is poorly determined by the usual fit parameters (masses, charge radii, giant resonance centroids).

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Nuclear Structure Studies with Gamma-Ray Beams

Anton Tonchev

Lawrence Livermore National Laboratory, 94550 Livermore, California/USA

In stable and weakly bound neutron-rich nuclei, a resonance-like concentration of dipole states has been observed for excitation energies below the neutron separation energy [1]. This clustering of strong dipole states has been named the pygmy dipole resonance (PDR) in contrast to the giant dipole resonance that dominates the E1 response. Understanding the PDR is presently of great interest in nuclear structure [2,3] and nuclear astrophysics [4]. High-sensitivity studies of E1 and M1 transitions in N = 82 nuclei using the nearly monoenergetic and 100% linearly-polarized photon beams will be presented. The nuclear dipole-strength distribution of the PDR has been measured and novel information about the character of this mode of excitation has been obtained. The data will be compared to calculations using statistical and quasiparticle random-phase approximation methods.

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Dipole strength distributions from HIGS experiments

V. Werner[1,2], N. Cooper[2], P.M. Goddard[2,3], P. Humby[2,3], R.S. Ilieva[2,3], G. Rusev[4],
J. Beller[1], C. Bernards[2], B.P. Crider[5], J. Isaak[1], J.H. Kelley[6], E. Kwan[6,7], B. Löher[8,9],
E.E. Peters[10], N. Pietralla[1], R. Raut[6,7], C. Romig[1], D. Savran[8,9], M. Scheck[11,12], A.P.
Tonchev[7], W. Tornow[6,7], S.W. Yates[5,10], M. Zweidinger[1]

[1]*TU Darmstadt, Institut für Kernphysik, Schlossgartenstr. 9, 64289 Darmstadt, Germany*
[2]*WNSL, Yale University, P.O. Box 208120, New Haven, CT 06520, USA*
[3]*Department of Physics, University of Surrey, Guildford, GU2 7XH, UK*
[4]*Chemistry Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA*
[5]*Department of Physics & Astronomy, University of Kentucky, Lexington, KY 40506, USA*
[6]*Triangle Universities Nuclear Laboratory, Durham, NC 27708, USA*
[7]*Physics Division, Lawrence Livermore National Laboratory, Livermore, CA 94550, USA*
[8]*EMMI and Research Division, GSI, Planckstr. 1, 64291 Darmstadt, Germany*
[9]*FIAS, Ruth-Moufang-Str. 1, 60438 Frankfurt am Main, Germany*
[10]*Department of Chemistry, University of Kentucky, Lexington, KY 40506, USA*
[11]*School of Engineering, University of the West of Scotland, Paisley, PA1 2BE, UK*
[12]*SUPA, Scottish Universities Physics Alliance, Glasgow, G12 8QQ, UK*

The derivation of dipole strength distributions, with some focus on electric-dipole strength, will be presented. The ^{76}Se/^{76}Ge isobars have been investigated [1-3] in order to obtain a side-by-side comparison of the dipole response of these potential neutrino-less double-beta decay partners. Physics questions range from multi-phonon excitations (mixed-symmetry scissors mode or quadrupole-octupole coupled) to the investigation of a so-called electric Pygmy dipole resonance, and the M1 spin-flip resonance. Absolute excitation strengths have been determined making use of continuous-energy γ-ray beams from bremsstrahlung, using the S-DALINAC at TU Darmstadt. Subsequently, near-monoenergetic beams from the High-Intensity Gamma-ray Source (HIGS) at TUNL were used, which have multiple advantages over bremsstrahlung beams. Firstly, the near 100 % polarization allows to measure parities of dipole excited states in even-even nuclei using a simple polarimetry setup [4]. Secondly, especially at high energies the photon flux at HIGS is higher than that obtained from bremsstrahlung and sensitivity is much enhanced toward the high end of the spectrum. Thirdly, since states are excited within a narrow energy interval and one obtains information on their decay behavior to lower-lying excited states, which is difficult in bremsstrahlung experiments due to low-energy background. The investigation of branching decays gains more momentum through the new γ³ setup [5] for γγ-coincidence measurements at HIGS. To derive absolute cross sections at HIGS through a combination of data and simulation of the photon flux is possible, but cumbersome. Therefore, the bremsstrahlung data where cross sections have been obtained relative to calibration standards were used to calibrate the photon flux at HIGS. The new cross section data, combined with literature (γ,n) data, aid the test and derivation of photon strength functions. After correction for indirectly observed branching, calculations within a statistical approach show good agreement with parametrizations of the giant dipole resonance.

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Cross section measurements with applications to nuclear energy

Arjan Plompen[1], Peter Schillebeeckx[1], S. Kopecky[1]

[1]_European Commission, Joint Research Centre, Institute for Reference Materials and Measurements, 2440 Geel, Belgium_

Innovations in nuclear energy require accurate nuclear data with reliable uncertainty estimates for their design and the analysis of performance and safety features. A number of challenges were put forward through the High Priority Request List for nuclear data that have enjoyed considerable attention in the form of follow-up experiments and analyses. These and additional challenges to our knowledge of nuclear reactions originating from the field of nuclear energy were addressed through various recent European initiatives. The author would like to present a summary of some of these experiments, in particular where these touch on the subject of the conference. Examples will be taken from recent work at the IRMM and from European projects such as ANDES, ERINDA and EUFRAT. These include inelastic scattering measurements with the (n,n'g) technique, capture reactions for ^{241}Am and ^{238}U and some examples of fission cross section experiments.

Accuracy Improvement of Neutron Nuclear Data on Minor Actinides

H. Harada[1], O. Iwamoto[1], N. Iwamoto[1], A. Kimura[1], K. Terada[1], T. Nakao[1], S. Nakamura[1], K. Mizuyama[1], M. Igashira[2], T. Katabuchi[2], T. Sano[3], Y. Takahashi[3], K. Takamiya[3], C. H. Pyeon[3], S. Fukutani[3], T. Fujii[3], J. Hori[3], T. Yagi[3], H. Yashima[3]

[1]*Japan Atomic Energy Agency (JAEA) / Nuclear Science and Engineering Center (NSEC), 319-1195, Tokai-mura, Naka-gun, Ibaraki / Japan*
[2]*Tokyo Institute of Technology / Research Laboratory for Nuclear Reactors, 152-8550, O-okayama, Meguro-ku, Tokyo / Japan*
[3]*Kyoto University / Research Reactor Institute, 590-0494, Kumatori-cho, Sennan-gun, Osaka / Japan*

Improvement of accuracy of neutron nuclear data for minor actinides (MAs) and long-lived fission products (LLFPs) is required for developing innovative nuclear system transmuting these nuclei [1-2]. In order to meet the requirement, the project entitled as "Research and development for Accuracy Improvement of neutron nuclear data on Minor ACtinides (AIMAC)" has been started as one of the "Innovative Nuclear Research and Development Program" at October 2013. The AIMAC project team is composed of researchers in four different fields: differential nuclear data measurement, integral nuclear data measurement, nuclear chemistry, and nuclear data evaluation. By integrating all of the forefront knowledge and techniques in these fields, the team aims at improving the accuracy of the data.

The following research items have been conducted by the AIMAC project team:
1）Accurate measurements of thermal neutron capture cross-sections
2）High-precision quantification of sample amount used for TOF measurement
3）Resonance parameter determination by combining total and capture cross sections
4）Extension of capture cross sections to high energy neutrons
5）High quality evaluation based on iterative communication with experimenters

The background, overall plan, and recent progress of the AIMAC project will be reviewed.

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Total Absorption Gamma-ray Spectroscopy measurements for basic and applied β-decay studies

Jose L. Tain[1]

[1]*Instituto de Fisica Corpuscular, CSIC-U.Valencia, E-46071 Valencia, Spain*

Total Absorption Gamma-ray Spectroscopy (TAGS) is the most accurate method to determine the β-decay intensity distribution far from stability. The technique is free from the systematic error known as *Pandemonium* effect [1], which shifts the apparent decay intensity to low excitation energy and affects a large fraction of the data obtained with high-resolution γ-ray spectroscopy. The TAGS technique relies on the use of a γ-ray calorimeter and a sophisticated analysis method. TAGS must be supplemented with particle spectroscopy for nuclei undergoing β-delayed particle emission in order to recover the full β-decay distribution. The technique was introduced in a pioneering work [2] at ISOLDE-CERN and subsequent work was carried out at LNPI (Gatchina), INEL (Idaho) and GSI (Darmstadt). Currently, in Europe, experiments are carried out or are being prepared at ISOLDE, JYFL (Jyväskylä) and ALTO (Orsay). Work is also being done to prepare future measurements at NUSTAR-FAIR and DESIR-Spiral2.

The range of applications of TAGS to β-decay studies is very broad. In recent years it has been applied to: 1) The study of nuclear shapes in regions of shape coexistence (neutron deficient nuclei around A=80 and A=190), 2) Search for candidates for a possible monochromatic neutrino beam facility based on the acceleration of EC decaying isotopes, 3) The study of important contributors to the short time decay heat in reactors leading to an improvement of decay heat summation calculations, 4) The study of important contributors to the antineutrino spectrum from reactors, with implications in the possible deployment of neutrino detectors for remote monitoring of reactor activity (non-proliferation) and the analysis of reactor antineutrino experiments (neutrino oscillations, reactor antineutrino anomaly), 5) Study of the β-strength distribution in neutron rich nuclei and its impact on $T_{1/2}$ and P_n predictions for r-process calculations, 6) Study of the competition between gamma and neutron emission from neutron unbound states populated in β-decay, and 7) The improvement of nuclear matrix elements in ^{100}Tc in order to improve double beta decay calculations for ^{100}Mo.

In the talk the principles of the technique will be briefly reviewed and some examples of recent work will be presented with an emphasis on physics results. Finally the plans for future measurements will be outlined.

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Validating (d,pγ) as a Surrogate for Neutron Capture

A. Ratkiewicz[1], J.A. Cizewski[1], S.D. Pain[2], A. Adekola[1], J.T. Burke[3], R.J. Casperson[3], M. McCleskey[4], C.M. Shand[1,5], R.A.E Austin[6], S. Burcher[1], M.P. Carpenter[7], M. Devlin[8], J.E. Escher[3], N. Fotiadis[8], S. Hardy[1,5], R. Hatarik[3], M.E. Howard[1], R.O. Hughes[9], K.L. Jones[10], R.L. Kozub[11], C.J. Lister[12], B. Manning[1], W.A. Peters[2,10], T.J. Ross[9], N.D. Scielzo[3], D. Seweryniak[7], and S. Zhu[7].

[1]*Department of Physics and Astronomy, Rutgers University, New Brunswick, NJ 08903*
[2]*Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831*
[3]*Lawrence Livermore National Laboratory, Livermore, CA 95440*
[4]*Cyclotron Institute, Texas A&M University, College Station, TX 77843*
[5]*Department of Physics, University of Surrey, Guildford, Surrey, GU2 7XH, UK*
[6]*Astronomy and Physics Department, St. Mary's University, Halifax, Nova Scotia, Canada*
[7]*Physics Division, Argonne National Laboratory, Argonne, IL 60439*
[8]*Los Alamos National Laboratory, Los Alamos, NM 87545, USA*
[9]*Department of Physics, University of Richmond, Richmond, VA 23173*
[10]*Department of Physics and Astronomy, University of Tennessee, Knoxville, TN 37996*
[11]*Physics Department, Tennessee Technological University, Cookeville, TN 38505*
[12]*Department of Physics and Applied Physics, University of Massachusetts Lowell, Lowell, MA 01854*

The stellar *r*-process is responsible for creating roughly half of the elements heavier than iron. It has recently been determined that the rates at which neutron capture reactions with exotic nuclei proceed at late times in the *r*-process may dramatically affect the final abundance pattern [1]. However, direct measurements of neutron capture reaction rates on exotic nuclei are not possible, necessitating the development of a surrogate technique. The (d,pγ) reaction at low energies was identified as a promising surrogate for the (n,γ) reaction, as both reactions share many characteristics in common. We report on a program to validate (d,pγ) as a surrogate for (n,γ) using ^{95}Mo as a target. The experimental campaign includes direct measurements of the gamma-ray intensities from the decay of excited states populated in the ^{95}Mo(n,γ) reaction as a function of neutron energies, as well as in the ^{95}Mo(d,pγ) reaction. Preliminary results from the completed measurements and plans to extend the technique to inverse kinematics with exotic beams will be presented.

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Session 17 – Room 120: Nuclear Structure

Exotic nuclei studied with the 8pi spectrometer at TRIUMF

A.B. Garnsworthy[1] on behalf of the 8pi Collaboration

[1]TRIUMF, 4004 Wesbrook Mall, Vancouver, BC, Canada

The 8pi spectrometer was used in radioactive-decay studies of exotic beams provided by the TRIUMF-ISAC-I facility from the year 2002 to December 2013. Over this time, a powerful suite of ancillary detectors was integrated with the HPGe array to enable a wide program of research in the fields of nuclear structure, nuclear astrophysics and fundamental symmetries. The 8pi spectrometer consisted of 20 Compton-suppressed HPGe detectors and was coupled to an array of 20 plastic scintillators (SCEPTAR) for coincidence beta-tagging, 5 in-vacuum Si(Li) detectors (PACES) for internal conversion electron measurements and an array of 10 fast scintillators of BaF_2/$LaBr_3$ (DANTE) for measurements of short-lifetimes of excited states in daughter nuclei.

An extensive program of high-precision measurements of branching ratios and half lives of the superallowed Fermi beta emitters has been carried out. These data are crucial input for testing the unitary of the CKM matrix through precise determination of the V_{ud} element. Thirteen such measurements, ranging from ^{10}C to ^{74}Rb (See for example Refs. [1-5]), have been made with the 8pi spectrometer at ISAC.

Very-high-statistics beta-decay studies of nuclei close to stability have provided new insights into nuclear structure through the identification of very low-intensity decay branches that carry significant amounts of the transition strength. Examples of this type of investigation include the stable Cd [6] and Sn [7] isotopes, along with the neutron-rich Zr isotopes [8].

A wide range of beta- and isomer-decay studies have been carried out across the chart of nuclides including extending the level scheme of ^{32}Mg [9], halo properties involved in the decay ^{11}Li [10] and the discovery of a new isomer in ^{174}Tm [11]. Recently, with the development of actinide targets at ISAC, several experiments have been performed with neutron-rich beams to study shape coexistence around N=60, isotopes which lie at the boundary of the island of inversion [12], and the properties of nuclei in the proximity of the astrophysical r-process [13]. Highlights from the program will be presented along with the most recent results and a look at future opportunities with the new GRIFFIN facility [14] at TRIUMF-ISAC.

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Shape-coexisting nature in the Pb region at REX Isolde

<u>K. Wrzosek-Lipska</u>[1,2], N. Bree[1], A. Petts[3], N. Kesteloot[1,4]
for the IS452/IS479/IS494 collaboration

[1]KU Leuven, Instituut voor Kern- en Stralingsfysica, B-3001 Leuven, Belgium
[2] Heavy Ion Laboratory, University of Warsaw, PL-02-093 Warsaw, Poland
[3] Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 7ZE, United Kingdom
[4] Belgian Nuclear Research Centre SCK CEN, B-2400 Mol, Belgium

Shape coexistence whereby two or more shapes coexist at low excitation energy in the atomic nucleus is an intriguing phenomenon. In the region around the light lead isotopes, with proton number Z=82, a substantial amount of information has been collected using a wide spectrum of experimental probes like decay studies, optical spectroscopy studies and in-beam spectroscopy investigations. However, direct experimental information on the exact nature of the quadrupole deformation or on the mixing of the states belonging to the coexisting structures is limited.

In order to probe the electromagnetic properties of yrast and non-yrast states of the radioactive even-even $^{182-188}$Hg [1], $^{196-202}$Po and $^{188-198}$Pb isotopes, Coulomb excitation experiments were performed at the REX-ISOLDE facility in CERN with a beam energy around 2.9 MeV/u. Next to that, lifetimes of yrast states in ^{182,184,186}Hg were determined with the Recoil Distance Doppler-Shift (RDDS) method [2-4] and γ-ray branching ratios and conversion coefficients were extracted from a decay study of the ^{182,184}Tl isotopes [5]. All the experimental data were combined in the Coulomb excitation analysis to obtain, for the first time, magnitudes and relative signs of   E2 matrix elements that couple ground and low-lying excited states in $^{182-188}$Hg. Information on the deformation of the ground and the first excited 0^+ states was deduced using the quadrupole sum-rules approach. The results show that the ground state of the light mercury isotopes is slightly deformed, and of oblate nature, while the deformation of the excited 0^+ states of ^{182,184}Hg is larger. A comparison with beyond mean field and interacting-boson based models [6,7] and an interpretation within a two-state mixing model firmly establishes the presence of two different structures in the light even-mass mercury isotopes that coexist at low excitation energy.

The study of the polonium isotopes focuses around ^{200}Po that appears to be a transitional nucleus between a general-seniority-type regime observed in the heaviest polonium isotopes and a shape-coexistence character in the lightest polonium isotopes. New results will be presented in comparison with recent results from beyond mean-field and interacting-boson based models.

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Spectroscopy of the Heaviest Elements

U. Forsberg[1], D. Rudolph[1], P. Golubev[1], L.G. Sarmiento[1], A. Yakushev[2], L.-L. Andersson[3], Ch.E. Düllmann[2,3,4], J.M. Gates[5], K.E. Gregorich[5], F.P. Heßberger[2,3], R.-D. Herzberg[6], J. Khuyagbaatar[2,3], J.V. Kratz[4], K. Rykaczewski[7], M. Schädel[2,8], S. Åberg[1], D. Ackermann[2], M. Block[2], H. Brand[2], B.G. Carlsson[1], D. Cox[6], X. Derkx[3,4], A. Di Nitto[4], K. Eberhardt[4], J. Even[3], C. Fahlander[1], J. Gerl[2], C.J. Gross[7], E. Jäger[2], B. Kindler[2], J. Krier[2], I. Kojouharov[2], N. Kurz[2], B. Lommel[2], A. Mistry[6], C. Mokry[4], H. Nitsche[5], J.P. Omtvedt[9], P. Papadakis[6], I. Ragnarsson[1], J. Runke[2], H. Schaffner[2], B. Schausten[2], P. Thörle-Pospiech[4], T. Torres[2], A. Türler[10], A. Ward[6], N. Wiehl[3,4]

[1]*Lund University, S-22100 Lund, Sweden*
[2]*GSI Helmholtzzentrum für Schwerionenforschung GmbH, D-64291 Darmstadt, Germany*
[3]*Helmholtz Institute Mainz, D-55099 Mainz, Germany*
[4]*Johannes Gutenberg-Universität Mainz, D-55099 Mainz, Germany*
[5]*Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[6]*University of Liverpool, Liverpool L69 7ZE, United Kingdom*
[7]*Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA*
[8]*Advanced Research Center, Japan Atomic Energy Agency, Tokai, Japan*
[9]*University of Oslo, NO-0315 Oslo, Norway*
[10]*Paul Scherrer Institute and University of Bern, CH-5232 Villingen, Switzerland*

During the past decade, a number of correlated α-decay chains, which all terminate by spontaneous fission, have been observed in several independent experiments using ^{48}Ca-induced fusion-evaporation reactions on actinide targets [1]. These are interpreted to originate from the production of isotopes with proton numbers Z=113-118.

In November 2012, a three-week experiment was conducted at the GSI Helmholtzzentrum für Schwerionenforschung GmbH in Darmstadt, Germany, using high-resolution α, electron, *X*-ray and γ-ray coincidence spectroscopy to provide the first insight into the structure of these heaviest known elements. The reaction ^{48}Ca+^{243}Am was used, with fusion-evaporation products being focused into the TASISpec set-up [2-4], which was coupled to the gas-filled separator TASCA [5,6].

A beam integral of roughly 7*10^{18} ^{48}Ca particles led to the observation of 30 correlated α decay chains with characteristics similar to those previously published [7,8]. Using the new detailed spectroscopic data the first levels schemes for five isotopes of superheavy elements have been proposed. These level schemes will be motivated and presented. Electric dipole (E1) transitions observed in ^{276}Mt are most exciting from the nuclear structure perspective and will be highlighted.

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Session 18 – Room 028: Nuclear Reactions

Measurements of neutron-induced reactions in inverse kinematics

René Reifarth[1], Yuri A. Litvinov[2,3]

[1]Goethe-Universität Frankfurt am Main, 60438 Frankfurt am Main, Germany
[2]GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany
[3] Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany

Neutron capture cross sections of unstable isotopes are important for neutron-induced nucleosynthesis [1] as well as for technological applications [2]. A combination of a radioactive beam facility, an ion storage ring and a high flux reactor would allow a direct measurement of neutron induced reactions over a wide energy range on isotopes with half lives down to minutes [3].

The idea is to measure neutron-induced reactions on radioactive ions in inverse kinematics. This means, the radioactive ions will pass through a neutron target. In order to efficiently use the rare nuclides as well as to enhance the luminosity, the exotic nuclides can be stored in an ion storage ring. The neutron target can be the core of a research reactor, where one of the central fuel elements is replaced by the evacuated beam pipe of the storage ring. Using particle detectors and Schottky spectroscopy, most of the important neutron-induced reactions, such as (n,γ), (n,p), (n,α), (n,2n), or (n,f), could be investigated.

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The Neutron Time-of-Flight Cross Section Program
at the University of Kentucky

J.R. Vanhoy[1], S.F. Hicks[2], B.P. Crider[3], A.J. French[2], E.A. Garza[1],
S.L. Henderson[2], T.J. Howard[2], S.H. Liu[3], S.Nigam[3], L. Pecha[2], E.E. Peters[3],
F.M. Prados-Estévez[3], M.T. McEllistrem[3], B.G. Rice[1], T.J. Ross[3], Z.C. Santonil[2],
L.C. Sidwell[2], J.L. Steves[1], and S.W. Yates[3].

[1]*U.S. Naval Academy, 21402 Annapolis, Maryland USA*
[2]*University of Dallas,75062 Irving, Texas USA*
[3]*University of Kentucky, 40506 Lexington, Kentucky USA*

Elastic and inelastic neutron differential cross sections are measured at the University of Kentucky Accelerator Laboratory (www.pa.uky.edu/accelerator/) at incident energies in the fast neutron region. The laboratory's facilities and instrumentation will be described and our measurement and analysis procedures outlined. Many corrections are required for neutron scattering experiments and the analysis utilizes information from many other cross section data sets and model calculations. Exploring and understanding the limitations of the foundational information and procedures are important for controlling the accuracy of the cross section results. We are examining the limitations in neutron detection efficiency, the normalization of (n,n'γ) cross sections, background reduction, spectrum stripping techniques, and attenuation and multiple scattering corrections. The resulting differential cross sections provide information on the compound elastic and coupled channels reaction mechanisms important for advanced reactor designs. Data from (n,n') and (n,n'γ) on ^{23}Na, ^{nat}C, ^{nat}Fe, and ^{54}Fe, will be shown for illustration.

Total absorption spectroscopy of ^{238}U fission products*

K.P. Rykaczewski[1], A Fijałkowska[2,3,4], M.Karny[2], M.Wolińska-Cichocka[4,5], R.K. Grzywacz[1,3,4], C.J.Gross[1], B.C.Rasco[6], K.C.Goetz[3], R.Goans[7], J.Johnson[1], D.Miller[3], C.Jost[3], M.Madurga[3], K.Miernik[2], S.V.Paulauskas[3], M. Al-Shudifat[3], E.Spejewski[7], D.Stracener[1], E.Zganjar[6], J.H.Hamilton[8] and A.V.Ramayya[8]

[1] *ORNL, Oak Ridge, TN 37830, USA*
[2] *Faculty of Physics, University of Warsaw, Warsaw, PL 00-681, Poland*
[3] *University of Tennessee, Knoxville, TN 37996, USA*
[4] *JINPA, Oak Ridge, TN 37830, USA*
[5] *Heavy Ion Laboratory, University of Warsaw, Warsaw, PL 02-093, Poland*
[6] *Louisiana State University, Baton Rouge, LA 70803, USA*
[7] *ORAU, Oak Ridge, TN 37830, USA*
[8] *Vanderbilt University, Nashville, TN 37235, USA*

Total absorption spectroscopy is a detection technique used in beta-decay studies. It refers to the measurements performed with a very efficient beta and gamma detector array surrounding the activity.

The Modular Total Absorption Spectrometer (MTAS) was constructed at Oak Ridge National Laboratory (ORNL) to study the decays of fission products. The array has about 80% to 70% efficiency for detecting the full energy of a single gamma transition between 300 keV to 5 MeV, respectively. MTAS measurements reveal the true beta-gamma decay pattern in complex decays of fission products. In particular, the decay heat released in beta decay can be determined enabling better modelling of the processes occurring during the nuclear fuel cycle.

Twenty two decays of mass-separated ^{238}U fission products [1], from ^{85}Se to ^{142}Ba, have been measured with MTAS at ORNL. The nuclei studied included ^{86}Br, ^{87}Br, ^{89}Kr, ^{90}Kr, ^{137}I, ^{137}Xe and ^{139}Xe, i.e., the activities produced abundantly in nuclear reactors and having the highest priority for decay heat analysis [2]. The comparison of MTAS results to earlier data shows a substantial increase of average gamma energy emitted in these beta-gamma decays, typically from 20% to 40% [3]. Corresponding average beta transition energy is decreased. These results indicate increased beta feeding to high energy states in daughter nuclei and subsequent gamma de-excitations.

New beta decay patterns deduced from MTAS measurements also affect the energy spectra of anti-neutrinos produced during the operation of nuclear reactors. Since beta decay energy is shared between electron and anti-neutrino, the average energy of anti-neutrino per decay is reduced. This effect changes the expected number of reactor anti-neutrino interactions with protons.

The results of MTAS measurements will be presented and discussed with respect to the decay heat analysis and anti-neutrino interactions with matter.

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Session 19 – Room 120: Nuclear Structure

In-beam γ-ray spectroscopy of very exotic *N* = 32 and 34 isotones

D. Steppenbeck[1], S. Takeuchi[2], N. Aoi[3], P. Doornenbal[2], M. Matsushita[1], H. Wang[2], H. Baba[2], N. Fukuda[2], S. Go[1], M. Honma[4], J. Lee[2], K. Matsui[5], S. Michimasa[1], T. Motobayashi[2], D. Nishimura[6], T. Otsuka[1,5], H. Sakurai[2,5], Y. Shiga[7], P.-A. Söderström[2], T. Sumikama[8], H. Suzuki[2], R. Taniuchi[5], Y. Utsuno[9], J. J. Valiente-Dobón[10] and K. Yoneda[2]

[1]*Center for Nuclear Study, University of Tokyo, Bunkyo, Tokyo 113-0033, Japan*
[2]*RIKEN Nishina Center, 2-1, Hirosawa, Wako, Saitama 351-0198, Japan*
[3]*Research Center for Nuclear Physics, University of Osaka, Ibaraki, Osaka 567-0047, Japan*
[4]*Center for Math. Sciences, Aizu University, Aizu-Wakamatsu, Fukushima 965-8580, Japan*
[5]*Department of Physics, University of Tokyo, Bunkyo, Tokyo 113-0033, Japan*
[6]*Deparment of Physics, Tokyo University of Science, Noda, Chiba 278-8510, Japan*
[7]*Department of Physics, Rikkyo University, Toshima, Tokyo 171-8501, Japan*
[8]*Department of Physics, Tohoku University, Sendai, Miyagi 980-8578, Japan*
[9]*Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan*
[10]*Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Legnaro, Legnaro 35020, Italy*

Recent experimental investigations of neutron-rich $N = 32$ and 34 isotones have highlighted the presence of sizable subshell closures at these neutron numbers that are absent in stable and near-stable nuclei. For example, the onset of a new subshell closure at $N = 34$ has been reported in ^{54}Ca [1], while other studies have focused on the development of the $N = 32$ subshell closure along the Cr [2,3], Ti [4,5], and Ca [6] isotopic chains. On the theoretical side, these subshell closures have been investigated in the framework of tensor-force-driven shell evolution [7], among other methods, and were attributed to a reordering of the $\nu f_{5/2}$ orbital relative to the $\nu p_{3/2}$ and $\nu p_{1/2}$ spin-orbit partners as protons are removed from the $\pi f_{7/2}$ state. It has also been reported that no significant $N = 34$ subshell closure exists in Ti isotopes [5,8], which contain two protons in the $\pi f_{7/2}$ orbital, despite the fact that an inversion of the $\nu f_{5/2}$ and $\nu p_{1/2}$ orbitals occurs [9]. Thus, the strength of the $N = 34$ subshell closure in Sc isotopes, which contain only one proton in the $\pi f_{7/2}$ orbital, provides further important input to the evolution of the $\nu f_{5/2}$ orbital in exotic systems. Moreover, the structures of very neutron-rich Ar isotopes, which are presently reported up to ^{48}Ar [10], can provide information on the magnitude of the $N = 32$ subshell closure below $Z = 20$. In the present work, the low-lying structures of ^{50}Ar, ^{53,54}Ca, and ^{55}Sc are reported to investigate further the evolution of the $N = 32$ and 34 subshell closures in nuclei far from stability.

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High precision mass measurements of rare isotopes at TITAN[*]

S. Ettenauer[1,2,3,11+], A. Bader[1], U. Chowdhury[1,4], A. T. Gallant[1,2], A. Lennarz[1,5], R. Klawitter[1,6], T. MacDonald[1,2], J. M. Rauch[1], S. Seeraji[9],V. V. Simon[1,6], M. Brodeur[7], T. Brunner[1,8], A. Chaudhuri[1], A. Großheim[1], A.A. Kwiatkowski[1], K. G. Leach[1], E. Mané[1], M. C. Simon[1], B. E. Schultz[1], C. Andreoiu[9], M. Good[1], G. Gwinner[4], D. Frekers[5], A. Lapierre[7], D. Lunney[10], R. Ringle[7], M. R. Pearson[1],and J. Dilling[1,2]

[1]*TRIUMF, 4004 Wesbrook Mall, Vancouver BC, Canada V6T 2A3*
[2]*Department of Physics and Astronomy, UBC, Vancouver, BC, V6T 1Z1, Canada*
[3]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
[4]*Department of Physics and Astronomy,University of Manitoba,Winnipeg, MB R3T 2N2, Canada*
[5]*Institut für Kernphysik, Westfälische Wilhelms-Universität, 48149 Münster, Germany*
[6]*MPI Heidelberg, Germany*
[7]*NSCL, Michigan State University, Michigan 48824, USA.*
[8]*Physik Department E12, Technische Universität München, Garching, Germany*
[9]*Simon Fraser University, Canada*
[10]*CSNSM-IN2P3-CNRS, Universite de Paris Sud, 91405 Orsay, France*
[11]*CERN, CH-1211 Geneva 23, Switzerland*

Atomic masses of rare isotopes continue to be a fundamental ingredient for studies of nuclear structure, nuclear astrophysics, and fundamental symmetries. In the endeavor to explore the nuclear mass surface towards the limits of nuclear existence, TRIUMF's Ion Trap for Atomic and Nuclear Science (TITAN) has pioneered Penning trap mass spectrometry along two aspects: Firstly, it is uniquely capable to handle very short lived nuclides with half-lives even below 10 ms [1]. Secondly, it is pushing on the precision frontier by utilizing an electron beam ion trap to breed short-lived nuclides delivered from ISAC / TRIUMF to a higher charge state [2]. The precision of the mass measurement in a Penning trap is thereby boosted by a factor identical to the charge state q of the ion. In combination with advanced excitation schemes such as the recently introduced Ramsey technique [3], this approach for rare isotopes opens the path towards gains of 1-2 orders of magnitude in experimental precision.

Recently, these unique experimental capabilities at a radioactive ion beam facility allowed TITAN to make contributions in a variety of physics questions. These range from nuclear structure topics as neutron-rich Ca-isotopes as a superb testing ground for 3-body forces [4] or studies around the island of inversion [5], over tests of the IMME [6], to solar neutrino physics [7]. For the latter, the Q-values of $^{71}Ga(v,e^-)^{71}Ge$ and $^{51}Cr(e^-, v)^{51}V$ were determined accurately using ions with up to q=22+. Previously these Q-values represented nuclear physics uncertainties relevant for the discrepancy observed in the SAGE and GALLEX neutrino calibration measurements [8].

This talk will provide an overview over the TITAN facility and a summary of recent results in high precision mass measurements.

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Masses of exotic calcium isotopes and three-nucleon forces

J. Menéndez[1,2], J. D. Holt[1,2], J. Simonis[1,2], and A. Schwenk[2,1]
[1]*Institut für Kernphysik, Technische Universität Darmstadt, 64289 Darmstadt, Germany*

[2]*ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany*

Nuclear structure calculations based on nuclear forces are now feasible using two- and three-nucleon (NN and 3N) interactions from chiral effective field theory (EFT). 3N forces have been shown crucial for a correct description of nuclear structure from the spectra of light nuclei, and to describe properties of medium-mass nuclei, the neutron dripline of oxygen [1,2] and the existence of the shell closure at N=28 [3].

In the framework of many-body perturbation theory (MBPT) we obtain an effective Hamiltonian to be used in valence-shell model calculations. Both single-particle energies and two-body matrix elements are calculated, without further modifications. The NN and 3N forces are included consistently to third order in MBPT.

Our calculations have been found to be in excellent agreement with the two-neutron separation energies for the neutron-rich calcium isotopes up to ^{54}Ca, measured in recent experiments at TRIUMF [4] and ISOLTRAP [5]. In particular, the two-neutron separation energy at ^{54}Ca unambiguously establishes the subshell closure at neutron number N=32 predicted by calculations with NN and 3N forces. Excitation spectra can also be calculated within this approach, and the lowest 2^{+} state in ^{54}Ca, key for the determination of the N=34 subshell closure, was also predicted [6] in reasonable agreement with the subsequent experimental measurement at RIKEN [7]. This interplay between precision measurements and microscopic nuclear structure calculations permits to use new measurements of exotic nuclei to pin down nuclear forces.

I will show these results and first calculations for the electric quadrupole moments, magnetic moments and electromagnetic transitions of neutron-rich calcium isotopes, based on calculations including NN and 3N forces. For these observables we also find a very good agreement with experiment, in particular for the most neutron-rich isotopes measured.

Furthermore, I will present a new study on the important question of the theoretical uncertainty of nuclear structure calculations. By exploring the sensitivity of the results to the cutoffs of the two- and three-nucleon forces and to the low-energy couplings of chiral EFT, we evaluate the theoretical uncertainties, and include them in the comparison to the experimental measurements. This gives an insight on which aspects of theoretical calculations need to be improved in future developments.

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Do nuclei go pear-shaped?
Coulomb excitation of [220]Rn and [224]Ra at REX-ISOLDE(CERN)

M.Scheck[1,2,3], L.P.Gaffney[3,4], P.A.Butler[3], A.B.Hayes[5], F.Wenander[6], M.Albers[7], B.Bastin[8], C.Bauer[9], A.Blazhev[7], S.Boenig[9], N.Bree[4], J.Cederkall[10], T.Chupp[11], D.Cline[5], T.E.Cocolios[6], T.Davinson[7], H.De Witte[4], J.Diriken[4], T.Grahn[13,14], A.Herzan[13], M.Huyse[4], D.G.Jenkins[15], D.T.Joss[3], N.Kesteloot[4], J.Konki[13], M.Kowalczyk[16], Th.Kroell[9], E.Kwan[17], R.Lutter[18,19], K.Moschner[7], P.Napiorkowski[16], J.Pakarinen[6,13], M.Pfeiffer[7], D.Radeck[7], P.Reiter[7], K.Reynders[4], S.V.Rigby[3], L.M.Robledo[20], M.Rudigier[7], S.Sambi[4], M.Seidlitz[7], B.Siebeck[7], T.Stora[6], P.Thoele[7], P.Van Duppen[4], M.J.Vermeulen[15], M.von Schmid[9], D.Voulot[6], N.Warr[7], K.Wimmer[19], K.Wrzosek-Lipska[3,16], C. Y. Wu[17], and M. Zielinska[21]

[1]University of the West of Scotland, PA1 2BE Paisley, UK
[2]SUPA, Scottish Universities Physics Alliance, G12 8QQ Glasgow, UK
[3]University of Liverpool, L69 7ZE Liverpool, UK, [4]KU Leuven, B-3001 Leuven, Belgium
[5]University of Rochester, NY 14627-0171 Rochester, USA
[6]ISOLDE, CERN, CH-1211 Geneva, Switzerland, [7]Universitaet zu Köln, D-50937 Köln, Germany
[8]GANIL, F-14076 Caen, F-14076, France, [9]TU Darmstadt, D-64289 Darmstadt, Germany
[10]Lund University, 221 00 Lund, Sweden, [11]University of Michigan, MI 48104 Ann Arbor, USA
[12]University of Edinburgh, EH9 3JZ Edinburgh, UK,
[13]University of Jyvaskyla, FI-40014 Jyvaskyla, Finland
[14]Helsinki Institute of Physics, FI-00014 Helsinki, Finland
[15]University of York, YO10 5DD York, UK, [16]University of Warsaw, 02-093 Warsaw, Poland
[17]Lawrence Livermore National Laboratory, CA 94551 Livermore, USA
[18]Ludwig-Maximilians-Universitaet, D-85748 Garching, Germany
[19]TU Muenchen, D-85748 Garching, Germany
[20]Universidad Autonoma de Madrid, 28049 Madrid, Spain
[21]CEA Saclay, F-91191 Gif-sur-Yvette, France

It is long known that in nuclei the interplay of quadrupole and octupole degree of freedom gives rise to E1 moments. Consequently, the presence of static deformations of both type in the ground state of a nucleus results in a CP-violating nuclear Schiff moment [1,2]. The mass region near Z=88 and N=136 has been long known for softness in the octupole degree of freedom [3]. In order to answer the long-standing question whether some of these nuclei possess octupole correlations in their ground state information about the B(E3, 0^+ -> 3^-)-transition strength is needed. However, owed to the radioactive nature of the nuclei in this mass region experimental information about this quantity is sparse. Prior to this work only for [226]Ra this information was available [4]. Here, we report about Coulomb-excitation experiments which provide quantitative information for this crucial quantity in [220]Rn and [224]Ra [5]. The experiments exploited the unique capability of the ISOLDE facility to produce and the REX linac to post accelerate these nuclei in sufficient quantities for Coulomb-excitation studies. The data was obtained employing the MINIBALL spectrometer [4].

A nuclear Schiff moment would amplify an atomic Schiff moment. Hence, the presented results serve to identify suitable candidates for the search for CP-violating atomic Schiff moments (e.g., see Ref. [7]).

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Session 20 – Room 028: Statistical Properties

Statistical properties of warm nuclei

S. Siem[1], L. Bernstein[2], D. Bleuel[2], T. Eriksen[1], F. Giacoppo[1], A. Görgen[1], M. Guttormsen[1], A.C. Larsen[1], L.G.Moretto[3,4], H.T. Nyhus[1], T. Renstrøm[1], S.J. Rose[1], T.Tornyi[1], G.M. Tveten[1], A. Voinov[5], M. Wiedeking[6], J. Wilson[7]

[1]University of Oslo, Dept. of Physics, Oslo, Norway
[2] Lawrence Livermore National Laboratory, Livermore, CA, USA
[3]Department of Chemistry, University of California, Berkeley, CA, USA
[4]Lawrence Berkeley National Laboratory, Berkeley, CA, USA
[5] Dept of Physics and Astronomy, Ohio University, Athens, OH, USA
[6] iThemba LABS, Somerset West, South Africa
[7] Institut de Physique Nucleaire d'Orsay, Orsay Cedex, France

The nuclear physics group in Oslo has developed a unique technique to extract simultaneously the level density and γ-strength function from primary γ-ray spectra [1].
Level densities and gamma strength functions are fundamental properties of the atomic nucleus and important input parameters in reaction cross-section calculations. These cross sections are used in simulations of nuclear reactors and in astrophysics in large network calculation of formation of heavy elements in explosive stellar environments.
In this talk I will give an overview of the latest results from experiments performed in Oslo, starting with the latest status of the low energy enhancement of the γ-strength function first seen in Fe and Mo isotopes [2]. This low energy enhancement has the potential of increasing neutron-capture rates with up to two orders of magnitude if also present in very neutron-rich nuclei [3].
For the thorium fuel cycle there are still neutron capture cross sections for some isotopes which are poorly known or not measured. At the Oslo Cyclotron we have started a program to study actinides relevant for the thorium fuel cycle, including the incorporation of a PPAC fission detector into our experimental setup. I will present the level densities and gamma strength functions measured for $^{231-233}$Th, ^{232,233}Pa, and $^{237-239}$U nuclei [4,5]. These nuclei show a strong M1 scissors mode resonance in the gamma strength function that can significantly enhance neutron capture rates. These nuclei exhibit a constant temperature level density. In a recently submitted paper we show that the observed constant temperature level densities is a strong signature of a first-order phase transition and it is completely consistent with the BCS framework. [6].

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Statistical Model Calculations for (n,g) Reactions

Mary Beard[1,2], Ethan Uberseder[1,3], Michael Wiescher[1]

[1]University of Notre Dame, IN, USA
[2]ExtreMe Matter Institute, GSI, Germany
[3]Texas A&M University, TX, USA

Hauser-Feshbach (HF) cross sections are of enormous importance for a wide range of applications, from waste transmutation and nuclear technologies, to medical applications, and nuclear astrophysics. It is a well observed result that different nuclear input models sensitively affect HF cross section calculations. Less well-known however are the effects on calculations originating from model-specific implementation details (such as level density parameter, matching energy, backshift and giant dipole parameters), as well as effects from non-model aspects, such as experimental data truncation and transmission function energy binning. To investigate the effects or these various aspects, Maxwellian-averaged neutron capture cross sections have been calculated for approximately 340 nuclei. The relative effects of these model details will be discussed.

Low-energy enhancement of magnetic dipole radiation

S. Frauendorf[1], A. C.Larsen[2], R. Schwengner[3], K. Wimmer[4]

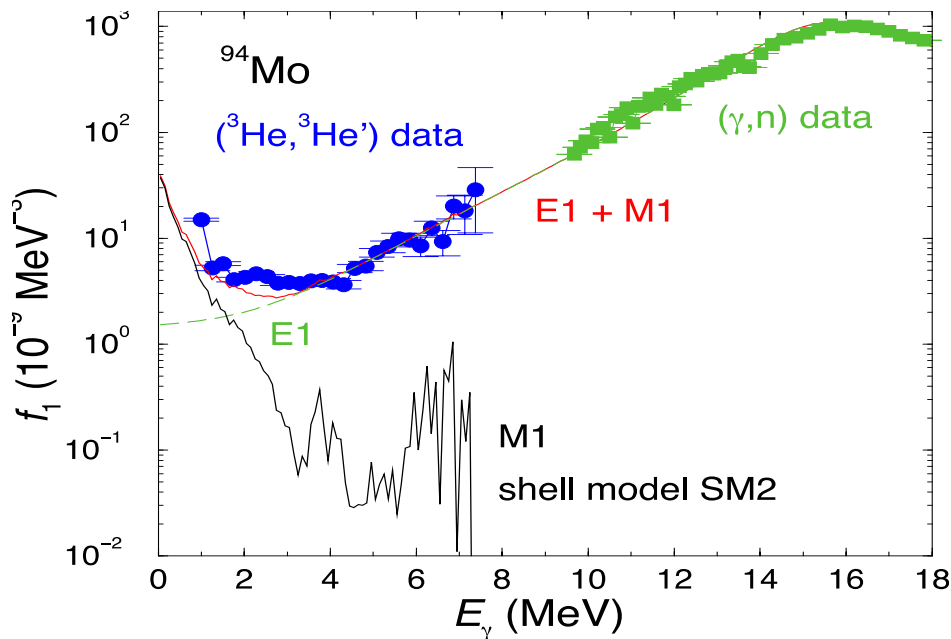[1]University Notre Dame, Notre Dame, IN 46557, USA
[2]University of Oslo, 0316 Oslo, Norway
[3]Helmholtz-Zentrum Dresden-Rossendorf, 01328 Dresden, Germany
[4]Central Michigan University, Mt Pleasant, MI 48859, USA

Enhancement of strength function for magnetic radiation has been found by means of shell model calculations for the Mo and Zr isotopes [1], which explains the experimentally observed increase of the dipole strength. It originates from statistical low-energy M1-transitions between many excited (several MeV), which correspond to a reorientation of the nucleonic angular momenta. The calculated enhancement is consistent with experimental gamma-strength functions observed in (particle,gamma) reactions on the studied nuclei. Additional calculations for neutron-rich nuclei will be presented, for which the enhancement will have a significant impact on reaction rates in the r-process in explosive stellar environments. The enhancement is predicted to occur in nuclides where Magnetic Rotational bands are found. The reliability of this prediction will be investigated by carrying out Shell model calculations for nuclei that do not show Magnetic Rotation. The results will be reported.

In contrast to the common Porter-Thomas distribution of electromagnetic transitions between nuclear compound states, the calculated reduced widths are distributed according to a **power law** ($1/n$ noise)**.** This deviation from the distribution of the Gaussian Orthogonal Ensemble (GOE) can be traced to the missing of a single particle energy scale for the M1 transitions that cause the low-energy enhancement. The phenomenon is a consequence small size of the nucleus, which allows for large angular momenta of the nucleon orbitals, which may rearrange without energy cost.

Comparison of the calculated dipole gamma strength function with experiment

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First evidence of low energy upbend in germanium isotopes

T. Renstrøm[1], L. A. Bernstein [2], D. L. Bleuel [2], A. D.M. Filipescu [3,4], I. Gheorghe[4],
T. Glodariu[4], A. Görgen [1], M. Guttormsen [1], T. W. Hagen[1], A. C. Larsen [1], D. Negi [5], H.-T.
Nyhus [1], I. E. Ruud [1], R. Schwengner [6], T. Shima [7], S. Siem [1], K. Takahisa [7], O. Tesileanu[3],
T. G. Tornyi [1,8], G. Tveten [1], H. Utsunomiya [9], and M. Wiedeking [5]

1 Department of Physics, University of Oslo, N-0316 Oslo, Norway
2 Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore, California 94550-9234, US
3 Extreme Light Infrastructure Nuclear Physics, str Atomistilor nr. 407, Bucharest-Magurele, P.O.BOX MG6, Romania
4 National Institute for Physics and Nuclear Engineering Horia Hulubei, str Atomistilor nr. 407, Bucharest-Magurele, P.O.BOX MG6, Romania
5 iThemba LABS, P.O. Box 722, 7129 Somerset West, South Africa
6 Institute of Radiation Physics, Helmholtz-Zentrum Dresden-Rossendorf, 01328 Dresden, Germany
7 Institute of Nuclear Research of the Hungarian Academy of Sciences (MTA Atomki), Debrecen, Hungary
8 Research Center for Nuclear Physics, Osaka University, Suita, Osaka 567-0047, Japan
9 Department of Physics, Konan University, Okamoto 8-9-1, Higashinada, Kobe 658-8501, Japan

An unexpected enhancement in the γ–ray stength function (γSF) at low energies was first reported in [1]. Since then data from the Oslo Cyclotron Laboratory (OCL) have shown a similar feature for several investigated nuclei in the light-medium mass region. The findings were reproduced for ^{95}Mo by a different group [2], eight years after the first reported case from OCL. Until recently the electromagnetic character and multipolarity of the upbend have been unknown, but in [3] the multipolarity was discovered to be of dipole character for ^{56}Fe. Lately two theories concerning the origin of the upbend have been published [4,5].

The measurements of the γSF of ^{74}Ge was performed as a part of an international campaign to compare γSF obtained when using different experimental techniques and methods.

The γSF in quasi-continuum has been measured for ^{74}Ge using the Oslo method [6]. This method makes it possible to extract the level density and γSF from the same dataset. The reaction used in this case was ^{74}Ge(^{3}He, ^{3}He'γ)^{74}Ge. A matrix containing particle-γ coincidens data from the experiment is the main input in the Oslo method. From this starting-point a new matrix containing excitation indexed first generation γ-spectra is deduced. The level density and γSF are obtained form the factorization of our first-generation matrix, but the data are not normalized. Inspired by the need of normalizing the γSF, photoneutron cross section of ^{74}Ge was measured at the synchrotron radiation facility NewSUBARU [7]. From the photoneutron cross sections we found the γSF for energies between the neutron separation energy of ^{74}Ge and ~13 MeV.

The normalized level density and γSF of ^{74}Ge will be presented at this symposium.

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Session 21 – Room 120: Fundamental Properties

Gravity Resonance Spectroscopy constrains Dark Matter and Dark Energy Scenarios

H. Abele[1]

[1] for the qBounce Collaboration

We report on precision resonance spectroscopy measurements of quantum states of ultracold neutrons confined above the surface of a horizontal mirror by the gravity potential of Earth. Resonant transitions between several of the lowest quantum states are observed for the first time. These measurements demonstrate that Newton's inverse square law of gravity is understood at micron distances on an energy scale of 10^{-14} eV. At this level of precision, we are able to provide constraints on any possible gravitylike interaction. In particular, a dark energy chameleon field is excluded for values of the coupling constant $\beta > 5.8 \times 10^8$ at 95% confidence level (C.L.), and an attractive (repulsive) dark matter axionlike spin-mass coupling is excluded for the coupling strength $g_s g_p > 3.7 \times 10^{-16}$ ($5.3 \times 10{-16}$) at a Yukawa length of $\lambda < 20$ μm (95% C.L.).

Investigations of the time-modulated orbital electron capture decays

Yuri A. Litvinov[1,2] and F. Bosch[1] for the TBWD Collaboration

[1]GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany
[2] Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany

Periodic time modulations were found recently in the measurements of the two-body orbital electron capture (EC) decay of hydrogen-like ^{140}Pr^{58+} and ^{142}Pm^{60+} ions stored and cooled in the Experimental Storage Ring (ESR). The modulations in both investigated systems can be characterized by periods T_P near to 7 s and amplitudes a of about 20% [1]. The observed phenomenon caused intensive discussions in the physics community on its possible explanation. Numerous suggestions were proposed. However, no consensus is presently reached and the effect remains still unexplained.

In the last years, a new Schottky detector has been developed [2], which allowed for an unambiguous determination of the EC decay-time of each individual stored and cooled parent ion, with a very high time accuracy of merely a few tens of milliseconds. The EC decay of H-like ^{142}Pm^{60+} ions was re-investigated in the ESR by employing the previously used Schottky pick-up as well as this new detector [3]. The data recorded by both detectors confirmed that the exponential EC decay is modulated with a period T_P =7.11(8) s (mean of both detectors), in full accordance with the modulation period T_P = 7.10(25) s obtained for ^{142}Pm^{60+} in the previous experiment. However, the mean modulation amplitude of both detectors of a = 12(2)%, although being statistically significant, is almost two times smaller than the one seen previously. Also the three-body β + decays of H-like ^{142}Pm^{60+} ions has been analyzed in the new experiment. No significant modulation period could be observed.

The nature of the modulated EC decays, if undoubtedly confirmed in future experiments, is still unclear and, since it might be related to physics beyond the Standard Model, it requires urgently additional experimental investigations and theoretical interpretation. In this contribution the present status of the experiment and future perspectives will be discussed in detail.

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Improving CKM Unitarity Limits via Low-Energy Nuclear Physics

P.Finlay[1], G.Ball[2], T.Bastin[3], M.Bissel[1], S.Ettenauer[4], R.Glover[3], O.Naviliat-Cuncic[5] G.Neyens[1], E.Rand[6], N.Severijns[1], C.Svensson[6], P.Velten[1], and D.Zakoucky[7]

[1]K.U. Leuven, Instituut voor Kern- en Stralingsfysica, B-3001 Leuven, Belgium
[2]TRIUMF, V6T 2A3 Vancouver, Canada
[3]Institut de Physique Nucleaire, Atomique et de Spectroscopie, Universite de Liege, B-4000 Liege, Belgium
[4]CERN, 1211 Geneva 23, Switzerland
[5]National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, 48824 East Lansing, USA
[6]Department of Phyics, University of Guelph, N1G 2W1 Guelph, Canada
[7]Nuclear Physics Institute, ASCR, 250 68 Rez, Czech Republic

If the current three-generation standard model is complete, then the Cabibbo-Kobayashi-Maskawa matrix, which relates the mass and weak-interaction eigenstate of the quarks, should be unitary. The strictest test of unitarity currently comes from the top-row sum, with the most precise value for the largest element, V_{ud}, coming from superallowed Fermi beta decays[1]. Previous determinations of CKM unitarity from the top-row sum have seen equal contributions from V_{ud} and the next largest element, V_{us}. However, recent advances in lattice QCD calculations have led to a reduction of the uncertainty in V_{us}[2], making V_{ud} the largest contributor to the uncertainty in the unitarity sum, and hence the largest uncertainty in constraining new physics beyond the Standard Model.

Currently the uncertainty in the corrected Ft values from the superallowed decays which contribute to V_{ud} is not dominated by experiment, but rather by theory. While some progress in reducing the uncertainty in the value of V_{ud} extracted from the superallowed data can be, and is being, made by improving the precision in select experimental superallowed ft values[3], the primary challenge towards future progress in CKM unitarity tests lies with understanding the theoretical isospin-symmetry-breaking (ISB) corrections, which currently dominate the uncertainty in the corrected Ft values. While this has prompted many theoretical investigations of the ISB corrections[4], experimental input for the improvement of these calculations is also possible, and this talk will highlight some of the ongoing prospects for low-energy nuclear physics experiments to contribute to the understanding and refinement of the ISB corrections.

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Nuclear Diagnostics at the National Ignition Facility

D.L. Bleuel[1], L.A. Bernstein[1], E.J. Bond[1], J.A. Caggiano[1], D.T. Casey[1], W. Cassata[1], C.J. Cerjan[1], J.A. Church[1], G.W. Cooper[2], D. Fittinghoff[1], J.A. Frenje[3], V. Yu. Glebov[4], N. Gharibyan[1], J.M. Gostic[1], G. Grim[5], C.A. Hagmann[1], R. Hatarik[1], H.W. Herrmann[5], M. Gatu Johnson[3], J.P. Knauer[4], R.J. Leeper[5], J. McNaney[1], F.E. Merrill[4], K.J. Moody[1], C.L. Ruiz[6], D. Sayre[1], D.H.G. Schneider[1], D.A. Shaughnessy[1], W. Stoeffl[1], M.A. Stoyer[1], C.A. Velsko[1], C.B. Yeamans[1]

[1]_Lawrence Livermore National Laboratory, 94550 Berkeley, CA USA_
[2]_University of New Mexico, 87131 Albuquerque, NM USA_
[3]_Massachusetts Institute of Technology, 02139 Cambridge, MA USA_
[4]_Laboratory for Laser Energetics, UR, 14623 Rochester, NY USA_
[5]_Los Alamos National Laboratory, 97545 Los Alamos, NM USA_
[6]_Sandia National Laboratory, 87131 Albuquerque, NM USA_

At the National Ignition Facility (NIF), 192 lasers focus up to 1.9 MJ of energy into a cylindrical gold hohlraum, creating a near-Planckian x-ray bath which compresses a 2 mm capsule of deuterium-tritium (DT) fuel through ablation of an outer plastic shell. At densities approaching 1000 g/cm3 and temperatures over 4 keV, the DT fuel fuses, producing energy, gamma rays, alpha particles, and neutrons. A suite of nuclear diagnostics measures fusion and capsule assembly conditions inside the ~50 μm implosion. Activation diagnostics[1], including zirconium, copper, indium, thulium, and aluminium samples deployable at over twenty locations around and inside the NIF chamber, measure neutron yield, areal density asymmetries, and bulk fuel velocity. Neutron time-of-flight diagnostics[2], three at 20 m from the implosion and several more at ~4 m, measure neutron yield, fuel areal density, ion temperature, and fuel velocity via the neutron spectrum. A magnetic recoil spectrometer[3] also measures neutron yield, fuel areal density, and ion temperature. Images of both the burning fuel and surrounding dense, cold, fuel scattering layer are generated by the neutron imaging system[4]. The gamma reaction history diagnostic[5], consisting of four variable-thresholding Cerenkov detectors, measures reaction "bang time" and fusion burn duration. Solid gold debris[6] from exploding hohlraums are collected on removable surfaces 50 cm from the implosion, providing areal density measurements through the ratio of thermal to fast neutron activation reactions. Gaseous debris is collected on cryogenic collectors, measuring the same ratio from reactions on capsule-implanted xenon isotopes. Integrated analysis of all these implosion properties has produced a comprehensive model of capsule performance, leading to the recent "high-foot" experimental campaign[7,8] designed to reduce inferred Rayleigh-Taylor fuel compression instabilities. This campaign achieved a fuel gain exceeding unity with nearly 10^{16} fusion reactions (25kJ) in a single shot.

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Cross Section Measurements at LANSCE for Defense, Energy and Science Applications

R. O. Nelson

Los Alamos National Laboratory, Los Alamos, NM 87501 USA

Neutron-induced nuclear reaction cross section measurements have been a focus of research at Los Alamos for most of its history. Measurements at the Los Alamos Neutron Science Center (LANSCE) using intense spallation neutron sources driven by the LANSCE 800-MeV proton linear accelerator continue this work, providing nuclear data with improved accuracy and for a wide range of applications. The neutron energy range available at LANSCE spans the entire region from thermal to hundreds of MeV. Current experimental efforts are concentrated on precise fission cross section measurements using a time projection chamber, and on measurements of the fission neutron spectra, prompt yields and fragment kinetic energies. Fission measurements on samples as small as 10 nanograms, and on very radioactive samples are made with a lead-slowing down spectrometer as well. Partial gamma ray cross section measurements using the GEANIE array of germanium detectors provide a window into nuclear reactions for many diverse applications, and neutron-induced charged particle production cross section measurements provide data for such needs as reactor vessel damage due to He and H build-up and other processes. Data on fission cross sections and gamma ray production provide improved reference cross sections for other measurements. The applications of the data and evaluations based on it, are diverse including such topics as: nuclear reactor simulations, diagnostics for a variety of nuclear systems, understanding potential backgrounds in fundamental physics experiments, and understanding nucleosynthesis.

Prompt gamma-ray production in neutron-induced fission of [239]Pu

J.L. Ullmann[1], S.M. Mosby[1], M. Jandel[1], C.Y. Wu[2], J.A. Becker[2], E.M. Bond[1], T.A. Bredeweg[1], A. Chyzh[2], A. Couture[1], J. Gostic[2], R.C. Haight[1], A.C. Hayes[1], R. Henderson[2], T. Kawano[1], H.Y. Lee[1], E. Kwan[2], J.M. O'Donnell[1], I. Stetcu[1], T.N. Taddeucci[1], P. Talou[1], D.J. Vieira[1], J.B. WIlhelmy[1]

[1]*Los Alamos National Laboratory, Los Alamos, NM, USA 87545*
[2]*Lawrence Livermore National Laboratory, Livermore, CA. USA 94550*

Detailed knowledge of the properties of gamma rays emitted from fission is important not only for understanding the basic fission process and energy balance, but also for applications such as nuclear energy and global security. A comparison of measurements to theoretical calculations tests our ability to model gamma-ray emission. A measurement of the total gamma energy, individual gamma energy, and multiplicity spectra for neutron-induced fission of [239]Pu [1] was recently made using the nearly 4π DANCE detector at the Los Alamos Neutron Science Center (LANSCE). The measurement was made over the neutron energy range from 10 eV to roughly 30 keV, but the published spectra were limited to results from the 10.93 + 11.89 eV 1[+] resonance complex. Fission events were tagged using a small PPAC, containing roughly 1 milligram of highly-enriched (99.967%) [239]Pu. The PPAC was inserted into the center of the DANCE array. Even with a highly-efficient detector array, corrections for detector response are important, and two methods for making the correction are described.

The methods for correcting for detector response will be discussed. The resulting spectra will be compared to other data, global parameterizations, and recent model calculations. The average total gamma-ray energy was estimated to be 7.46 ± 0.06 MeV/fission, about 10% higher than the ENDV/B-VII.1 evaluation. Results for additional resonances will be presented. Anomalous spectra were observed for resonances near 35, 41, 45, and 53 eV, consistent with anomalies observed in prompt fission neutron spectra and attributed to (n,γf) reactions.

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LA-UR-22854

Relating nuclear molecular structure and sub-Coulomb fusion in the ^{12}C + ^{12}C collision using time-dependent wave-packet dynamics

Alexis Diaz-Torres[1], Michael Wiescher[2]

[1]_ECT* , Villa Tambosi, 38123 Villazzano, Trento, Italy_
[2]_JINA and University of Notre Dame, Indiana 46656, USA_

A quantitative study of the ^{12}C + ^{12}C sub-Coulomb fusion will be presented. It is carried out using full-dimensional, time-dependent wave-packet dynamics, a quantum reaction model that has not been much exploited in nuclear physics, unlike in chemical physics [1]. The low-energy collision is described in the rotating center-of-mass frame within a nuclear molecular picture [2]. A collective Hamiltonian drives the time propagation of the wave-packet through the collective potential-energy landscape that is calculated with a realistic two-center shell model [3]. Among other preliminary results [4], the theoretical sub-Coulomb fusion resonances for ^{12}C + ^{12}C seem to correspond well with observations. The method appears to be useful for expanding the cross-section predictions towards stellar energies.

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[137]Ba Double Gamma Decay Measurement with GAMMASPHERE

E. Merchan[1], C.J. Lister[1], K. Moran[1], E.A. McCutchan[2], D.J. Millener[2],
D. Sutter[2], M.P. Carpenter[3], T. Lauritsen [3], S. Zhu[3]

[1]*University of Massachusetts Lowell, Lowell, MA, USA*
[2]*Brookhaven National Laboratory, Upton, NY, USA*
[3]*Argonne National Laboratory, Argonne, IL, USA*

The study of the electromagnetic moments, and decay probability, provides detailed information about nuclear wave functions. The well-know properties of the EM interactions are good for extracting information about the motion of individual nucleons. However, the lowest multipoles are not always the only ones included in the decay process. It has been observed previously [1,2] in the case of a $(0^+ \rightarrow 0^+)$ transitions, where a single gamma transition is forbidden, the simultaneous emission of two gamma-rays can occur. A great opportunity to further investigate this phenomena is by using the standard ^{137}Cs source populating via beta-decay the $J^\pi = 11/2^-$ isomeric state at 662 keV in [137]Ba. In this case two photon process can have contributions from quadrupole-quadrupole or dipole-octupole multipolarities in direct competition with the high multipolarity M4 decay. Since the yield of the double gamma decay is around 10^{-6} orders of magnitude less than the first order transition very good statistics are needed in order to observe the phenomena. Gammasphere is ideal since its configuration allows a good coverage of the angular distribution and the Compton events can be suppressed. Nevertheless the process to understand and eliminate the Compton background is a challenge. Geant4 simulations were carried out to help correct for those factors. A new direct cascade via the low-lying $J^\pi = 1/2^+$ has been found.

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Measurements of Gamma-ray Energy and Multiplicity from ^{235}U(n$_{thermal}$) and ^{252}Cf with STEFF.

[1]A.J. Pollitt, [2]A.G. Smith, [3]I. Tsekhanovich, [2]E. Murray, [3]J. Matarrantz.

[1]*Institut Laue-Langevin, 6 Rue Felix Horrowitz, 38042 Grenoble, France.*
[2]*University of Manchester, Manchester, M13 9PL, United Kingdom.*
[3]*CENBG, Chemin du Solarium, 33175 Gradignan Cedex, France.*

The amount of energy carried by gamma-rays during the fission process is an important consideration when developing new reactor designs. Many studies of gamma-ray energy and multiplicity, from a multitude of fissioning systems, were measured during the 1970's. However the data from such experiments largely underestimates the heating effect caused by gamma-rays in the structure of a reactor. It is therefore essential to obtain more accurate measurements of the energy carried during gamma emission. As such, the OECD Nuclear Energy Agency has put out a high priority request [1] for measurements of the mean gamma-ray energy and multiplicity to an accuracy better than 7.5% from several fissioning systems; including ^{235}U(n$_{thermal}$) and ^{252}Cf. Measurements of the gamma-rays from these fissioning nuclei were performed with the SpecTrometer for Exotic Fission Fagments (STEFF). This is a 2 velocity, 2 energy spectrometer with an array of 12 NaI(Tl) detectors, each with 5" × 4" crystals. Current progress and results will be discussed.

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MICROSCOPIC NATURE OF THE PHOTON STRENGTH FUNCTION: STABLE AND UNSTABLE Ni AND Sn ISOTOPES

O. Achakovskiy[1], A. Avdeenkov[1], S. Goriely[2], S. Kamerdzhiev[1], S. Krewald[3], D. Voitenkov[1]

[1]*Institute for Physics and Power Engineering, 249033 Obninsk, Russia*
[2]*Institut d'Astronomie et d'Astrophysique, ULB, CP 226, B-1050, Brussels, Belgium*
[3]*Intitut für Kernphysik, Forschungszentrum Jülich, D-52425 Jülich, Germany*

The E1 photon strength functions (PSF) of many Ni and Sn even-even isotopes have been calculated microscopically within the self-consistent version of the Extended Theory of Finite Fermi Systems which includes the HFB+QRPA approach and, in addition, phonon coupling [1,2].The calculations are self-consistent in the sense that the HFB mean field, effective interaction and phonons have been calculated using the Skyrme force SLy4 with the known parameters, see details in [3]. Contrary to usual phenomenological approaches [4], these PSF have structures, with the most interesting ones being in the energy region of the pygmy-dipole resonance. These structures are caused by both the QRPA and the phonon coupling effects. The microscopically obtained PSF have been used in the EMPIRE3.1 and TALYS codes to calculate the radiative neutron capture cross sections, capture gamma-ray spectra and average radiative widths. In almost all the quantities considered, the contribution of phonon coupling turned out rather noticeable. A reasonable agreement with the available experimental data have been obtained, including the explanation of the PSF in ^{116}Sn [5] (see Fig.1) and integral characteristics of the pygmy-dipole resonance in the unstable ^{68}Ni [6]

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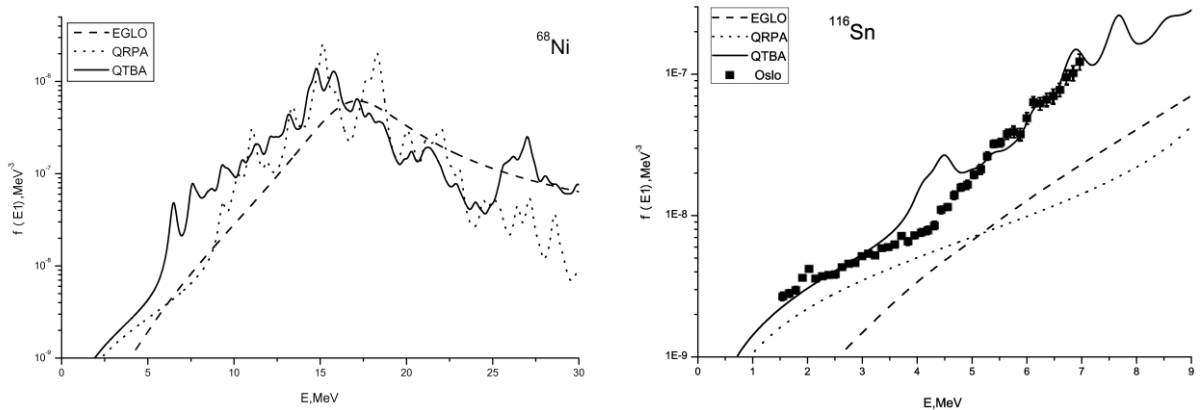
Fig. 1. Photon strength functions of ^{68}Ni and ^{116}Sn calculated within the HFB + QRPA (dots) and self-consistent version of the Extended Theory of Finite Fermi Systems (full lines) with the smoothing parameter of 200 keV. The dashed lines are the phenomenological EGLO variant from [4]. The experimental data (squares) for ^{116}Sn were taken from [5].

Lifetime Measurements and Direct Determination of Ground-State Transition Widths with the Method of Self Absorption

C. Romig[1], T. Beck[1], J. Beller[1], J. Birkhan[1], J. Glorius[2], J. Isaak[3,4], N. Pietralla[1], A. Sauerwein[2], D. Savran[3,4], M. Scheck[1,5,6], K. Sonnabend[2], V. Werner[1], and M. Zweidinger[1]

[1]*Institut für Kernphysik, TU Darmstadt, D-64289 Darmstadt, Germany*
[2]*Institut für Angewandte Physik, Goethe Universität Frankfurt am Main, D-60438 Frankfurt am Main, Germany*
[3]*ExtreMe Matter Institute EMMI and Research Division, GSI Helmholtzzentrum für Schwerionenforschung GmbH, D-64291 Darmstadt, Germany*
[4]*Frankfurt Institute for Advanced Studies FIAS, D-60438 Frankfurt am Main, Germany*
[5]*School of Engineering, University of the West of Scotland, Paisley PA1 2BE, UK*
[6]*SUPA, Scottish Universities Physics Alliance, Glasgow G12 8QQ, UK*

The method of relative self absorption (RSA) [1,2] allows for a study of nuclear absorption lines using the transmission of ©-ray beams through materials of interest. It is sensitive to absolute ground-state transition widths Γ_0, absolute level widths Γ, and, thus, lifetimes, as well as total ground-state decay branching ratios Γ_0/Γ in a model-independent way.

The intensity of a ©-ray beam passing through an absorber made of the material of interest is compared to the beam intensity without absorber at the resonance energy. Since absorption spectra cannot directly be measured, a so-called scatter target made of the same material as the absorber serves as analyzer for the depth of the absorption lines, *i.e.*, the transmitted beam intensity at resonance energy. Two nuclear resonance fluorescence (NRF) [3] measurements, *i.e.*, photon scattering experiments are performed: one with and one without absorber target. The difference of NRF intensity from the scatter target at resonance energy is a measure for its ground-state transition width. In combination with the (classical) NRF measurement without absorber target in the beam, also the total level width, thus, the lifetime of the excited state, as well as the total ground-state decay branching ratio Γ_0/Γ can be determined.

We developed a new approach to normalize both measurements to each other which allows the determination of the desired quantities with high accuracy.

Recently, we performed a first high-precision RSA measurement on the T=1 0^+ state of ^{6}Li at 3562 keV excitation energy at the Darmstadt High Intensity Photon Setup at the S-DALINAC at TU Darmstadt. This 0^+ state exhibits a strong isovector M1 transition to the 1^+ ground state. The transition is of particular interest since it can serve as sensitive benchmark for modern *ab-initio* calculations that recently showed, *e.g.*, that chiral currents contribute significantly to the transition strength [4].

Furthermore, we exploited the RSA method to firstly determine directly the total ground-state decay branching ratios of individual dipole states in the energy region of the pygmy dipole resonance (PDR) [5]. The data were obtained on ^{140}Ce.

The method of RSA, our new normalization approach, both measurements, and the procedure of data analysis will be presented. The results will be discussed.

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Session 24 – Room 028: Nuclear Reactions/Data

Present and future research at DANCE

Marian Jandel

Nuclear and Radiochemistry Group
Los Alamos National Laboratory

Measurements of correlated data on capture gamma-rays and prompt-fission gamma-rays have been carried out for various isotopes in recent years using Detector for Advanced Neutron Capture Experiments (DANCE). An improved accuracy, below 3%, for the capture cross section determination was achieved using the methods of gamma-ray calorimetry. We will describe how similar methods can be applied for other actinide targets such as ^{236}U and ^{238}U. We continue to develop new methodologies for the multidimensional data deconvolution, advanced background subtraction and Monte Carlo uncertainties propagation using features of correlated gamma-emission.

For the prompt-fission gamma-rays we have developed models that conveniently parametrize the correlated data of gamma-ray multiplicity and energy. To enhance are understanding of gamma-ray emission after fission and capture, new detection capabilities are under development at DANCE. A construction of a compact segmented array NEUANCE (NEUtron detector Array at daNCE) is under development and will provide an improved sensitivity for measurements of correlated data for the neutron-induced fission reaction. In addition, it will provide the efficient tool for measurements of delayed gamma-ray emission from short-lived nuclear states populated in neutron capture and neutron-induced fission.

New measurements of the ^{239}Pu(n,g) cross section

S. Mosby[1], T. A. Bredeweg[1], A. Chyzh[2], A. Couture[1], R. Henderson[2], M. Jandel[1], E. Kwan[2], J. M. O'Donnell[1], J. Ullmann[1], and C. Y. Wu[2]

[1]Los Alamos National Laboratory, Los Alamos, NM, USA 87545
[2]Lawrence Livermore National Laboratory, Livermore, CA. USA 94550

Nuclear energy campaigns and defence programs both require high fidelity measurements of the ^{239}Pu(n,g) cross section. The Advanced Reactor Concepts (ARC) program is considering new reactor designs which utilize a faster neutron spectrum than traditional light water reactors, and requires improved nuclear data in the keV regime for modelling these designs [1].

Measuring neutron capture on fissile isotopes is particularly challenging because the fission gamma-ray spectrum does not have unique features to discriminate fission from capture. The Detector for Advanced Neutron Capture Experiments (DANCE), in conjunction with the beams available at the Los Alamos Neutron Science Center (LANSCE), is capable of making these measurements through the use of complementary experimental configurations to disentangle the relevant backgrounds. Details of the measurement technique will be described, and the status of this experimental campaign discussed. Results have been published from 10 eV to 1 keV [2], while on-going analysis will extend the measurement into the hundreds of keV.

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Detector-response correction of two-dimensional γ-ray spectra from neutron capture

G. Rusev[1], M. Jandel[1], C. W. Arnold[1], T. A. Bredeweg[1], A. Couture[1], S. M. Mosby[1], J. L. Ullmann[1]

[1]*Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*

The neutron-capture reaction produces a large variety of γ-ray cascades with different γ-ray multiplicities. A measured spectral distribution (E_γ) of these cascades for each multiplicity (M_γ) is of importance to applications and studies of γ-ray statistical-properties. The Detector for Advanced Neutron-Capture Experiments (DANCE) is a 4π ball of 160 BaF_2 crystals is an ideal tool for measurements of neutron-capture γ-rays. The high granularity of DANCE enables measurements of high-multiplicity γ-ray cascades with a small summing of two γ-rays in one crystal. The measured two-dimensional spectra (E_γ, M_γ) have to be corrected for the DANCE detector response in order to compare them with predictions of the statistical model or use them in applications. The detector-response correction problem becomes more difficult for a 4π detection system than for a single detector. The method of Gold [1] for decomposition of γ-ray multiplets, providing always non-negative solutions, has been successfully applied [2] for a detector-response correction of one-dimensional high-resolution spectra from Gammasphere. In this talk, we will discuss application of decomposition methods [1,3] for two-dimensional γ-ray spectra measured at DANCE from γ-ray sources and from the $^{10}B(n,\gamma)$, $^{87}Sr(n,\gamma)$, and $^{113}Cd(n,\gamma)$ reactions.

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Enhancing the Detector for Advanced Neutron Capture Experiments

A. Couture[1], C. Arnold[2], B. Baramsai[2], T. A. Bredeweg[2], M. Jandel[2], S. Mosby[1], J. M. O'Donnell[1], G. Rusev[2], J. L. Ullmann[1], and C. L. Walker[2], C. Y. Wu[3]

[1]Los Alamos National Laboratory/LANSCE-NS, 87544 Los Alamos, New Mexico/USA
[2]Los Alamos National Laboratory/C-NR, 87544 Los Alamos, New Mexico/USA
[3]Lawrence Livermore National Laboratory, 94550 Livermore, California/USA

The Detector for Advanced Neutron Capture Experiments (DANCE) has been used for extensive studies of neutron capture, gamma decay, photon strength functions, and prompt and delayed fission-gamma emission [1-5, e.g.]. Despite these successes, the potential measurements have been limited by the data acquisition hardware that was based on 8-bit, 128 kSample cPCI digitizers [6]. While they were state of the art at the time of DANCE was designed and built, major advances in digitizer technology have taken place.

We are currently in the process of performing a major upgrade of the DANCE data acquisition that simultaneously enables strait-forward coupling to auxiliary detectors, including high-resolution high-purity germanium detectors and neutron tagging array. The primary upgrade will enhance the time domain accessible for time-of-flight neutron measurements as well as improve the resolution in the DANCE barium fluoride crystals for photons, particularly below 500 keV. The auxiliary detectors will enhance the studies we have performed in the past as well as open the door to new measurements that have not been possible in the past. The planned upgrade and instrumentation, as well as the physics opportunities they offer, will be discussed.

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Nuclear level density predictions

D. Bucurescu [1], T. von Egidy [2]

[1]Horia Hulubei National Institute for Physics and Nuclear Engineering, Bucharest, Romania

[2]Physik-Department, Technische Universität München, D-85748 Garching, Germany

In Refs. [1,2] we proposed simple formulas for the parameters of the back-shifted Fermi gas (BSFG) and constant temperature (CT) models of the nuclear level densities, in particular for the a parameter of the BSFG model [2]:

$$a = (0.199 + 0.0096\ S') \ A^{0.869} \ ,$$

where A = nuclear mass number and S' = (S + 0.5 Pa') with the shell correction S and the deuteron pairing energy Pa'. S and Pa' are calculated with mass values from mass tables. The free parameters are empirically determined by a fit to the known low-lying level energies and the level spacings at the neutron binding energy of 310 nuclei close to stability. Since these formulas require only quantities which can be extracted from mass tables, we propose to use them for the prediction of level density parameters for other nuclei. Here we discuss these predictions for all nuclei from the mass tables of 2003 (evaluation using the mass tables of 2012 are in progress). Because the 310 nuclei used as a basis cover regions and essentially all types of structural behaviours (spherical, deformed, and transitional) and also shell closure effects (which are strongly present in the nuclear masses), it is hoped that these simple formulas represent a realistic extrapolation to nuclei far off stability. We present the behaviour of the predicted parameters for the ~3000 nuclei from the mass tables, 2200 of them having measured masses, while for the rest the tabulated values are extrapolations of the mass surfaces.

A figure with all values $a/(0.199\ A^{0.869})$ as a function of mass A shows that most of the predicted values lie within a region of ±10% around an average value of $0.2\ A^{0.87}$ MeV^{-1} (for which the shell and pairing corrections are zero) . We identify in the chart of nuclides the main regions (Z,N) where there are deviations larger than this limit. These are related to the classical shell closures and other points of structural changes. The location of these regions with respect to the paths of different nucleosythesis processes is pointed out. Based on the predicted behaviour of the 3000 nuclei, one might expect that also in regions far from stability the above average value may be a reasonable approximation (within about ±10%) for many of these nuclei, exceptions being the nuclei at the shell closures.

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Overview of In-Beam Gamma-Ray Spectroscopy at the RIBF

Pieter Doornenbal[1]

[1]*RIKEN Nishina Center, Wako, Saitama 351-0198, Japan*

At the Radioactive Isotope Beam Factory stable primary beams are accelerated up to 345 MeV/nucleon and incident on a target to produce secondary beam cocktails with the fragment separator BigRIPS [1] ranging from the lightest nuclei up to the uranium region. For in-beam gamma-ray spectroscopy, the secondary beams impinge on a reaction target at energies between 100 and 300 MeV/nucleon. Reaction residues are detected with the ZeroDegree spectrometer and gamma-rays detected with the NaI(Tl) based DALI2 array[2].

In my presentation I will give an overview of recent experiments performed at the RIBF employing this technique including the measurements inside and beyond the "Island of Inversion" as well as investigations around the doubly-magic nuclei 100Sn, 78Ni and 132Sn (e.g. Refs. [3-5]).

Besides discussing selected results a description of the setup and an overview of in-beam gamma-ray spectroscopy physics program at the RIBF will given.

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Studies of K-Isomers in Trans-Fermium Nuclei near the N=152 Sub-Shell Closure[*]

F.G. Kondev[1]

[1]*Argonne National Laboratory, Argonne IL 60439, U.S.A.*

Deformed nuclei in the trans-fermium region are known to exhibit high-K isomerism, because of the presence of high-Ω Nilsson orbitals near both the proton and neutron Fermi surfaces. The properties of such isomers provide important information on the single-particle structures and on the role played by the pairing, and residual nucleon-nucleon interactions in the region. The existence of high-K states at relatively low excitation energies could also lead to a possible enhancement of the stability of the super-heavy elements [1]. However, the knowledge is very limited owing to the paucity of experimental data.

A number of experiments on Fm, No and Rf nuclei near the N=152 sub-shell closure, aimed at the discovery of isomeric states and the elucidation of their properties, were carried out at Argonne National Laboratory using the Fragment Mass Analyzer and the implant-decay correlation technique [2]. Recently, studies were initiated on the ^{254}Rf isotope (N=150) using the ^{50}Ti+^{206}Pb reaction that has a cross section of only 2 nb. A follow-up experiment was also carried out at Lawrence Berkeley National Laboratory using the same reaction and the Berkeley Gas-filled Mass Separator. A digital data acquisition system was deployed in both experiments, which allowed the identification of implant and decay events that were separated in time as short as hundreds of nanoseconds. Numerous events, comprising of an implanted ^{254}Rf recoil followed by a burst of electrons, including electron-electron coincidences, and subsequent fission of the ^{254}Rf ground state, were observed. The electrons were produced in the decay of two isomeric states in ^{254}Rf with lifetimes of ~4 μs and ~300 μs, the latter being an order of magnitude longer-lived than the ground state ($T_{1/2}$=23 (3) μs [3]). In addition, isomers in ^{244}Cm and ^{246}Cm were also studied following beta decays of ^{244}Am (Kπ=6-) and ^{246}Am (Kπ=7-) mass-separated sources, respectively. The emphasis was on elucidating details of the level schemes, which allowed reliable values for the strength of the K-forbidden transitions do be determined and compared with systematics known in different regions of the nuclear chart.

The data from those experiments will be presented and the results will be compared with predictions of multi-quasiparticle blocking calculations that include empirical estimates for the residual configuration-dependent, nucleon-nucleon interactions.

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p-process nucleosynthesis via proton-capture reactions in thermonuclear supernovae explosions

Anne Endres[1], C. Arda[1], P. Erbacher[1], J. Glorius[1], K. Göbel[1], O. Hinrichs[1], E. Mevius[1], M. Reich[1], K. Sonnabend[1], B. Thomas[1], and T. Thomas[1]

[1]*Institut für Angewandte Physik, Goethe Universität Frankfurt, D-60438 Frankfurt a.M., Germany*

Per definition, *p* nuclei are those isotopes which cannot be produced via neutron-capture reactions in the *s* and *r* processes. There are about 35 of these proton-rich nuclei. Within the current understanding, various processes in different astrophysical scenarios contribute to the production of these isotopes ranging from ^{74}Se to ^{196}Hg.

This contribution focusses on the production of the most abundant *p* nucleus ^{92}Mo via proton-capture reactions in thermonuclear supernovae explosions. Two recent publications [1,2] found a significant contribution to the overall abundance by a reaction chain via proton-capture reactions on ^{90}Zr and ^{91}Nb . This triggered already an experiment on the ^{90}Zr(p,γ) reaction using the in-beam summing-crystal method [3].

Within the so-called PARIS project, this reaction was measured again using the in-beam technique with high purity germanium detectors in order to obtain the total cross section and partial cross sections as well. First results of our experimental investigation of this reaction using high-resolution γ-ray spectroscopy will be shown.

In addition, ongoing developments for the determination of the cross section of the ^{91}Nb(p,γ) reaction, a proton-capture reaction with radioactive target, in direct kinematics will be explained.

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Triaxiality of heavy nuclei as an essential feature to predict radiative capture

E. Grosse[1], A.R. Junghans[2], and R. Massarczyk[1,2]

[1]*Institute of Nuclear and Particle Physics, Technische Universität Dresden, 01062 Dresden, Germany*

[2]*Institute of Radiation Physics, Helmholtz-Zentrum Dresden-Rossendorf, 01314 Dresden, Germany*

Cross sections for neutron capture in the range of unresolved resonances and average level distances near the neutron emission threshold are simultaneously predicted for more than 100 spin-0 target nuclei with A >70. Assuming triaxiality in nearly all these nuclei a combined description of both, photon strength and level density, is presented – needing very few fit parameters only. The electric dipole strength functions used are derived from a global fit to IVGDR shapes by the sum of three Lorentzians, adding up to the TRK sum rule and based on theoretical predictions for the A-dependence of pole energies and spreading widths [1]. Information as available from photon scattering and other experiments helps to quantify strength not related to the IVGDR, which significantly adds to capture yields.

For the case of even-even target nuclei standard Fermi gas formulae [2], modified to incorporate triaxiality [3], describe average neutron capture resonance distances well. Only one free global fit parameter, a surprisingly small surface term quantifying the difference of the level density parameter from the value predicted for nuclear matter, is needed. The energy dependence of the state density is assumed to be exponential [2] in the pairing dominated phase below the transition point. Agreement to capture data on absolute scale – including Maxwellian average cross sections around 30 keV – indicates a significant collective enhancement due to the deviation from axial symmetry, even if the triaxiality is small. The agreement is improved when a shell correction as derived from nuclear mass formulae [4, 5] is applied to the excitation energy; the effect of alternate procedures [6] has been investigated as well. Reliable predictions for compound nuclear reactions also outside the valley of stability − as important for nuclear astrophysics and for the transmutation of nuclear waste − are expected to result from the derived global parameterization.

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Fission study by prompt gamma-ray spectrometry

T. Materna[1], A. Letourneau[1], Ch. Amouroux[1], A. Marchix[1], O. Litaize[2], O. Sérot[2], D. Regnier[2], A. Blanc[3], M. Jentschel[3], U. Koester[3], P. Mutti[3], T Soldner[3], G. Simpson[4], G. de France[5] and W. Urban[6]

[1]*IRFU, CEA Saclay, 91191 Gif-sur-Yvette, France*
[2]*CEA, DEN, Cadarache, 13108 Saint-Paul-lez-Durance, France*
[3] *ILL, 6 rue Jules Horowitz, 38042 Grenoble CEDEX 9, France*
[4] *LPSC, 53 rue des Martyrs, 38026 Grenoble CEDEX, France*
[5] *GANIL, BP 55027, 14076 Caen CEDEX 5, France*
[6] *Institute of Experimental Physics, University of Warsaw, Hoza 69,00-681 Warsaw, Poland*

Nuclear fission is a complex process, still not yet well described by microscopic models, and its main observables are difficult to measure with precision. Following the capture of a thermal neutron the compound nucleus fissions in two fragments, which will fly apart with speeds around one ns/cm. Most of the energy of the process is transferred in kinetic energy (KE), whereas the nuclei are let in few tens of MeV excited states. The majority of this intrinsic excitation energy is then lost within some picoseconds by the evaporation of a few neutrons and the emission of gamma-rays in cascade. To overcome the low accuracy of microscopic models in the prediction of the fission observables, nuclear technology, from reactor operation to nuclear waste, relies on libraries of evaluated data and semi-empirical models, e.g. the GEF model [1]. Such a strategy requires systematic and accurate experimental data on the few possible observables, amongst them, the yields and the KE of the fragments. A unique instrument for that purpose is the fission fragment mass separator Lohengrin installed at the Institut Laue Langevin (France). It made possible to measure yields and KE of the light fragments for most actinides in the thermal regime with a mass resolution better than 0.3 mass unities and, in the recent past, this activity was extended to study the mass and isotopic yields of the heavy fragments produced in the ^{235}U(n$_{th}$,f), ^{239}Pu(n$_{th}$,f), ^{241}Pu(n$_{th}$,f), ^{233}U(n$_{th}$,f) or ^{242}Am(n$_{th}$,f) processes [2]. On the other hand, Lohengrin is limited to the detection of only one of the fission fragments and, its 23 m flight path makes the detection of the prompt gamma-ray cascade impossible except in the presence of microsecond isomeric states.

Here we would like to present a feasibility study of fragment-pair yield determination using a gamma-ray detector array directly placed around the actinide target in a thermal or cold neutron beam. Such a setup was already installed at the ILL in 2012 (EXILL) and campaigns were performed with ^{235}U and ^{241}Pu targets [3]. The feasibility study is largely motivated by the possible installation of a permanent germanium detector array at the ILL, which may be coupled to fission fragment detectors in a first construction phase and a fragment separator in a second phase (FIPPS) [4]. Another important outcome of a germanium array directly placed around the fission target is the study of the gamma-ray cascade occurring in both fission fragments with an unambiguous determination of two fragments. The cascades are known to be linked to the angular momentum of the fragments after scission, which is one of the less precise and understood properties. With the development of new simulation codes for the neutron evaporation and the gamma-ray cascade like Fifrelin [5], systematic studies and comparisons with the large experimental data resulting from double and triple gamma-ray coincidence analysis may become possible.

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Session 26 – Room 028: Techniques/Reactions

Resonant atomic collisions as a probe for nuclear properties

Carsten Brandau[1,2]

[1]Inst. f. Atomic and Molecular Physics (IAMP), Justus-Liebig-University,
Leihgesterner Weg 217, 35392 Giessen, Germany
[2]ExtreMe Matter Institute(EMMI) and Research Division GSI Helmholtzzentrum für
Schwerionenforschung, Planckstr.1, 64291 Darmstadt,Germany

The utilization of resonant atomic electron-ion collisions for precision spectroscopic applications of highly charged heavy ions. In particular the exploitation of the resonant channel of photorecombination, the dielectronic recombination (DR), has become a versatile alternative to the long-established conventional approaches [1] in atomic physics. The initial step of DR is time-inverse to autoionization, hence, DR collision spectroscopy can be understood as "inverse" Auger spectroscopy. Applying this electron-ion collisions spectroscopy approach a broad range of topics in astrophysics, plasma physics, fundamental interactions, in atomic and nuclear physics are addressed [1,2].

In this presentation I will discuss recent developments in the exploitation of DR as a sensitive spectroscopic probe for the investigation of nuclear properties such as charge radii, magnetic moments and nuclear spins [1,3,4]. Compared to laser spectroscopy, the main advantage of the present approach is that the studies are performed with few-electron ions, that is, with Li-like electron configuration. Here, the interpretation of the data is not masked by many-body effects and can be performed on a full QED level [3-5]. Recent advances in the field are exemplified by a series of experimental studies conducted at the heavy ion storage rings ESR in Darmstadt and TSR in Heidelberg. The experiments were carried out with stable ions, but also with in-flight produced radioisotopes or even on long-lived nuclear excited states (isomers).

Typically, the experiments are carried out under merged-beams collision geometry at the electron cooler or a cooler-like electron target of a heavy-ion storage ring. The measurements decisively benefit from the well-defined experimental conditions and phase-space cooling of the stored beam. A primary asset of the technique is the combination of large atomic cross sections, of the repeated interaction (1-2 MHz) of the circulating ions with the target electrons and a ~100% collection efficiency of the recombined-ion reaction products. These features render DR collision spectroscopy ideally placed for experiments with dilute primary beam intensities such as artificially synthesized radioisotopes [6].

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High-Resolution Laser Spectroscopy for Nuclear-Structure Studies

D. T. Yordanov

Institut de Physique Nucléaire d'Orsay, 91405 Orsay, France

At the beginning of the 21st century experimental nuclear physics would appear to have mutely entered a new era of a fundamental push into the far-off regions of the nuclear landscape. The signs are everywhere - while new facilities are coming online the experimental techniques are reaching unprecedented sensitivity and precision. Laser spectroscopy certainly makes no exception in this respect. In recent years we are witnessing a number of innovations, such as: multiple orders of magnitude background suppression by the introduction of cooled and bunched beams, wavelengths ever closer to the elusive boundary of 200 nm, and an application of atomic clocks for ultimate frequency calibration. Advances in laser ionization methods make an important impact as well.

This talk will comprise a number of nuclear-structure topics ranging from hallo nuclei, an "island of inversion", a monopole inversion of states, and finally "one simple structure in complex nuclei". Special attention will be devoted to the technical innovations, but whenever available theoretical interpretation of the results will be discussed as well.

Scissors mode in ^{162,164}Dy from (n,γ) reactions

S.Valenta[1] for EXILL and DANCE collaborations

[1]*Charles University in Prague, CZ-180 00 Prague 8, Czech Republic*

In 1978 Lo Iudice and Palumbo [1] predicted an isovector magnetic-dipole vibrational mode of deformed nuclei which is conventionally referred to as a scissors mode (SM). Decisive evidence for the SM was provided by nuclear resonance fluorescence experiments [2] in which, as a signature of the SM, a resonance-like enhancement of the M1 ground-state transitions in even-even nuclei at γ-ray energies near 3 MeV was observed.

Concerning a non-trivial question about possible SM enhancement of M1 transitions to excited levels, the study of two-step γ cascades (TSCs) following the thermal neutron capture in ^{162}Dy [3,4] strongly indicated that the SM vibration is a generic phenomenon responsible for a major part of the M1 strength at γ-ray energies near 3 MeV, regardless the energies of the final levels involved. This finding has been corroborated many times, e.g. by the data on multi-step γ cascades (MSCs) accompanying the neutron capture at isolated resonances [5]. These data were obtained from measurements on the 4π BaF$_2$ detector system DANCE installed at the LANSCE spallation neutron source in Los Alamos [6,7].

Recently, employing the same setup, we measured the spectra of MSCs, emitted from neutron capture at isolated resonances of ^{161,163}Dy. Furthermore, spectra of γ-rays following the capture of thermal neutrons in target nucleus ^{161}Dy were measured in Grenoble using the EXOGAM HPGe detector array installed on a cold-neutron beam of the ILL High-Flux Reactor. Synthesis of methodologies for data treatment from previous TSC [8] and MSC [5] experiments allowed us to extract high-resolution spectra of MSCs connecting the thermal capturing state with several low-lying levels in ^{162}Dy. These spectra and the DANCE spectra of MSCs, depopulating strong resonances of the systems ^{161,163}Dy+n, are compared with predictions of the extreme statistical model under various assumptions on photon strength functions.

The main goal of this analysis is to assess whether the SM enhancement plays the equally important role even in not yet well explored M1 primary transitions to levels at energies above 5 MeV. Thanks to relatively high neutron separation energy of ^{162}Dy and the favorable J^{π} values of low-lying levels, this product nucleus is suitable for observation of M1-M1-M1 cascades formed by transitions enhanced simultaneously by SM vibration. Such cascades are very sensitive to the SM parametrization and their possible observation may verify whether the enhancement is stable, even in conditions when the SM vibration couples to levels with high excitation energies. The status of analysis and preliminary results are presented.

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The statistical properties of Sn-isotopes studied with the Oslo-method

G. M. Tveten[1][**], F. L Bello Garrote[1], L. C. Campo[1], T. K. Eriksen[1], F. Giacoppo[1], M. Guttormsen[1], A. Görgen[1], T. W. Hagen[1], K. Hadynska-Klek[1], M. Klintefjord[1], A. C. Larsen[1], S. Maharromova[1], H. T. Nyhus[1], T. Renstrøm[1], S. J. Rose[1], E.Sahin[1], S. Siem[1], T. Tornyi[1,2]

[1]*Department of Physics, University of Oslo, Oslo, Norway*
[2] *Institute of Nuclear Research, MTA ATOMKI, Debrecen, Hungary*

The γ-ray strength function and level density of the moderately proton-rich [111, 112, 113]Sn has been studied at the Oslo Cyclotron Laboratory up to the neutron binding energy by applying the Oslo method [1] to particle-γ coincidence data. The results for the γ-ray strength function, and in particular, the pygmy resonances in the studied isotopes will be discussed and compared to previous results for the more neutron-rich Sn-isotopes studied at OCL[2,3]. The results will also be compared to recent theoretical calculations for the pygmy resonances, and results from other types of experiments [4]. Pairing in the quasi-continuum in the studied Sn-isotopes, as deduced, from the experimental level densities will also be presented.

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Photon Strength Functions and Nuclear Level Densities in Gd Nuclei from Neutron Capture Experiments

J. Kroll[1,2], U. Agvaanluvsan[3], B. Baramsai[4], J. A. Becker[5], F. Bečvář[2], T. A. Bredeweg[4],
A. Chyzh[5], A. Couture[4], D. Dashdorj[5], R. C. Haight[4], M. Jandel[4], A. L. Keksis[4], M. Krtička[2],
G. E. Mitchell[1], J. M. O'Donnell[4], W. Parker[5], R. S. Rundberg[4], I. Tomandl[6], J. L. Ullmann[4],
S. Valenta[2], D. J. Vieira[4], C. L. Walker[4], J. B. Wilhelmy[4], J. M. Wouters[4], C. Y. Wu[5]

[1]North Carolina State University, Raleigh, NC 27695 and Triangle Universities Nuclear Laboratory, Durham, NC 27708, USA
[2]Charles University in Prague, CZ-180 00 Prague 8, Czech Republic
[3]MonAme Scientific Research Center, P.O.Box 24-603, Ulaanbaatar, Mongolia
[4]Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[5]Lawrence Livermore National Laboratory, Livermore, CA 94551, USA
[6]Nuclear Physics Institute of Czech Academy of Science, CZ-250 68 Řež, Czech Republic

Spectra of γ rays following neutron capture at isolated resonances of $^{152,154-158}$Gd were measured with highly segmented BaF_2 detector DANCE [1] installed at LANSCE spallation neutron source in Los Alamos National Laboratory. In addition, the two-step γ-cascades experiments were performed on ^{155,157}Gd targets using the coincidence two-HPGe-detector facility installed at a pure sub-thermal neutron beam of the LVR-15 reactor in Řež near Prague [2]. The main objective of these measurements was to get new information on nuclear level densities and photon strength functions with emphasis put on the role of M1 scissors mode vibration. An analysis of the γ-ray spectra accumulated in both types of experiments, made within the extreme statistical model [3], leads to the consistent conclusion that the scissors mode significantly affects the ground state transitions, as well as the transitions between all accessible excited states of studied nuclei [4-6]. The same models of nuclear level density and photon strength functions -- including the energy, damping width, and total strength of the scissors mode -- were found to describe γ-ray spectra from both experiments in even-even Gd nuclei. Resonance experimental data also show that the electric dipole transitions in odd Gd isotopes cannot be described with the identical model of photon strength function [6]. The obtained results will be discussed and compared with what has been deduced from NRF data for the ground state scissors mode [7,8] and from the data on ^{3}He-induced reactions on neighboring nuclei using the so-called Oslo method [9-11].

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E-mail address: jkroll@ncsu.edu

<u>Session 27 – Room 120: Nuclear Structure/Applications</u>

Laser spectroscopy of neutron deficient Francium isotopes at TRIUMF

<u>Matthew R. Pearson[1]</u>,
for the Laser spectroscopy collaboration at TRIUMF

[1]TRIUMF, 4004 Wesbrook Mall, Vancouver, CANADA

Francium is the heaviest known alkali element. Being one of the few elements with no stable or naturally occurring isotopes it is also the least well understood of the alkali group. Its relatively simple atomic structure, large nuclear volume and high nuclear charge make it an ideal laboratory for the investigation of parity non-conservation effects in atoms as well as the time evolution of fundamental constants. In order for any of these effects to be extracted with any degree of certainty it is important to have a thorough understanding of the atomic and nuclear structures involved both theoretically as well as experimentally over as wide a range of isotopes and if possible nuclear isomeric states as possible. To this end a series of measurements has been undertaken at the ISAC facility at TRIUMF using high resolution laser spectroscopy to unambiguously determine some of the most fundamental nuclear properties of the neutron deficient Francium isotopes. These include the nuclear spins, nuclear moments as well as the evolution of the mean squared charge radii. The coupling of laser spectroscopy with a resolution high enough to fully resolve the atomic hyperfine structure, along with techniques more commonly utilised in atomic physics experiments has enabled, for the first time, the nuclear ground state properties of francium isotopes below A=207 to be determined. These measurements will be discussed along with future plans and objectives.

New results from laser spectroscopy

Kieran T Flanagan[1]

[1]School of Physics and Astronomy, University of Manchester, Manchester M13 9PL, UK

More than 40 years have passed since the first laser spectroscopy techniques were developed for measuring the properties of radioactive isotopes [1]. From the very beginning the field has endeavoured to combine high resolution with high sensitivity in order study rare isotopes at on-line facilities. A variety of laser based techniques have been developed that are routinely used at facilities around the world. They can be broadly categorized into three groups: in-source, trapping and collinear methods. In-source methods use resonance ionization spectroscopy (RIS) and offer the highest sensitivity and have measured rare isotopes produced at rates down to 0.01 atoms/s, but are currently limited in resolution due to Doppler and collisional broadening. Collinear techniques compress the Doppler broadened profile through acceleration but have a relatively low sensitivity and are in general limited to yields greater than 1000 atoms/s. There has been a long standing proposal to perform RIS in a collinear geometry to combine both high resolution and high sensitivity into one technique [2]. This method has recently been successfully demonstrated at ISOLDE by studying the neutron deficient francium isotopes [3]. The technique also offers the ability to select a long-lived excited nuclear state, which can be subsequently studied by decay spectroscopy or mass spectrometry[4].

This talk will report on the successful commissioning of the CRIS experiment and the recent laser spectroscopy results and laser assisted decay spectroscopy on the neutron deficient francium isotopes.

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Measurements of correlations in beta-decay using laser and ion traps

M. Anholm[1,2], D. Ashery[3], R.S. Behling[4,5], R. Burch[4], J.A. Behr[1], B. Fenker[4,6], A. Gorelov[1], G. Gwinner[7], L. Kurchaninov[1], M. Mehlman[4,6], D. Melconian[4,6], K. Olchanski[1], P.D. Shidling[4], C. Warner[1,8]

[1]TRIUMF, V6T 2A3 Vancouver, BC Canada
[2]Department of Physics & Astronomy, University of British Columbia, V6T 1Z1 Vancouver, BC Canada
[3]School of Physics & Astronomy, Tel Aviv University, 69978 Tel Aviv, Israel
[4]Cyclotron Institute, Texas A&M University, 77843 College Station, TX USA
[5]Department of Chemistry, Texas A&M University, 77843 College Station, TX USA
[6]Department of Physics & Astronomy, Texas A&M University, 77843 College Station, TX USA
[7]Department of Physics & Astronomy, University of Manitoba, R3T 2N2 Winnipeg, MB Canada
[8]Department of Physics & Astronomy, University of Waterloo, N2L 3G1 Waterloo, ON Canada

Precision measurements in the low-energy frontier of nuclear physics provide an elegant way to complement searches at colliders for physics beyond the standard model of particle physics. The polarized and unpolarized angular distributions of nuclear β decay are sensitive to possible scalar and tensor interactions which may participate weakly in the decay. Precision measurements of the correlation parameters, on the order of 0.1% of their value, would be sensitive to (or meaningfully constrain) new physics.

By combining neutral atom trapping techniques with optical pumping methods, the TRINAT collaboration at TRIUMF has the ability to highly-polarize (>99%) a very cold (<1 mK), localized (<1 mm^3) source of short-lived (~1 s) ^{37}K atoms. This is an ideal source of radioactive atoms which allows unprecedented precision in measuring the polarized observables of β decay.

Although known predominantly for their incredible mass-measurement abilities, ion traps are another technology that can provide a clean, localized source of short-lived nuclei for precision β-decay experiments. TAMUTRAP is a new Penning trap facility being constructed at the Cyclotron Institute at Texas A&M University. At the heart of this facility is a large-bore 7-Tesla magnet which will house a cylindrical Penning trap with an inner diameter of 180 mm. The unprecedented open-area of TAMUTRAP is ideal for 4π collection of the delayed protons following the superallowed β decays of T = 2 nuclei.

In this talk I will give an overview of the TRINAT and TAMUTRAP facilities and their experimental programs. Preliminary results from a recent run at TRIUMF measuring the β asymmetry parameter, A_β, will be presented.

Development of medicine-intended isotopes production technology at Yerevan Physics Institute

A. Avetisyan[1], R. Avagyan[1], I. Kerobyan[1], R. Dallakyan[1], G. Harutyunyan[1]

[1]*Alikhanyan National Science Laboratory (Yerevan Physics Institute),*

Alikhanyan Brothers Street 2,

0036 Yerevan,Armenia

Accelerator-based ^{99m}Tc and ^{123}I isotopes production technologies were created and developed at Alikhanyan National Science Laboratory (formerly Yerevan Physics Institute (YerPhI)). The method involves the irradiation of natural molybdenum (for ^{99m}Tc production) and natural xenon (for ^{123}I production) using high-intensity bremsstrahlung photons from the electron beam of the LUE50 linear electron accelerator located at the YerPhi. We have developed and tested the ^{99m}Tc extraction from the irradiation of natural MoO_3 and ^{123}I extraction from the irradiation of natural xenon. The production method has been developed and shown to be successful [1].

The current activity is devoted to creation and development of the direct production technology of ^{99m}Tc using the proton beam from an IBA C18 cyclotron using ^{100}Mo and/or $[^{100}Mo]O_3$ as target materials.

The C18 proton cyclotron (producer – IBA, Belgium) was purchased and will be installed nearby AANL (YerPhI) during summer of 2014 and commissioned in the fall 2014. The 18 MeV protons will be used to investigate accelerator-based schemes for the direct production of ^{99m}Tc. In the coming years our main topics of studies will include experimental measurement of ^{99m}Tc production yield for different energies of protons, irradiation times, intensities, development of new methods of ^{99m}Tc extraction from irradiated materials, development of target preparations technology, development of target material recovery methods for multiple use and others. Implementation of the method which we will develop for ^{99m}Tc direct production could provide enough activity covering the entire demand for ^{99m}Tc in Armenian clinics.

That studies are inline with the goals of Coordinated Research Project (CRP) "Accelerator-based Alternatives to Non-HEU production of ^{99}Mo/^{99m}Tc" sponsored by the IAEA.
Earlier results were published in Refs. [1,2].

1. R.Avagyan, A.Avetisyan et al. "Photo-production of ^{99}Mo/^{99m}Tc with electron linear accelerator beam" submitted to Nuclear Medicine and Biology.
2. Overview of work performed within the IAEA CRP Accelerator-based Alternatives to Non-HEU production of Mo-99/Tc-99m. 2nd Research Co-ordination Meeting , October 7-11, 2013, Legnaro, Italy

Session 28 – Room 028: Nuclear Astrophysics

Search for Supernova-produced ^{60}Fe in the Earth's Fossil Record

S. Bishop[1], P. Ludwig[1], R. Egli[2], V. Chernenko[1], T. Faestermann[1], N. Famulok[1], L. Fimiani[1], T. Frederichs[3], J. Gomez[1], K. Hain[1], M. Hanzlik[4], G. Korschinek[1], S. Merchel[5], G. Rugel[5]

[1]_Technische Universität München, Physik Department_
[2]_ZAMG, Wien_
[3]_Universität Bremen, Geowissenschaften_
[4]_Technische Universität München, Fakultät für Chemie_
[5]_HZDR, Dresden_

Approximately 1.8 to 2.8 Myr before the present our planet was subjected to the debris of a supernova explosion. The terrestrial proxy for this event was the discovery of live atoms of ^{60}Fe in a deep-sea ferromanganese crust [1]. The signature of this supernova event should also reside in magnetite (Fe_3O_4) magnetofossils produced by magnetotactic bacteria, which live in the ocean sediments, extant at the time of the Earth-supernova interaction. We have conducted accelerator mass spectrometry (AMS) measurements, searching for live ^{60}Fe in the magnetofossil component of a Pacific Ocean sediment core (ODP Core 848); additional AMS measurements are now ongoing with a second sediment core (ODP Core 851) in which we expect to find a higher ^{60}Fe signal. This talk will present the current preliminary status of our ^{60}Fe search results for both sediment cores.

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Critical Nuclear Physics in Nucleosynthesis

Carla Frohlich[1]

[1]*University of North Carolina, 27695 Raleigh NC, USA*

The origin of the elements heavier than iron, and in particular the "lighter heavy elements" (or LEPP elements) is an important open question in nuclear astrophysics. Recent observations of elements in old metal-poor stars hint at an additional nucleosynthesis processes, operating at the lowest metallicities and being responsible for the lighter heavy elements between iron group nuclei and the r-process peak at mass number A~130. This nucleosynthesis process is in addition to the traditional rapid (r-) and slow (s-) neutron-capture processes. A candidate for the additional nucleosynthesis process is the νp-process which is thought to occur in the innermost proton-rich ejecta of core-collapse supernovae. The importance of the νp-process lies in the fact that it contributes to the heavy elements above the iron group and that the path lies on the proton-rich side of the valley of beta-stability. In this region, nuclear masses are partly unknown and all nuclear reaction rates are based on theoretical predictions. To address the role of the νp-process in the origin of the heavy elements, the critical nuclear physics inputs have to be determined and the impact of their uncertainties on the final abundances has to be investigated.

Here, we will report on a systematic study to identify the critical nuclear physics for νp-process nucleosynthesis. We will discuss the importance of nuclear masses and nuclear reaction rates and we will summarize the resulting uncertainties in the final abundance predictions from the νp-process.

Hydrogen and Helium Burning in Type I X-Ray Bursts:
Experimental Results and Future Prospects

C. M. Deibel[1]

[1]Department of Physics and Astronomy, Louisiana State University, Baton Rouge, LA 70803 USA

Type I X-ray bursts (XRBs) occur in binary systems consisting of a neutron star accreting matter from a companion, typically a main sequence star, onto its surface. As the temperature increases the triple-α reaction ignites the burst and proton-rich nuclei up to A ~ 100 are synthesized via the αp and rapid proton capture (rp) processes. The helium and hydrogen burning that occurs through these two processes, respectively, determines the final elemental abundances and the energy output produced from the burst, as well as the shape of the XRB luminosity profile. As the vast majority of the nucleosynthesis proceeds through reactions involving only unstable nuclei, many of these reactions have been difficult, if not impossible, to measure experimentally due to the lack of intense radioactive ion beams (RIBs). However, due to the recent advances in RIB production at a variety of facilities some of the nuclei involved in these reactions can now be accessed for the first time. In addition, developments in detector technology aimed at taking full advantage of these RIBs have allowed some of the most important reactions in XRB nucleosynthesis to be studied both indirectly and directly. These recent advances in beam and detector technology and the resulting experimental studies of reactions important for hydrogen and helium burning in XRBs will be discussed, as well as plans for future measurements.

Measurements of the ^{12}C+^{12}C fusion reaction for astrophysics: current challenges and future outlook

B. Bucher[1,2], X. Fang[1], X.D. Tang[1,3], W.P. Tan[1], S. Almaraz-Calderon[1], A. Alongi[1], A.D. Ayangeakaa[1], M. Beard[1], A. Best[1], J. Browne[1], C. Cahillane[1], M. Couder[1], E. Dahlstrom[1], P. Davies[1], R. deBoer[1], A. Kontos[1], L. Lamm[1], A. Long[1], W. Lu[1], S. Lyons[1], C. Ma[1], A. Moncion[1], M. Notani[1], D. Patel[1], N. Paul[1], A. Roberts[1], D. Robertson[1], K. Smith[1], E. Stech[1], R. Talwar[1], S. Thomas[1], M. Wiescher[1]

[1]*Nuclear Science Lab, University of Notre Dame, Notre Dame, Indiana USA 46556*
[2]*Lawrence Livermore National Lab, Livermore, California USA 94551*
[3]*Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou, China*

The ^{12}C+^{12}C fusion reaction is considered one of the most important nuclear reactions in astrophysics. It strongly influences late stellar evolution and nucleosynthesis in massive stars, and is believed to initiate the explosions of type Ia supernovae as well as x-ray superbursts. Unfortunately, this reaction is extremely difficult to study in the laboratory at the energies relevant for astrophysical scenarios. This is primarily due to a low cross section which falls off exponentially with decreasing energy, but is additionally hampered by large beam-induced backgrounds created from target contaminants which are difficult to control. Since stellar models must rely on an extrapolation of the measured cross section at high energies, the astrophysical reaction rates remain uncertain. This matter is further complicated by the presence of large resonances in the excitation function which likely exist down to astrophysical energies, yet there is currently no information which can help predict where these resonances occur or how strong they are. As a result, the extrapolated cross section is quite uncertain. Recent measurements at the University of Notre Dame have been geared towards improved experimental techniques for studying the ^{12}C+^{12}C reaction as well as improving the low-energy extrapolation. This talk will focus on some of these new techniques which include direct measurements of the ^{12}C(^{12}C,p) and ^{12}C(^{12}C,α) channels as well as the successful measurement of ^{12}C(^{12}C,n) at astrophysical energies which has implications for s-process nucleosynthesis. Improvements to the low-energy extrapolations will also be highlighted. These include the establishment of an upper limit for the total fusion cross section based on correlations with the carbon isotope fusion reactions along with an accurate low-energy prediction of ^{12}C(^{12}C,n) based on direct measurements of the mirror ^{12}C(^{12}C,p_i) channels.

Session 29 – Room 120: Nuclear Structure

Spectroscopy of the cadmium isotopes

John L. Wood

School of Physics, Georgia Institute of Technology, Atlanta, Ga 30332, USA

The structure of the cadmium isotopes is among the most widely studied of any isotopic chain on the nuclear mass surface. This now extends across the entire 50-82 neutron shell with the recent identification of seniority-dominated structure in ^{130}Cd [1]. At mid-shell the low-energy structure is collective, but the interpretation of this collectivity has recently undergone a major change from vibrational to quasi-rotational [2]. This change has come from comprehensive information on excited states and transitions in ^{110,112,114,116}Cd using (n,n'γ) carried out at the Univ. of Kentucky Accelerator Laboratory [3,4,5,6]; and detailed spectroscopic information from radioactive decay, inelastic scattering of charged particles, and transfer reactions [7]. Further, it has recently become possible to carry out microscopic calculations in a shell model basis for low-energy states in the low-mass Cd isotopes up to and including where collectivity emerges [8]. A major remaining challenge is the understanding of excited 0^+ states in these nuclei. While one of the low-lying 0^+ states is an intruder state with large deformation [9], a second low-lying 0^+ state remains to be interpreted [10]. The evidence for established structures will be reviewed and plans and directions for future work will be outlined. Particular emphasis will be placed on the difficulties of elucidating details of complex nuclear collectivity and the interplay of data with models.

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Test of IMME in fp shell via direct mass measurements of $T_Z = -3/2$ nuclides

Y. H. Zhang[1], H. S. Xu[1], Yu. A. Litvinov[1,2,3], and CSR mass measurement collaboration

[1] *Laboratory of High Precision Nuclear Spectroscopy, Center for Nuclear Matter Science, Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, People's Republic of China*
[2] *Helmholtzzentrum für Schwerionenforschung, Planckstraße 1, 64291 Darmstadt, Germany*
[3] *Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany*

The isobaric multiplet mass equation (IMME) is the most basic prediction to follow from the concept of isospin in nuclear and particle physics. The test of IMME is clearly of fundamental importance for which precise atomic masses of at least four $T \geq 3/2$ members are needed. In a recently commisioned cooler storage ring CSRe in Lanzhou, atomic masses of eight $T_Z = -3/2$ isotopes ^{41}Ti, ^{43}V, ^{45}Cr, ^{47}Mn, ^{49}Fe, ^{51}Co, ^{53}Ni, and ^{55}Cu have been measured [1,2] directly using the isochronous mass spectroscopy, providing mass data for testing the validity of IMME in the fp shell. In this talk, experimental details and data analysis method are described and atomic masses of the above-mentioned $T_Z = -3/2$ isotopes are reported. We have fitted the mass data of four isobars of A=41,45,49, and 53, respectively, using a cubic expression by the inclusion of a $d \cdot T_Z^3$ term. The d coefficients are consistent with zero within error bars for the A=41,45, and 49 isobars. However the d coefficient for the A=53 isobar is more than 3σ deviated from zero, giving a signature of breakdown of the isobaric multiplet mass equation at A=53, T=3/2. This result calls for more precise determinations (in the order of keV) of ground-state mass of ^{53}Ni and excitation energy of the isobaric analog state in ^{53}Co.

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Resonances in ^{11}Li through inelastic scattering reactions

R. Kanungo[1], J. Tanaka[2], A.Sanetuallev[1,3], I. Tanihata[2], S. Ishimoto[4], A.A.Chen[5], G. Christian[3], B. Davids[3], J.Fallis[3], J. P. Fortin[6], N. Galinski[3], A. T. Gallant[3], P.E. Garrett[7], G. Hackman[3], B. Hadinia[7], M. Keefe[1], R. Kruecken[3], J. Lighthall[3], D. Miller[3], J. Purcell[1], J. S. Randhawa[1], T.Roger[8], A. Rojas[3], H. Savajols[8], A. Shotter[9], C.Unsworth[3,], Z. Wang[3]

[1] *Saint Mary's University, Halifax, Canada*
[2] *RCNP, Osaka University, Osaka, Japan*
[3] *TRIUMF, Vancouver, British Columbia,Canada*
[4] *KEK, Ibaraki, Tsukuba, Japan*
[5] *McMaster University, Hamilton, Ontario, Canada*
[6] *University of Laval, Quebec City, Quebec, Canada*
[7] *University of Guelph, Guelph, Canada*
[8] *GANIL, Caen, France*
[9] *University of Edinburgh, Edinburgh, United Kingdom*

The weakly bound halo neutrons in ^{11}Li [1], with unusual orbital arrangement, that breakis the N=8 magic number due to parity inversion between the $p_{1/2}$ and $2s_{1/2}$ orbital, also open the possibility of the existence of new kind of excitation modes. Shortly after the finding of the halo the possibility of a low-energy dipole enhancement was suggested due to the long neutron density tail [2]. Following this, a novel phenomenon was proposed where the two halo neutrons (i.e. the halo around the core) could oscillate against the core giving rise to very low-lying soft dipole resonance states [3]. Since then there have been several experiments searching for the existence of such low-lying dipole resonance states [4-9] using different techniques such as pion scattering [4] and pion capture reactions [5], proton inelastic scattering [6], invariant mass spectroscopy [7], Coulomb dissociation [8] and multi-nucleon transfer reaction [9]. Till date however no firm conclusion has been reached.

We will report results from a newly constructed reaction spectroscopy facility, IRIS, at TRIUMF, Canada that utilizes thin solid hydrogen and solid deuteron targets for low-energy reactions with radioactive beams [10]. Two different inelastic scattering reactions ^{11}Li(p,p') and ^{11}Li(d,d') were performed in order to investigate the possible existence of low-lying dipole states in ^{11}Li. The presentation will show the different observations from the two different types of reactions. This allows a new understanding on the dipole resonance nature in ^{11}Li.

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Session 30 – Room 028: Nuclear Astrophysics/Reactions

Nuclear reaction studies with GRETINA at the NSCL

K. Wimmer[1]

[1] *Department of Physics, Central Michigan University, Mount Pleasant, Michigan 48859, USA and National Superconducting Cyclotron Laboratory, East Lansing, Michigan 48824, USA*

During 2012/2013 the GRETINA gamma-ray spectrometer has been installed at the S800 spectrograph at the National Superconducting Cyclotron Laboratory (NSCL). The GRETINA array is the first critical step towards a full 4pi GRETA device. Its high angular and energy resolution provide the necessary position resolution for Doppler correction at intermediate beam energies and allow for the rejection of Compton scattering events to reduce the background.

The physics program at the NSCL includes a wide range of topics in nuclear structure and nuclear astrophysics. The combination of intense rare isotope beams and state-of-the-art detection devices allows for spectroscopic studies of exotic nuclei far from stability. Over the period of one year 23 experiments have been performed investigating single-particle and collective properties of rare isotopes.

In this talk I will present an overview of the GRETINA physics program at NSCL and report on first results from experiments studying nuclei across the nuclear chart.

Decay spectroscopy of exotic nuclei with EURICA spectrometer at RIBF

S.Nishimura[1], P.Doornenbal[1], G.Lorusso[1], P.-A.Söderström[1], T.Sumikama[2], H.Watanabe[3,1], J.Wu[4,1], Z.Y.Xu[5], H.Baba[1], G.Benzoni[6], F.Browne[7,1], A.Bruce[7], R.Daido[8], Y.F.Fang[8], R.Gernhäuser[9], G.Gey[10,1], E.Ideguchi[11], T.Isobe[1], H.S.Jung[12], A.Jungclaus[13], I.Kojouharov[14], R.Krücken[8,15], N.Kurz[13], Y.K.Kwon[16], R.Lozeva[17], Z.Li[4], D.Lubos[8,1], M.Tanaka[10], C.B.Moon[18], K.Moschner[19,1], F.Naqvi[20], M.Niikura[5], H.Nishibata[8], T.Nishizuka[2], A.Odahara[8], Z.Patel[21,1], S.Rice[21,1], E.Sahin[22], H.Sakurai[1,5], H.Schaffner[13], G.Simpson[9], L.Sinclair[20,1], D.Sohler[23], K.Steiger[8], J.Taprogge[12], A.Yagi[8], Z.Vajta[23], R.Yokoyama[24], V.Werner[20], and the EURICA collaboration

[1]RIKEN, Japan, [2]Tohoku University, Japan, [3]Beihang University, China, [4]Peking University, China, [5]University of Tokyo, [6]INFN sezione di Milano, Italy, [7]University of Brighton, United Kingdom, [8]Osaka University, [9]Technische Universität München, Germany, [10]Université Joseph Fourier Grenoble, France, [11]RCNP, Japan, [12]University of Notre Dame, USA, [13]Universidad Autonoma de Madrid, Spain, [14]GSI, Germany, [15]TRIUMF, Canada, [16]IBS, Republic of Korea, [17]Institut Pluridisciplinaire Hubert Curien, France, [18]Hoseo University, Republic of Korea, [19]University of Köln, Germany, [20]Yale University, [21]University of Surrey, United Kingdom, [22]University of Oslo, Norway, [23]Hungarian Academy of Sciences, Hungary, [24]CNS, Japan

This Beta-gamma spectroscopy is one of the powerful methods to study on the evolution of nuclear structure far from the stability by reconstructing their level scheme of nuclei from the delayed γ-rays. Beta-decay half-lives, beta-delayed neutron emission, and masses are also essential decay parameters to understand the mechanism of a rapid-neutron capture process (r process) nucleosynthesis, which is responsible for the production of elements heavier than ion in the universe. Most of the nuclei on the r-process path are, however, still not accessible experimentally due to its extremely low production yield at the present laboratories.

New generation radioactive isotope beam facility (RIBF) has started providing very neutron-rich nuclei by means of in-flight fission of high intensity ^{238}U beam at RIKEN Nishina Center[1]. Bringing together the high efficiency γ-rays detectors (Euroball germanium cluster detectors), a new project EURICA (EUROBALL RIKEN Cluster Array)† has started surveying the decay properties of exotic nuclei via beta-gamma spectroscopy method [2,3]. A new β-rays counting system WAS3ABi‡ consisting of highly segmented double-sided silicon-strip detectors was utilized inside the EURICA spectrometer to stop and identify the β-decays of various isotopes, simultaneously.

Highlights of the EURICA project around ^{78}Ni (Z=28, N=50), ^{128}Pd (N=82), and isotopes heavier than ^{132}Sn (Z=50) will be presented to discuss the nuclear shell evolution and their impacts to the r-process nucleosynthesis.

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Complete and incomplete fusion in the ^{9}Be+^{169}Tm, ^{181}Ta and ^{187}Re reactions

Y. D. Fang[1], X. H. Zhou[1], P.R.S. Gomes[2], J. Lubian[2]

[1]*Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*
[2]*Instituto de Física, Universidade Federal Fluminense, Avenida Litoranea s/n, Gragoatá, Niterói, Rio de Janeiro, 24210-340, Brazil*

Fusion reactions between heavy ions have been a subject of great interest in recent decades. More recently, great theoretical and experimental efforts have been devoted to the investigation of the behavior of fusion of weakly bound nuclei, both stable and radioactive [1]. Such nuclei have low breakup energy threshold and the breakup process feeds states in the continuum. Stable weakly bound nuclei are ^{6}Li, ^{7}Li and ^{9}Be, with breakup threshold energies of the order of 1.5 to 2.5 MeV. Particularly important in this field is the investigation of the effect of the breakup of the weakly bound nuclei on the fusion cross sections.

In the literature, some measurements of fusion cross sections of the weakly bound ^{9}Be projectile on different targets have been reported. For light targets like ^{27}Al and ^{64}Zn, only total fusion (TF) was measured. For heavier targets, complete fusion (CF) was measured and for some of them, incomplete fusion (ICF) was also measured. Those targets were ^{89}Y, ^{124}Sn, ^{144}Sm, ^{186}W, ^{208}Pb and ^{209}Bi [2]. For all systems where CF was measured, some CF suppression was found at energies above the barrier, and some enhancement was found at sub-barrier energies when compared with coupled channel calculations that do not include the breakup channel. However, contrary to what was found for the CF of another stable weakly bound projectile, ^{6}Li, for which a CF suppression of the order of 20 to 30% was observed for any target, for the CF of ^{9}Be the suppression was found to vary with target from 10% to 40% of the theoretical CF predictions, without any observed systematic related to the target charge or mass. The reason for this peculiar behaviour is not clear.

In order to contribute to the investigation of the fusion of ^{9}Be, and to investigate a systematic behavior of dynamic breakup effects on the fusion cross section, we recently measured the complete and incomplete fusion of the ^{9}Be+^{169}Tm,^{181}Ta and ^{187}Re systems at near barrier energies, using the off-line gamma ray spectroscopy method. In this talk, we will present the results of these three systems. The experimental fusion cross sections will be compared with coupled channel calculations that do not take into account the coupling of the breakup channel, using a double folding potential as bare potential. Different behaviors of prompt and delay breakup processes of weakly bound ^{9}Be are used to explain the observed CF suppression.

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Session 31 – Room 120: Nuclear Structure/Astrophysics

Observation of low-lying resonances in the quasicontinuum of ^{195,196}Pt and enhanced astrophysical reaction rates

F. Giacoppo[1], F.L. Bello Garrote[1], T.K. Eriksen[1], A. Görgen[1],
M. Guttormsen[1], T.W. Hagen[1], A.C. Larsen[1], B.V. Kheswa[1,2],
M. Klintefjord[1], P.E. Koehler[1], L.G. Moretto[3], H.T. Nyhus[1],
T. Renstrøm[1], E. Sahin[1], S. Siem[1], and T.G. Tornyi[1,4]

[1]*Department of Physics, University of Oslo, N-0316 Oslo, Norway*
[2]*Department of Physics, University of Stellenbosch, 7602 Stellenbosch, South Africa*
[3]*Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, California 94720, USA*
[4]*Institute of Nuclear Research of the Hungarian Academy of Sciences, H-4001 Debrecen, Hungary*

In the last decades, a lot of attention has been attracted by the observed enhancement of the gamma strength of many nuclei in the low-energy tail of the giant dipole resonance. The presence of such a pygmy-resonance structure in the vicinity of the neutron threshold may have profound implications for the heavy-element nucleosynthesis [1]. In particular the element Pt is predominantly produced in rapid neutron-capture (*r-*) processes in extremely neutron-rich astrophysical environments that are still to be uniquely identified [2]. Moreover, the Pt isotopes are located at the A≈195 *r*-process peak in the solar-system element abundance. Therefore the availability of direct data in this region is essential to obtain a reasonable accuracy of the relevant (n, γ) reaction rates.

The properties of ^{195,196}Pt for excitation energies in the quasicontinuum have been recently investigated at the Oslo Cyclotron Laboratory. In particular, a double-humped enhancement in the E_γ= 4-8 MeV region of the γ-ray strength functions has been observed [3]. In this work, the data are presented together with neutron-capture cross section and astrophysical reaction rate calculations. The former are in very good agreement with measured cross sections. The (n, γ) reaction rates are increased by up to a factor of 2 when these newly observed pygmy resonances are included. Further, new data on Au isotopes show similar enhancement and will be also presented [4].

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Investigation of dipole strength up to the neutron-separation energy at the ELBE accelerator

R. Massarczyk[1,2], R. Schwengner[1], A. R. Junghans[1], A.Wagner[1]

[1] *Institute of Radiation Physics, Helmholtz-Zentrum Dresden-Rossendorf, Germany*
[2]*Technical University Dresden, Germany*

At the bremsstrahlung facility of the ELBE accelerator there exists the possibility to investigate dipole strength distributions up to the neutron-separation energies with photon energies up to 16 MeV. The facility and various results for nuclides measured during recent years will be presented. One example is the study of ^{86}Kr that complements a systematic study of stable isotones at the shell closure of neutron number N = 50 [1].

The other presented example is the work on measurements within the chain of xenon isotopes [2] which aimed to investigate the influence of nuclear deformation to the dipole strength in the pygmy region.

An overview on the analysis is given. GEANT4 simulations were performed to determine the non-nuclear background that has to be removed from the measured spectra. This opens up the possibility to take into account also the strength of unresolved transitions. Simulations of gamma-ray cascades were carried out that consider the transitions from states in the quasi continuum and allow us to estimate their branching ratios. As a result, the photo-absorption cross sections obtained from corrected intensities of ground-state transitions are compared with theoretical predictions and the results within the chain of isotopes.

With the help of the measured dipole distribution it is possible to describe gamma-ray spectra after neutron capture more precisely [3,4].

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Study of the isospin character of 1⁻ states using hadronic probes at intermediate energies

V. Derya[1], J. Endres[1], M.N. Harakeh[2,3], D. Savran[4,5], M. Spieker[1], H. J. Wörtche[2], A. Zilges[1]

[1]*Institute for Nuclear Physics, Univ. of Cologne, 50937 Cologne, Germany*
[2]*Kernfysisch Versneller Instituut, Univ. of Groningen, 9747 AA Groningen, The Netherlands*
[3]*GANIL, CEA/DSM-CNRS/IN2P3, 14076 Caen, France*
[4]*ExtreMe Matter Institute EMMI and Research Division, GSI, 64291 Darmstadt, Germany*
[5]*Frankfurt Institute for Advanced Studies FIAS, 60438 Frankfurt am Main, Germany*

Low-lying electric dipole excitations, in particular the electric Pygmy Dipole Resonance (PDR), were investigated in neutron-rich nuclei using various experimental methods [1]. Aiming at unraveling the isospin character of these 1⁻ states, it has been demonstrated that the complementary studies of real-photon scattering up to the neutron threshold and high-resolution $(\alpha,\alpha'\gamma)$ coincidence experiments at 136 MeV allow separating isovector and isoscalar dipole response which is important for a deeper understanding of the underlying mechanisms generating the dipole strength.

These two complementary techniques were used to study the isospin properties of low-lying E1 excitations in the doubly-magic nucleus ^{48}Ca [2]. In contrast to heavier nuclei, a state-to-state change in isospin character was revealed in ^{48}Ca and a dominant isoscalar excitation was found which is theoretically interpreted as a pure isoscalar oscillation [2,3]. Results of this study in comparison to theoretical results will be presented.

Additionally, protons at 80 MeV were recently used as an isospin-mixed probe in a $(p,p'\gamma)$ coincidence experiment on ^{140}Ce for the first time. Preliminary results will be presented and compared to the results from (γ,γ') and $(\alpha,\alpha'\gamma)$ experiments on this nucleus.

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Decay properties of low-lying dipole strength in Sn isotopes

D. Symochko[1]

[1] *Institut für Kernphysik, Technische Universität Darmstadt, D-64289 Darmstadt, Germany*

Concentration of low-lying dipole strength around the neutron separation threshold has been experimentally observed in stable and neutron-rich nuclei. According to microscopic calculations, this excitation mode has a collective nature and is related to an oscillation of a neutron skin against a symmetric core with N=Z and is usually referred to as Pygmy dipole resonance (PDR) [1]. Although, the complete picture of the low-lying dipole strength is still missing, and theoretical descriptions of experimental results obtained with different probes (photons and α-particles) are still a subject to the strong debates.

Understanding the PDR mechanism could give a direct access to the information about the pure neutron matter, being described by the nuclear equation of state (EoS) [2] in which the nuclear symmetry energy goes into. It has been found that the density dependence of the nuclear symmetry energy close to the saturation density (typical for the neutron skin) is directly coupled to the PDR. Additionally, the precise and systematic knowledge of the low-lying dipole strength is essential for a correct description of the r- and p-processes of nucleosynthesis.

In order to obtain a complete picture of the dipole strength function evolution with increasing N/Z asymmetry, we are carrying out a series of experiments along the Sn isotopic chain – from stable ^{112}Sn to short-lived ^{134}Sn. The proposed program includes experiments with real photons (High Intensity γ-ray Source facility, Duke University and low energy photon tagger NEPTUN, TU Darmstadt), virtual photons in Coulomb excitation (GSI) and inelastic scattering of α-particles (RIKEN). The current presentation will give an overview of the project and cover the preliminary results from the first completed measurements of ^{124}Sn(γ,γ') reaction, carried out at HIγS using the γ^3-setup [3].

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The γ-ray strength functions of ^{138}La and ^{139}La and their impact on galactic production of ^{138}La

B.V. Kheswa[1,2], M. Wiedeking[1], F. Giacoppo[3], S. Goriely[4], M. Guttormsen[3], A.C. Larsen[3], F. Bello[3], T.K. Eriksen[3], A. Görgen[3], T.W. Hagen[3], P.E. Koehler[3], M. Klintefjord[3], H.T. Nyhus[3], P. Papka[2], T. Renstrøm[3], S. Rose[3], E. Sahin[3], S. Siem[3] and T. Tornyi[3]

[1] *iThemba LABS, Somerset West, South Africa*
[2] *Physics Department, University of Stellenbosch, Stellenbosch, South Africa*
[3] *SAFE Department, University of Oslo, Oslo, Norway*
[4] *Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles, Brussels, Belgium*

Observed abundances for the large majority of nuclei heavier than iron can be explained by means of the s- and r-processes. The notable exceptions are the 35 p-nuclei which are found on the proton-rich side, distributed across the nuclear chart, and are either stable or very long-lived with half-lives on the order of Gyr, and their production through neutron capture processes is prohibited. Most *p*-nuclei with A>110 are thought to be produced in photodisintegration reactions i.e. (γ,n), (γ,p) or (γ,a), originating from seed nuclei which are produced in the s- or r-processes. Photodisintegration can explain the observed solar abundances of the p-nuclei, with a few exceptions, one of them being ^{138}La for which more exotic processes are invoked to satisfactorily explain its abundance. The most promising theory brough forward, suggests electron-neutrino capture on ^{138}Ba to be responsible for the synthesis of ^{138}La [1,2]. Although, neutrino reactions can explain the observed abundance of ^{138}La, it was clearly pointed out [2] that the significance of the photodisintegration process cannot be ruled out due to the limited knowledge and uncertainties of nuclear properties entering the ^{138}La production, such as the nuclear level densities (NLD) and γ-ray strength function (γSF). These are critical model input parameters for the astrophysical reaction rate calculations and measurements are necessary to place the nuclear properties on a solid footing in order to make statements regarding the importance of neutrino reactions.

In this presentation I will discuss our experimental work to extract the NLD and γSF of ^{138,139}La from measurements using the ^{139}La(^{3}He,^{3}Heγ)^{139}La and ^{139}La(^{3}He,αγ)^{138}La reactions with a beam energy of 38 MeV. The particle-γ coincidences were measured using the SiRi (8x8 particle telescopes) and CACTUS (26 NaI detectors) arrays at the Cyclotron Laboratory of the University of Oslo. I will also present ^{137}La(*n*,γ) and ^{138}La(*n*,γ) cross sections and astrophysical rates, calculated with the combinatorial plus Hartree-Fock-Bogoliubov model of NLD, using our experimental γSF as input parameters, and address the astrophysical implications pertaining to the neutrino process.

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Session 32 – Room 028: Techniques/Data

DESCANT and β-delayed neutron measurements at TRIUMF

V. Bildstein[1] for the GRIFFIN and DESCANT collaborations

[1]*University of Guelph, Guelph, ON N1G 2W1, Canada*

With the advent of radioactive beam facilities like TRIUMF neutron-rich nuclei far from stability have become available for β-decay studies. However, the further we go away from the "valley of stability", the larger the Q-value of the β-decay becomes, which, combined with the lower neutron separation energies, gives rise to an increased probability for the delayed emission of one or more neutrons.

While it is possible to try and disentangle the pure β-decay from βn-decays via γγ-coincidences, the addition of neutron detectors to a HPGe array like GRIFFIN simplifies this and increases the precision in measuring the probability of β-delayed neutron emission.

The DESCANT array at TRIUMF is comprised of 70 close-packed deuterated liquid organic scintillators that can be coupled with the GRIFFIN array and its fast digital read-out ADC modules are seamlessly integrated into the GRIFFIN DAQ. Deuterated benzene has the same PSD capabilities to distinguish between neutrons and γ-rays interacting with the detector as un-deuterated scintillators. In addition, the anisotropic nature of *n-d* scattering as compared to the isotropic *n-p* scattering allows the determination of the neutron energy spectrum directly from the pulse-height spectrum, complementing the time-of-flight information.

A detailed overview of GRIFFIN and DESCANT will be presented.

In-Trap Decay Spectroscopy with the TITAN Facility at TRIUMF

K.G. Leach[1,2], A. Grossheim[1], A. Lennarz[1,3], T. Brunner[1,4,5], A.T. Gallant[1,6], M. Good[1], F. Jang[1,6], R. Klawitter[1,7], A.A. Kwiatkowski[1], T.D. Macdonald[1,6], B.E. Schultz[1], S. Seeraji[2], M.C. Simon[1], C. Andreoiu[2], J. Dilling[1,6], and D. Frekers[3]

[1]*TRIUMF, 4004 Wesbrook Mall, Vancouver BC, V6T 2A3, Canada*
[2]*Department of Chemistry, Simon Fraser University, Burnaby BC, V5A 1S6, Canada*
[3]*Institut fur Kernphysik, Westfalische-Wilhelms-Universitat Munster, D-48149, Germany*

[4]*Physik Department E12, Technische Universitat Munchen, D-85748, Germany*

[5]*Department of Physics, Stanford University, Stanford, CA 94305, USA*

[6]*Department of Physics and Astronomy, UBC, Vancouver, BC, V6T 1Z1, Canada*

[7]*Ruprecht-Karls-Universitat Heidelberg, D-69120 Heidelberg, Germany*

A new in-trap decay spectroscopy facility has been developed and constructed for use with TRIUMF's Ion Trap for Atomic and Nuclear science (TITAN). This apparatus consists of a 6 Tesla, open-access spectroscopy ion-trap, surrounded radially with up to 7 low-energy Si(Li) detectors that are separated from the trap by thin Be windows. The ion-trap environment allows for the detection of low-energy photons by providing backing-free storage, while simultaneously suppressing 511 keV positron annihilation background by more than an order of magnitude. This suppression is facilitated by the strong magnetic field of the trap, and in addition to an electron beam for charge breeding, allows for excellent ion confinement and long storage times. These advantages, along with careful monitoring and control, provide a significant increase in sensitivity and precision for the detection of X-rays from the electron-capture (EC) process. These measurements are particularly relevant for observing weak EC branching ratios in the odd-odd intermediate nuclei in the double beta-decay process [1]. The current progress of the facility and its commissioning measurements will be presented, along with possible directions this work may take in the future.

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Measurement of the prompt fission gamma-ray emission from fast neutron induced fission of ^{235}U and ^{238}U with LICORNE

P. Halipré[1], M. Lebois[1], J. N. Wilson[1], S. Oberstedt[2], A. Oberstedt[3]

[1]*Institut de Physique Nucléaire d'Orsay, Bâtiment 100, 15 rue G. Clemenceau, 91406 Orsay Cedex, France*
[2]*Institute for Reference Materials and Measurements, Retieseweg 111, 2440 Geel, Belgium*
[3]*Fundamental Fysik, Chalmers Tekniska Högskola, S-4196, Sweden*

Corresponding Author : halipre@ipno.in2p3.fr

Results from the first experiment carried out using the LICORNE neutron source at the IPNO will be presented, where the comparative prompt fission gamma-ray emission from fast neutron induced fission of ^{235}U and ^{238}U was measured for the first time.

The LICORNE neutron source produces intense, kinematically focused beams of fast neutrons between energies of 0.5 to 4 MeV using the p(^{7}Li, n)^{7}Be inverse reaction[1]. Typically, fluxes of around 10^7 n/s can be produced in a cone of 20° opening angle. This source was used to irradiate thin samples of ~7mg of ^{235}U and ^{238}U placed in an ionisation chamber, allowing detection of more than 10^5 fissions during the experiment.

Coincident gamma rays were detected in 14 large (10 cm x 14 cm) BaF_2 scintillator detectors and 3 smaller (5 cm x 5 cm) $LaBr_3$ scintillator detectors for the high (> 2 MeV) and low (< 2 MeV) energy parts of the gamma ray spectra respectively. The directionality of the neutron source allows these detectors to be placed outside the neutron cone and thus out of the flux of primary neutrons. The combined time resolution of these detectors and the ionization chamber was sufficient to perform discrimination between prompt fission neutrons and prompt fission gammas by the time of flight technique over a distance of ~30 cm.

First results of prompt fission gamma-ray spectra from the uranium ^{235}U (n, f) and ^{238}U (n, f) reaction will presented. Comparisons of low energy structures and high energy shapes will be shown, along with comparaisons with theoretical models and previous data from the ^{235}U(n, f) reaction for thermal neutron induced fission.

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Improved Neutron Capture Gamma-Ray Data and Evaluation

B. W. Sleaford[1], M.S. Basunia[2], F. Becvár[4], T. Belgya[5], L.A. Bernstein[1], H. Choi[6], J.E. Escher[1], R.B. Firestone[2], Ch. Genreith[8], F. Gunsing[9], A.M. Hurst[2], M. Krticka[4], Zs. Revay[7], M. Rossbach[8], N.C. Summers[1] and L. Szentmiklosi[5]

[1]*Lawrence Livermore National Laboratory, Livermore, CA 94551*
[2]*Lawrence Berkeley National Laboratory, Berkeley, CA 94720*
[4]*Charles University in Prague, Faculty of Mathematics and Physics, Czech Republic*
[5]*Centre for Energy Research, Hungarian Academy of Sciences, Budapest, Hungary*
[6]*Seoul National University, Korea*
[7]*Forschungsneutronenquelle Heinz Maier-Leibnitz (FRM II), Technische Universität, Munich, Germany*
[8]*Institute for Energy and Climate Research, IEK-6, Forschungszentrum, Juelich, Germany*
[9]*CEA Saclay, Gif-sur-Yvette, France*

The neutron-capture reaction is of fundamental use in identifying and analyzing the gamma-ray spectrum from an unknown object as it gives a fingerprint of which isotopes are present. Many isotopes have capture gamma lines from 5-10 MeV potentially making them easier to detect against background lines. There are data gaps in the Evaluated Nuclear Data File (ENDF) libraries used by modeling codes (the actinides have no lines for example) and we are filling these with the Evaluated Gamma-ray Activation File (EGAF), using an IAEA atlas of reactor measured lines and cross sections for over 260 isotopes. For medium to heavy nuclei, the unresolved part of the gamma cascades is not measured and are modeled using the statistical nuclear structure code Dicebox [1, 2]. ENDF libraries require cross sections for neutron energies up to 20 MeV and we plan to continue this approach through the resolved resonance region. Some benchmarking with gamma spectra from neutron time of flight experiments is possible but data is very limited. In the unresolved resonance and high energy regions, we are using Hauser-Feshbach modeling to predict the cross sections of capture gamma spectra in regions where multiple competing output channels are open. This work is performed in part under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

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Reference Database for Reaction Gamma-ray Data

P. Dimitriou[1], R.B. Firestone[2], S. Siem[3], F. Bečvář[4], M. Krticka[4], V.V. Varlamov[5], M. Wiedeking[6]

[1] *Nuclear Data Section, International Atomic Energy Agency, A-1400 Vienna, Austria*
[2] *Lawrence Berkeley National Laboratory, University of California, CA 94720, USA*
[3] *Department of Physics, University of Oslo, P.O. Box 1048 Blindern, N-0316 Oslo*
[4] *Charles University in Prague, V Holesovickach 2, 18000 Prague, Czech Republic*
[5] *CDFE, Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, 119991 Moscow, Russia*
[6] *iThemba LABS, P.O. Box 722, Somerset West 7129, South Africa*

Gamma-ray data from nuclear reactions are important for a large range of applications, as well as for basic sciences. In particular, photonuclear cross sections and gamma-ray data to extract Photon Strength Functions (PSF) are necessary for energy, safety and medical applications as well as for nuclear physics and astrophysics.

A wealth of gamma-ray data related to photonuclear reactions and PSFs accumulated in recent years need to be made available to researchers worldwide. These data are important sources of information for experimental data files such as EXFOR and evaluated data files such as RIPL, ENDF, EGAF, ENSDF etc supported by the International Atomic Energy Agency. They are also intricately related to the development and improvement of theoretical models describing the electromagnetic response of the nucleus.

The current situation with regards to photonuclear and reaction gamma-ray data was reviewed at a Consultant's Meeting organized by the Nuclear Data Section IAEA in November 2013 [1]. The meeting concluded that there was an urgent need for the compilation and evaluation of all relevant data in a dedicated database.

Furthermore, it recommended that the IAEA initiate a coordinated research project, with the primary task of compiling the relevant data, defining the database structure and formats, outlining the evaluation methodology, assessing experimental methods and understanding the source of discrepancies.

In this paper we report on the main issues that were addressed at the meeting and the latest developments regarding the coordinated effort to create a reference database for reaction gamma-ray data.

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Session 33 – Room 120: Nuclear Data

Fast neutron measurements at the nELBE time-of-flight facility

A. R. Junghans, R. Beyer*, E. Grosse*, R. Hannaske*, T. Kögler*, R. Massarczyk*,
R. Schwengner, A. Wagner

Helmholtz-Zentrum Dresden-Rossendorf, Postfach 510119, 01314 Dresden, Germany

The compact neutron-time-of-flight facility nELBE at the superconducting electron accelerator ELBE of Helmholtz-Zentrum Dresden-Rossendorf has been rebuilt. A new enlarged experimental hall with a flight path of up to 10 m is available for neutron time of flight experiments in the fast energy range from about 100 keV to 10 MeV. As the neutron radiator consist only of a liquid lead circuit no moderated neutron are produced and also the background from capture gamma rays is very small [1]. As the electron bunch length is only a few ps the energy resolution in the MeV range is dominated by the timing resolution of the detectors.   nELBE is intended to deliver cross section data of fast neutron nuclear interactions e.g. for the transmutation of nuclear waste and improvement of neutron physical simulations of innovative nuclear systems. The experimental programme consists of transmission measurements of neutron total cross sections, elastic and inelastic scattering cross section measurements, and neutron induced fission cross sections.

The inelastic scattering of ^{56}Fe was investigated both with a double-time-of-flight experiment i.e. the scattered neutron and the de-excitation photon are measured in coincidence using a BaF_2 scintillator and plastic scintillator arrays. In the same experiment, the gamma production cross section was measured with an HPGe detector and the inelastic neutron scattering cross section to the first few excited states in ^{56}Fe was determined. The neutron induced fission of ^{242}Pu was studied using fast ionisations chambers with homogeneous actinide deposits [2]. First results will be presented.

* also at Technische Universität Dresden, Institut für Kern- und Teilchenphysik, Dresden, Germany

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Posters: Nuclear Structure

Nuclear structure of [69]Zn from (n,γ) reaction studied with EXILL

P. Bączyk[1], M. Czerwiński[1], A. Korgul[1], C. Mazzocchi[1], T. Rząca-Urban[1], W. Urban[1],
A. Blanc[2], M. Jentschel[2], U. Köster[2], P. Mutti[2], T. Soldner[2], G. De France[3], and G. Simpson[4]

[1]*Faculty of Physics, University of Warsaw, ul. Hoża 69, PL-00-681 Warsaw, Poland*
[2]*Institut Laue-Langevin, 156X, 38042 Grenoble Cedex 9, France*
[3]*Grand Acclrateur National d'Ions Lourds (GANIL),*
CEA/DSM CNRS/IN2P3, BP. 55027, 14076 Caen Cedex 5, France
[4]*Laboratoire de Physique Subatomique et de Cosmologie, CNRS/IN2P3, UJF, INPG, France*

The contemporary Shell Model is able to describe nuclear excitations not only in closed-shell nuclei and their immediate neighbours but also in nuclei with larger number of valence nucleons, reproducing also collective effects there [1–4]. For this one needs, however, to know how the single-particle energies, which are input values for such calculations, vary when departing from closed shells, due to the tensor forces and the monopole shifts [5, 6]. Such information can be obtained from studies of the evolution of nuclear structure as a function the number of valence nucleons. The reliability of such studies critically depends on a precise information concerning the structure of nuclei of interest, like the identification of all low-lying excited levels, their spins, parities and decay properties.

It is well established that the neutron capture reactions serve as an excellent tool for such type of "complete" spectroscopy. With the development of very efficient arrays of γ spectrometers, the measurements of γ radiation following the neutron capture reactions offer now new, rich and complete information on nuclear structure.

Our recent measurements of gamma radiation following slow-neutron capture on [68]Zn and [70]Zn nuclei, performed with the very efficient germanium array EXILL at ILL Grenoble, provided rich, new information in the chain of Zn isotopes, in a region where various effects connected with the closure of the N=40 subshell are expected. In the paper we will present new results obtained for excited levels in [69]Zn and discuss nuclear structure effects observed in Zn isotopes, like the subshell-closure presence or the influence of single-particle structures on the decay pattern after neutron capture, including an interesting problem of the population of high-spin isomers starting from a capture level with much lower spin.

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Gamma bands in doubly odd rhenium and iridium nuclei

<u>M.Balodis</u>[1], J.Bērziņš[1], T.Krasta[1], L.Simonova[1]

[1]*Institute of Solid State Physics, University of Latvia, LV-1063, Rīga, Latvia*

Structure of nuclei belonging to the transitional A~190 region displays features characteristic both to the axially-symmetric and triaxial shapes. It poses serious challenges for level scheme development, especially in the case of doubly odd nuclei. One of the most prominent indications of triaxiality is a high level density even at relatively low excitation energies. In axially deformed odd-odd nucleus, valence proton and neutron form two configurations with parallel and antiparallel spins – the Gallagher-Moszkowski doublet. In the case of non-axial nuclear shape, orbital momentum projections Ω and K are not conserved and one observes a number of |K±2|, |K±4|,... side-bands for each two-quasiparticle configuration. These bands of collective origin are analogous to γ-vibrational bands in even-even deformed nuclei. The characteristic feature of these bands is intense decay to the levels of its parent K band, predominantly with E2, or M1+E2 transitions. However, due to high level density, one can identify these gamma-bands only for relatively weakly mixed (isolated) two-quasiparticle configurations, mostly involving high j value orbits with high Ω values. The best established gamma bands in doubly odd nuclei with A~190 are the 351.6 keV 2^+ |K-2| band of the ground state configuration $K^\pi=4^+$ (p:11/2[505]-n:3/2[512]) in ^{192}Ir [1], and the 2^+ |K-2| band at 518.6 keV in ^{194}Ir [2], based in the 147.1 keV 4^+ level with structure analogous to that of the 4^+ ground state in ^{192}Ir.

Using available experimental data [1-4], we propose new tentative triaxial gamma bands for rhenium and iridium nuclei: the 482.1 keV 2^+ |K-2| band of the $K^\pi=0^+$ (p:9/2[514]-n:9/2[505]) two-quasiparticle configuration in ^{188}Re; the 352.9 keV 6^+ |K+2| bandhead of the 4^+ ground state configuration, the 368.2 keV 4^+ |K-2| bandhead of the $K^\pi=6^+$ (p:11/2[505]+n:1/2[510]) state, and the 380.4 keV 4^- |K-2| bandhead of the $K^\pi=6^-$ (p:3/2[402]+n:9/2[505]) state in ^{192}Ir. Experimentally proposed structures are compared with the results of asymmetric PRC model calculations.

There are indications that the uninterpreted 270.9 keV 3^+ band in ^{194}Ir [2] can be a |K-2| gamma band of the $K^\pi=5^+$ (p:11/2[505]+n:1/2[510]) configuration established at 161.5 keV. But, in such a case, one must consider coexistence of different non-axial shapes in ^{194}Ir since energy of the 2^+ core state is much smaller than that for the 518.6 keV 2^+ |K-2| band. Coexistence of axially-symmetric and triaxial shapes is observed also in the case of ^{188}Re.

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QPM analysis of ^{205}Tl nuclear excitations below the Giant Dipole Resonance

N. Benouaret[1], J. Beller[1], J. Isaak[2,3], J.H. Kelley[4,5], H. Pai[1],
N. Pietralla[1], V.Yu. Ponomarev[1], R. Raut[5,6] , C. Romig[1], G. Rusev[5,6] , D. Savran[b,c],
M. Scheck[1], L. Schnorrenberger[1], K. Sonnabend[7], A.P. Tonchev[5,6], W. Tornow[5,6] ,
H.R. Weller[5,6], M. Zweidinger[1]

[1]Institut für Kernphysik, Technische Universität Darmstadt
64289 Darmstadt, Germany
[2]ExtreMe Matter Institute EMMI and Research Division
GSI Helmholtzzentrum für Schwerionenforschung GmbH
64291 Darmstadt, Germany
[3]Frankfurt Institute FIAS, 60438 Frankfurt am Main, Germany
[4]Department of Physics, North Carolina State University
Raleigh, North Carolina 27695, USA
[5]Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708, USA
[6]Department of Physics, Duke University, Durham, North Carolina 27708, USA
[7]Institut für Angewandte Physik, Goethe Universität Frankfurt am Main
60438 Frankfurt am Main, Germany

The actual nuclear research is focused on the energy region close to the low tail of the GDR where the sensitive NRF experiments shed light on the existence of an accumulation of electric dipole transition strengths in many shell closures so-called pygmy dipole resonance (PDR). It may increases considerably the reaction rates of elements nucleosynthesis. In the N=126 mass region, the PDR mode has been already investigated in double magic ^{208}Pb [1] and several neighboring even-even and odd mass isotopes [2,3]. Recently, the systematic has been complemented by the odd-nuclide ^{205}Tl [4]. We analyze the corresponding transition strengths distribution in the frame of the quasiparticle phonon model.

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Levels of ^{186}Re populated in thermal neutron capture reaction

J.Bērziņš[1], T.Krasta[1], L.Simonova[1], M.Jentschel[2], W.Urban[3]

[1]Institute of Solid State Physics, University of Latvia, LV-1063, Rīga, Latvia
[2]Institut Laue-Langevin, F-38042, Grenoble Cedex, France
[3]Faculty of Physics, University of Warsaw, 00-681 Warsaw, Poland

Gamma-ray spectra of ^{186}Re, following thermal neutron capture reaction with enriched ^{185}Re target, have been measured in the energy range from 100 keV to 1.5 MeV with the high-resolution crystal-diffraction spectrometer GAMS5 at the Institute Laue-Langevin. Energy and angular γγ-coincidence measurements at the PF1B cold neutron beam have been performed as well. Evaluation of single spectra obtained in the first, second, and third reflection orders allowed to obtain energies and intensities of more than 500 γ-lines assigned to ^{186}Re. These data have essentially higher resolution than those of the earlier crystal-diffraction measurements [1]. Evaluation of γγ-coincidence measurement results are in progress. Most of obtained transitions have been placed in the model-independent level scheme of the doubly odd ^{186}Re nucleus. This level scheme is developed taking into account the available data of earlier experiments [2] as well as the results of recent ^{187}Re(p,d)^{186}Re reaction measurements [3] performed with the Munich Q3D spectrograph. Structure of the ^{186}Re low-lying levels is analysed in terms of the particle-plus-rotor coupling model. The obtained nuclear level scheme of ^{186}Re is compared with that of the neighbouring ^{188}Re [4].

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Mixed-symmetry excitations of higher-order multipolarities in the N=52 isotones

A. Hennig[1], V. Werner[2,3], T. Ahn[2,4], N. Cooper[2], V. Derya[1], M. Elvers[1,2], J. Endres[1],
A. Heinz[2,5], G. Ilie[2,6], P. Petkov[1,7], S. G. Pickstone[1], D. Radeck[1,2], D. Savran[8,9], M. Spieker[1],
and A. Zilges[1]

[1]*Institute for Nuclear Physics, Univ. of Cologne, D-50937 Köln, Germany*
[2]*Wright Nuclear Structure Laboratory, Yale Univ., New Haven, Connecticut 06520, USA*
[3]*Institute for Nuclear Physics, Technical Univ. of Darmstadt, D-64277 Darmstadt, Germany*
[4]*National Superconducting Cyclotron Laboratory NSCL, Michigan State University,
East Lansing, Michigan 48824, USA*
[5]*Fundamental Physics, Chalmers Univ. of Technology, SE-41296 Göteborg, Sweden*
[6]*National Institute for Physics and Nuclear Engineering, Bucharest-Magurele,
RO-77125, Romania*
[7]*Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences,
BG-1784, Sofia, Bulgaria*
[8]*Extreme Matter Institute EMMI and Research Division, GSI Darmstadt, Germany*
[9]*Frankfurt Institute for Advanced Studies FIAS, Frankfurt, Germany*

The A=100 mass region shows a variety of nuclear structure phenomena. In particular, mixed-symmetry quadrupole excitations are well established in the stable N=52 isotones [1]. However, based on the observation of strong M1 transitions between the lowest-lying 3^- and 4^+ states, the existence of octupole and hexadecapole mixed-symmetry states has been proposed recently [2, 3].

To study the evolution of isovector octupole and hexadecapole excitations with increasing proton number, we have performed two experiments on the heaviest stable N=52 isotone ^{96}Ru. The first one was performed at the YRAST-ball spectrometer at WNSL, Yale University, the other one at the SONIC@HORUS spectrometer at the University of Cologne. In particular, nuclear level-lifetimes were extracted from proton-γ coincidence data of the Cologne experiment. Combining the experimental data from both experiments, absolute transition strengths in ^{96}Ru were deduced.

In this contribution, the experimental results are presented and the structure of the lowest-lying 4^+ states is discussed within the framework of sdg-IBM-2 and shell-model calculations. The results are compared to those obtained for the neighboring N=52 isotone ^{94}Mo.

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The decay pattern of the Pygmy Dipole Resonance

J. Isaak[1,2], T. Aumann[3,4], J. Beller[3], N. Cooper[5], V. Derya[6], M. Duchêne[3], J. Endres[6],
J. Kelley[7,8], M. Knörzer[3], B. Löher[1,2], N. Pietralla[3], C. Romig[3], D. Savran[1,2], M. Scheck[3,,9,10],
H. Scheit[3], J. Silva[1,2], A. Tonchev[11], W. Tornow[7], H. Weller[7], V. Werner[3,5], A. Zilges[6],
M. Zweidinger[3]

[1]*ExtreMe Matter Institute EMMI and Research Division, GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany*
[2]*Frankfurt Institute for Advanced Studies FIAS, 60438 Frankfurt am Main, Germany*
[3]*Institut für Kernphysik, TU Darmstadt, 64289 Darmstadt, Germany*
[4]*GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany*   [5]*WNSL, Yale University, P.O. Box 208120, New Haven, CT 06520-8120, USA*
[6]*Institut für Kernphysik, Universität zu Köln, 50937 Köln, Germany*
[7]*Department of Physics, Duke University, TUNL, Durham, NC 27708-0308, USA*
[8]*Department of Physics, North Carolina State University, Raleigh, NC 27607, USA*
[9]*School of Engineering, University of the West of Scotland, Paisley PA1 2BE, UK*
[10]*Scottish Universities Physics Alliance, Glasgow G12 8QQ, UK*
[11]*Physics Division, Lawrence Livermore National Laboratory, Livermore, CA 94550, USA*

The electric-dipole strength ($E1$) in atomic nuclei has been investigated intensively in the past decades, especially in the region of the Giant Dipole Resonance. However, for many nuclei additional low-lying $E1$ strength in the vicinity of the neutron threshold has been observed, which is usually denoted as Pygmy Dipole Resonance (*PDR*) [1]. The properties of this phenomenon have been studied in stable and in a few unstable nuclei, in particular in the Z=50 and N=82 mass regions. The underlying nature of the *PDR* is still unclear, and strong experimental and theoretical effort is put into its investigation. One suitable method to study the low-lying $E1$ strength below the neutron threshold is the Nuclear Resonance Fluorescence (*NRF*). So far, measurements have been restricted mostly to ground-state transitions. Still, for a complete understanding of the decay pattern, cascading transitions involving low-lying excited states have to be investigated as well. However, the branching ratios for these transitions are often too small to be observed in standard *NRF* experiments due to the large amount of low-energy background and the corresponding sensitivity limit.

Therefore, a unique experimental setup consisting of fast LaBr$_3$ detectors with high efficiency and HPGe detectors with high energy resolution was installed at the High Intensity γ-Ray Source (HIγS) [2] at the Triangle Universities Nuclear Laboratory by the γ^3 collaboration [3]. The combination of the quasi-monochromatic photon beam of the HIγS facility and the method of $\gamma-\gamma$ coincidences increases the experimental sensitivity substantially.

The γ^3-setup allows for investigating direct decays as well as cascade transitions via low-lying excited states. In addition, due to the finite spectral width of the photon beam it is possible to extract average decay properties in the *PDR* region. These average quantities can be used to study statistical properties, e.g. the so-called Photon Strength Function [4,5]. Results for nuclei in the N=82 mass region will be presented and compared to theoretical calculations.

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Analysis of distribution of total radiation widths from neutron resonances in Pt isotopes

P.E. Koehler[1], F. Bečvář[2], M. Krtička[2], K.H. Guber[3]

[1]LANL, Los Alamos, NM 87544, USA
[2]Charles Univ. in Prague, Fac. of Math and Physics, 180 00 Prague 8, Czech Republic
[3]Reactor and Nuclear Systems Division, ORNL, Oak Ridge, TN 37831, USA

High quality neutron capture and transmission data were measured on isotopically enriched ^{192,194,195,196}Pt and natural Pt samples at ORELA. R-matrix analysis of this data revealed resonance parameters for 159, 413, 423, 258, and 11 neutron resonances for neutron energies below 5.0, 7.5, 16.0, 16.0, and 5.0 keV for ^{192,194,195,196,198}Pt+n, respectively. Earlier analysis of data on reduced neutron widths, Γ_n^0, showed that distribution of Γ_n^0 for ^{192,194}Pt deviate significantly from the Porter-Thomas distribution (PTD) predicted by random matrix theory [1]. In this contribution we report on results of the analysis of distribution of total radiation widths, Γ_γ, in ^{192,194,195,196}Pt+n reactions. Comparison of experimental Γ_γ data with predictions made using the DICEBOX algorithm [2] within the framework of the nuclear statistical model indicates that standard models of Photon Strength Functions (PSFs) and Nuclear Level Density predict too narrow distributions. We found that satisfactory agreement between experimental and simulated distributions of Γ_γ can be obtained only by a strong suppression of the PSFs at low γ-ray energies and/or by violation of the usual assumption that primary transitions from neutron resonances follow the PTD. The shape of PSFs needed for reproduction of Γ_γ distribution nicely reproduces spectra from several (n,γ) data on neighbour ^{198}Au nucleus [3].

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Neutron Capture Cross Section Measurement with ANNRI: Ni-61 case

Leong Lou Sai[1], Kimura Atsushi[2], Harada Hideo[3], Nakamura Shoji[4]

2-4 Shirane,Shirakata,Tokai-mura,Naka-gun,Ibaraki 311-1195,Japan
Japan Atomic Energy Agency[1,2,3,4]

The neutron-nucleus capture cross section is an important ingredient in the simulation of neutron applications, as nuclear reactors, especially for thermal and epithermal fluxes where it is among the most probable channels. ANNRI, in MLF at J-PARC, is an outstanding neutron facility delivering neutrons produced by spallation neutrons. It is well suited for measurements of radiative capture cross sections as it produces the highest flux of thermal neutrons to intermediate neutrons when compared to other facilities. In addition as it is pulsed, it allows to measure the energy dependence of the cross section by using a time of flight.

Ni-61(n, γ) reaction cross section has been measured at ANNRI, using the time of flight method. The gamma detection was done by several HPGe detectors covering a substantial fraction of the solid angle.We focused the analysis on the capture rate to extract the corresponding cross section. We will show how the detection efficiency, the dead time correction, the background estimation, and the normalization have been estimated to get an accurate capture yield. Finally, the Ni-61 capture cross section in the thermal and epithermal energy domains (0.001 eV to 1 keV), will be reported and compared to recent evaluations.

Simulation of the EXILL detector-array and analysis of the neutron-capture experiment on ^{78}Se

Ch. Lorenz[1], R. Massarczyk[1], R. John, R. Schwengner[1], A. Blanc[2], M. Jentschel[2], U. Köster[2], P. Mutti[2], W. Urban[2], T. Belgya[3], S. Valenta[4]

^{1}Helmholtz-Zentrum Dresden-Rossendorf, Dresden, Germany
^{2}Institut Laue-Langevin, Grenoble, France
^{3}Hungarian Academy of Sciences, Budapest, Hungary
^{4}Charles University, Prague, Czech Republic

Neutron-capture reactions play an important role in astrophysical processes, such as the so-called s- and r-process, as well as in next-generation nuclear technologies, for example in transmutation of long-lived nuclides. Hence, a better understanding and description of neutron capture is needed. In particular, an improved knowledge of strength functions being one important input for statistical model calculations is required.

For this purpose, we carried out a neutron-capture experiment at the reactor of the ILL Grenoble. Gamma rays emitted in the ^{77}Se(n, γ) reaction were measured with the EXILL detector array consisting of eight EXOGAM detectors (from GANIL), six GASP detectors (from LNL) and two LOHENGRIN detectors (ILL). We recorded $2 \cdot 10^{9}$ two-fold $\gamma - \gamma$ coincidences during the beam time of three days. In a first step, several $\gamma-$ray cascades were established on the basis of the coincidence relations.

The present work aims at the analysis of the strength including the quasicontinuum part of the spectra. This analysis requires the subtraction of radiation caused by interactions in the detectors. Therefore the complete EXILL detector setup has been simulated using the Geant 4 toolkit [1]. In this way the detector response has been deduced. In the further analysis, strength functions of spectra in coincidence with the ground-state transition as well as with primary transitions shall be investigated.

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Study of Grodzins product rule with $N_p N_n$ for deformed nuclei

H.M. Mittal and Parveen Kumari

*Dr. B. R. Ambedkar National Institute of Technology,
Jalandhar 144011, Punjab, India*

Historically, the collectivity of the nuclei increases with increase of the valence nucleons in a closed shell. In even-even nuclei, the energy of the first 2^+ state, $E(2_1^+)$ decreases with increase in deformation (i.e. moment of inertia). Simultaneously, the quadrupole moment of $E(2_1^+)$ also increases and hence, the reduced excitation strength $B(E2, 0_1^+ \rightarrow 2_1^+)$ increases.

Grodzins [1] introduced a relationship between $E(2_1^+)$ and $B(E2, 0_1^+ \rightarrow 2_1^+)$ in product form as:

$$E(2_1^+) * B(E2)\uparrow \approx constant(Z^2/A)$$

Recently, Gupta [2] illustrated the complex nuclear structure at N=88 isotones and analyse that the Grodzins product rule breakdown in the Ba-Dy region. As the collectivity is directly depends on the valence protons, N_p and valence neutrons, N_n. Here, we use a simple rule of dividing the major shell space (Z=50-82, N=82-126) based on the particle and hole boson subshell space given earlier by Hamilton *et al.* [3].

We present for the first time the variation of Grodzins product $(E(2_1^+) * B(E2)\uparrow)$ with the product of valence protons and neutrons ($N_p N_n$) for well deformed nuclei. Grodzins product *vs.* $N_p N_n$ show good constancy for N≤104 region in Dy-W nuclei as shown in Fig.1. Detail results will be presented in the conference.
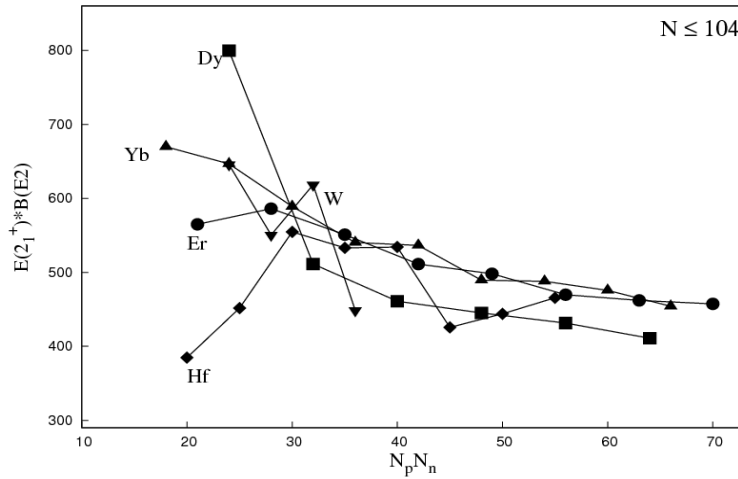

Fig. 1: Plot of $(E(2_1^+) * B(E2)\uparrow)$ *vs.* $N_p N_n$ for N≤104 region in Dy-W nuclei.

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Isospin symmetry breaking and large-scale shell-model calculations with the SS method

Takahiro Mizusaki[1], Kazunari Kaneko[2], Yang Sun[3] and Shigeru Tazaki[4]

[1] *Institute of Natural Sciences, Senshu University, Tokyo 101-8425, Japan*
[2] *Department of Physics, Kyushu Sangyo University, Fukuoka 813-8503, Japan*
[3] *Department of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, People's Republic of China, Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, People's Republic of China*
[4] *Department of Applied Physics, Fukuoka University, Fukuoka 814-0180, Japan*

Recent experimental data shed light on an asymmetry between spectra of isospin analogue states with mirror pair nuclei for mass 60-70 regions. This asymmetry, that is, **isospin symmetry breaking** is partly due to the Coulomb force and partly due to the strong nucleon-nucleon interaction. To analyze this isospin symmetry breaking, we have discussed mirror energy difference (MED), Coulomb energy differences (CED) and triplet energy differences (TED) [1,2]. Here we employ the large-scale shell-model calculations, extending it with isospin non-conserving interactions.

Generally, in large-scale shell model calculations, M-scheme (shell model space with definite total magnetic quantum number) is often used and third component T_z of isospin is also given, choosing proton and neutron numbers. For example, T=1 state can be calculated in the T_z=1 space. This is, however, no longer valid in the case of isospin non-conserving interactions and computational problem arises in solving eigen-states for approximated isospin $T \gg 1$ (This isospin is quite near T=1 but is not exact T=1!). It is, therefore, necessary to handle these analogue states in T_z =0 space, not in T_z =1 space because T_z=0 space contains T=0,1… These analogue states are central quantities to understand the isospin-symmetry breaking while they cannot be solved by widely used large-scale shell model codes due to limitation of the Lanczos method because these analogue states become highly excited state in T_z =0 space. To obtain MED, CED and TED, a new method is clearly needed beyond the Lanczos method.

We have proposed a new shell model method [3,4] based on the SS (Sakurai-Sugiura) method [5] where *large-scale shell model diagonalization can be solved by the help of the Cauchy integral on complex number plane*. To obtain $T \gg 1$ states, approximated state with definite isospin T=1 can be well utilized in the SS method [1,3]. Therefore, we can solve these analogue states quite easily although these analogue states are highly excited states in the T_z =0 space. In our presentation, we will show how to solve these analogue states by this new method in details, in addition to the nature of isospin symmetry breaking for mass 60-70 regions.

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Energy-dependence of skin-mode fraction in E1 excitations of neutron-rich nuclei

H. Nakada, T. Inakura, H. Sawai

Dept. of Physics, Chiba Univ.,Chiba 263-8522, JAPAN

By recent experiments, sizable E1 strengths have been observed at low excitation energy in a number of N>Z nuclei, and are often called pygmy dipole resonance (PDR). However, their character has not yet been established. Although oscillation of the neutron skin against the core (skin mode) has been argued in connection to the PDR, there remain other possibilities, e.g. fragmentation of the proton-neutron oscillation (pn mode). As low-energy E1 strengths may greatly influence (n,γ) reaction rates under astrophysical environment, it is significant to comprehend their character and thereby their energy- and nucleus-dependence. Moreover, the skin-mode strengths could be correlated to the slope parameter of the nuclear symmetry energy L, which attracts interest in relevance to structure of neutron stars.

We have investigated character of the low-energy E1 excitations by analyzing transition densities obtained from the HF+RPA calculations in the doubly-magic nuclei [1]. We propose a decomposition method of the E1 excitations into the pn mode and the skin mode via the transition densities, by which their mixing is handled in a straightforward manner. Crossover behavior of the E1 excitations is found, from the skin mode at low energy to the pn mode at higher energy. The ratio of the skin-mode strength to the full strength turns out to be a generic function of the excitation energy, insensitive to nuclide and to effective interactions in the energy region of the crossover. Depending on the excitation energy, the observed low-energy E1 excitations are not necessarily dominated by the skin mode, as exemplified for ^{90}Zr. Furthermore, owing to the generic nature of the skin-mode fraction, we may extract skin-mode strengths from the measured E1 strengths.

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Pygmy Dipole Resonance observed in (p,p'γ) and (d,pγ) experiments with SONIC@HORUS

S. G. Pickstone, V. Derya, A. Hennig, J. Mayer, M. Spieker,
M. Weinert, J. Wilhelmy, and A. Zilges

Institute for Nuclear Physics, University of Cologne, 50937 Cologne, Germany

Last year, the new silicon-detector array SONIC with 8 ΔE-E-telescopes was installed inside the existing γ-ray spectrometer HORUS consisting of 14 HPGe detectors. The combined setup SONIC@HORUS allows for a coincident detection of γ-rays and light particles from inelastic scattering and transfer reactions.

As a first physics case, the Pygmy Dipole Resonance in ^{92}Mo has been investigated by means of a (p,p'γ) experiment at E_p=10.4 MeV. Since a specific excitation energy can be chosen offline in the coincidence data, weak decay branchings of PDR states have been observed. Preliminary results of the decay behaviour of PDR states in ^{92}Mo will be shown.

Additionally, a second reaction mechanism for the excitation of the PDR states has been tested with the new setup. In a ^{119}Sn(d,pγ) transfer reaction at E_d=8.5 MeV, PDR states in ^{120}Sn could be excited. Since this one-neutron transfer is rather selective, it could reveal new information on the microscopic structure of the PDR. Preliminary results from this experiment will be presented.

T=0 and T=1 bands in N=Z odd-odd nucleus ^{62}Ga

R. Sahu[1], V.K.B. Kota[2] and P.C. Srivastava[3]

[1]*Physics Department, Berhampur **University,** Berhampur-760007, Odisha, India*
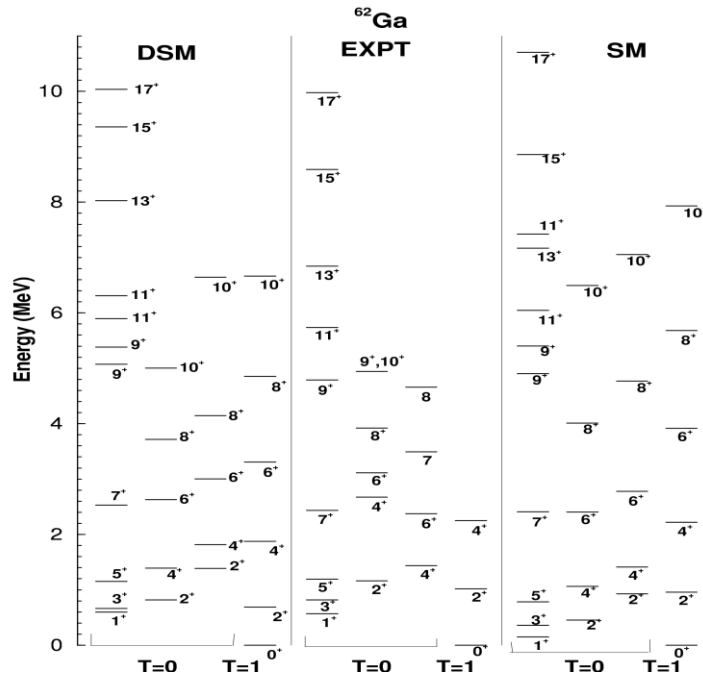[2]*Physical Research Laboratory, Ahmedabad-380009, India*
[3]*Department of Physics, Indian Institute of Technology, Roorkee-247667, India*

In the last few years, study of the structure of heavy (A>44) odd-odd N=Z nuclei has become an area of active research as these nuclei are expected to give new insights into neutron-proton (np) correlations that are unknown. They are also important for understanding rp-process nucleosynthesis. The recent experimental data for ^{62}Ga are from ref. [1].

Recently, we have developed the Deformed Shell Model based on HF single particle states with isospin projection [2] to study the T=0 and T=1 bands in ^{62}Ga and ^{66}As and T=0 and T=1 bands in ^{46}V and ^{50}Mn. Our calculation reproduced the low lying spectra of these nuclei quite well. Our results for ^{62}Ga were similar to the results obtained within the shell model and IBM-4 model. However, we restricted to low lying states in these calculations. David et al. [1] have recently identified many T=0 levels for **^{62}Ga** up to spin J=17^{+}. New shell model results are also not available for this nucleus. In view of the accumulation of wealth of data for this nucleus, we felt it necessary to revisit this nucleus.

The details of the model have been discussed in [2]. We have taken jj44b [3] as the effective interaction with ^{56}Ni as the core and 1p3/2, 0f5/2, 1p1/2 and 0g9/2 as the basis space. We have also performed the spherical shell model with the above effective interaction for comparison. The results are shown in figure. The agreement is quite satisfactory. We find

that 13^{+}, 15^{+} and 17^{+} levels originate from the configuration obtained by excitation to g9/2 orbital. We are calculating energy levels of ^{66}As for which detailed experimental data are recently available [4]. We will present results for both the nuclei.

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[4] P. Ruotsalainen et al., Phys. Rev. C88, 024320 (2013)

Photon strength functions in [177]Lu: Study of scissors resonance in high-spin region

S. Valenta[1], I. Tomandl[2], M. Krtička[1], F. Bečvář[1]

[1]*Charles University, Faculty of Mathematics and Physics , 180 00 Prague, Czech Republic*
[2]*Nuclear Physics Institute, 250 68 Řež, Czech Republic*

Thanks the high spin of thermal neutron capturing state of [176]Lu (13/2) and two low-lying high-spin rotational bands with opposite parity in the level scheme of the well-deformed ^{177}Lu nucleus, the thermal neutron capture on [176]Lu is an ideal tool for the investigation of the photon strength functions (PSFs), especially the scissors mode, in the high-spin region. We utilized the two-step cascade method [1] for the study of PSFs in [177]Lu. The thermal neutron capture experiment on a natural Lu target was performed at the γ-γ coincidence facility installed at the LVR-15 research reactor in Řež [2]. The two-step cascade population of seven low-lying levels was analyzed to obtain information on PSFs, especially on parameters of the scissors mode. The results of this analysis will be reported.

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Neutrinoless double beta nuclear matrix elements around mass 80 in the nuclear shell model

N. Yoshinaga[1], K. Higashiyama[2], D. Taguchi[1], and E. Teruya[1]

[1]*Department of Physics, Saitama University, Saitama City 338-8570, Japan*
[2]*Department of Physics, Chiba Institute of Technology, Narashino, Chiba 275-0023, Japan*

The double-β decay is a second order process of the weak interaction which converts two neutrons into two protons. There are possibly two modes of double-β decay. The 2ν mode ($2\nu\beta\beta$) is characterized by the additional emission of two electrons and two electron antineutrinos, and is expected within the Standard Model. At present, it has been experimentally observed in 10 nuclei. It is well known that the description of the nuclear matrix elements for this mode provides severe test of the nuclear wave functions. The 0ν mode ($0\nu\beta\beta$) involves the emission of two electrons and no neutrinos, and violates lepton-number conservation. The 0ν mode can only take place if the neutrino is a massive Majorana particle. Thus, the observation of the $0\nu\beta\beta$ is considered as one of the most sensitive probes of physics beyond the Standard Model.

Mainly three methods have been utilized so far to evaluate the nuclear matrix elements for the $0\nu\beta\beta$, the shell model in its original version [1] and in very recent large scale versions [2], and the quasiparticle random-phase approximation in its early form [3,4] and in the microscopic interacting boson model [5]. Unfortunately there still remain large discrepancies in estimating those nuclear matrix elements in various methods.

In this presentation, we estimate the nuclear matrix elements for the $0\nu\beta\beta$ in ^{76}Ge and ^{82}Se in terms of the nuclear shell model [6]. Our approach is different from other approaches in the respect that we obtain energy levels of excited states in addition to the ground state by adjusting the shell model Hamiltonian to the experimental energy levels in the mass around 80 region. Using the ground state wavefunctions, we estimate three types of matrix elements, i.e., Fermi, Gamow-Teller, and Tensor matrix elements [7] and compared to other predictions. The theoretical results will be presented and discussed in this conference.

[1] W. C. Haxton and G. J. Stephenson Jr., Prog. Part. Nucl. Phys. **12**, 409 (1984).
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Posters: Nuclear Reactions

Investigation of the ^{90}Zr(p,γ) reaction with in-beam γ-ray spectroscopy

Philipp Erbacher[1], Jan Glorius[1], Lars Netterdon[2], Anne Endres[1], Kerstin Sonnabend[1], Benedikt Thomas[1], Andreas Zilges[2]

[1]*Institut für Angewandte Physik, Goethe Universität Frankfurt, D-60438 Frankfurt a.M., Germany*
[2]*Institut für Kernphysik, Universität zu Köln, D-50937 Köln, Germany*

The *p* nucleus ^{92}Mo is believed to be mainly produced through photodisintegration reactions in type II supernovae. This production scenario however cannot solely account for the observed solar abundance of ^{92}Mo. Additional production scenarios have been suggested to explain this discrepancy.

One of these scenarios could be the production of ^{92}Mo in type Ia supernovae through a chain of proton-capture reactions. To verify this scenario, an accurate knowledge of the involved reaction rates is important. For this reason, we measured the ^{90}Zr(p,γ) reaction using an enriched ^{90}Zr target with in-beam high-resolution γ ray spectroscopy in the energy range from 3.6 MeV to 5.1 MeV. The measurements took place at the Horus-Spectrometer in Cologne. Besides the total cross section, various partial cross sections were obtained. The current status of the analysis will be presented.

The effect of the nuclear Coulomb field on atomic ionization at positron-electron annihilation in β+ decay

S.N. Fedotkin

Institute for Nuclear Research, Kiev, Ukraine

It is considered the process of annihilation of positron emitted at β^+- decay and K-electron of daughter's atom. A part of energy during this process is passed to other K-electron or to s-electrons from upper shells. As result this electron leaves atom. At calculation of probability of this process for the atomic electron are used hydrogen like wave functions. Nuclear charge screening is essential for the electrons of external shells. This screening is taken in to account by use the Sleter approach.

The parameter $Z\alpha c/\upsilon$ can be much bigger than 1 at very small velocity of the ejected electron υ and Born approximation becomes in this case incorrect (here Z is a nuclear charge, α is the fine structure constant, c is a light speed). Because of this in contrast to paper [1] the electron which leaves atom is described by the wave function of continuum spectra in Coulomb field. Besides instead of free particle Green function is used Green function for electron in a Coulomb field.

General expression for the probabilities of this processes are received for the atom with arbitrary Z. The use of wave function of continuum spectra in Coulomb field instead of plane wave approximation reduces probability of this process in a case of β^+-decay of ^{45}Ti in several times. But use of the Green function for electron in a Coulomb field gives opposite effect and probability of ionization of atom increases. Finally we have the following estimates for the ratio of probabilities of considered processes

$$W_{\beta^+K,K}^{coul}\big/W_{\beta^+}^{coul} \approx 3\,W_{\beta^+K,K}\big/W_{\beta^+} \approx 1.8\cdot 10^{-5},$$

where $W_{\beta^+K,K}^{coul}$, $W_{\beta^+K,K}$ are correspondingly probabilities of K- electron positron annihilation and following other K-electron knockout with and without Coulomb field accounting and $W_{\beta^+}^{coul}, W_{\beta^+}$ are analogous values for probabilities of usual β^+-decay. Thereby taking into account the Coulomb field influence is important as for calculations of probabilities of β^+-decay and of β^+-decay with following atomic ionization at positron annihilation so for the ratios of these probabilities.

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Measurement of ^{nat}Ag(γ,xn) reaction cross-sections with bremsstrahlung energies of 45, 50, 55, and 60 MeV

M. Zaman[1], G.N. Kim[1], K. Kim[1], M. Shahid[1], S.C. Yang[1], S-G. Shin[2], M-H. Cho[2], H. Naik[1,3]

[1]*Department of Physics, Kyungpook National University, Daegu 702-701, Republic of Korea*
[2]*Division of Advanced nuclear Engineering, Pohang University of Science and Technolohy, Pohang 790-784, Republic of Korea*
[3]*Radiochemistry Division, Bhabha Atomic Research Center, Mumbai 400085, India*

The cross-sections for ^{nat}Ag(γ,xn) reactions with bremsstrahlung end-point energies of 45, 50, 55, and 60 MeV have been determined by an activation and an off-line γ-ray spectrometric techniques using the electron linear accelerator in Pohang accelerator laboratory. The photon-induced reaction cross-sections of ^{nat}Ag as a function of photon energ were calculated using the TALYS 1.4. The flux-weighted average cross-sections were obtained from the existing experimental data and the theoretical values of the TALYS 1.4 with the mono-energetic photons. The present results are compared with the flux-weighted average values from the literature and those from the TALYS 1.4. It was shown that the ^{nat}Ag(γ, xn) reaction cross-sections increase sharply from their threshold values to certain energies, where other reaction channels opens. Then it remains constant a while, where the next reaction channel increases. There after it decrease slowly with increase of bremsstrahlung energy due to opening of different reaction channels.

Theoretical study of projectile fragmentations in relativistic heavy-ion reactions

R. Ogul[1], H Imal[1], A Ergun[1], N. Buyukcizmeci[1], A. Botvina[2,3], W. Trautmann[4]

[1]*Department of Physics, Selcuk University, 42079 Kampus, Konya, Turkey*
[2]*Institute for Nuclear Research, Russian Academy of Sciences, RU-117312 Moscow, Russia*
[3]*Frankfurt Institute for Advanced Studies, J. W. Goethe University, D-60438 Frankfurt am Main, GermanyGSI*
[4]*Helmholtzzentrum für Schwerionenforschung GmbH, D-64291 Darmstadt, Germany}*

Abstract. We have investigated and interpreted the production cross sections and isotopic distributions of projectile-like residues in the reactions ^{112}Sn + ^{112}Sn and ^{124}Sn + ^{124}Sn at an incident beam energy of 1 GeV/nucleon measured with the FRS fragment separator at the GSI laboratory [1]. For the interpretation of the data, calculations within the statistical multifragmentation model (SMM) for an ensemble of excited sources were performed with ensemble parameters determined previously for similar reactions at 600 MeV/nucleon [2]. The possible modification of symmetry energy parameter, in the multifragmentation region at the low density and hot freeze-out environment, is studied. It is reconfirmed that a significant reduction of the symmetry energy term is found necessary to reproduce experimental results at these conditions. We have also found a decreasing trend of the symmetry energy for large neutron-rich fragments of low excitation energy which is interpreted as a nuclear-structure effect.

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Influence of electronic environment on capture reaction rates

Jelena Vesić[1], Matej Lipoglavšek[1], Toni Petrovič[1,2], Aleksandra Cvetinović[1], Andrej Likar[1,3]

[1]*Jožef Stefan* Institute, Jamova cesta 39, 1000 Ljubljana, Slovenia
[2]*Cosylab d.o.o., Teslova ulica 30, 1000, Ljubljana, Slovenia*
[3]*Faculty of Mathematics and Physics, Jadranska 19, Ljubljana, Slovenia*

The nuclear reaction rates drop rapidly with decreasing beam energy thus making the cross section measurements difficult at low energies [1]. The probability for tunnelling through the Coulomb barrier depends on its height exponentially and even small changes to the barrier caused by electrons surrounding the reactants in laboratory experiments have a significant effect on the cross section. As a result, the measured reaction rates are enhanced compared to reaction rates for bare nuclei. Experimental studies of various nuclear reactions in metallic environments have shown the expected cross section enhancement at low energies [2-4]. However, the enhancements in metallic targets were significantly larger than expected from the adiabatic limit which is thought to provide the theoretical maximum for the magnitude of electron screening. The discrepancy between the measurement and the adiabatic limit is presently not understood under laboratory conditions, therefore the size of electron screening has to be measured for each metallic environment and each target separately. An additional problem is that a cloud of free electrons around the nucleus screens its charge also in stellar plasmas. Since screening in plasma is different from screening in laboratory, it is of significant importance to measure bare cross sections as well as possible to determine cross sections needed for precise determination of thermonuclear reaction rates. A good understanding of electron screening effects in laboratory is therefore needed to arrive at reliable cross section data at low energies.

To further investigate electron screening in laboratory for nuclear reactions involving low Z targets, the ^{1}H(^{7}Li,α)^{4}He reaction was studied in inverse kinematics at lithium beam energies from 0.4 to 2.1 MeV in different metallic environments, namely hydrogen implanted Pd, Pt, Zn and Ni targets. Large electron screening of a few keV was observed for all studied targets. These results motivated us to continue our experimental campaign with measurements of electron screening potentials in proton induced reactions on high Z targets. However, surprisingly no large electron screening was observed in the following proton capture reactions: ^{55}Mn(p,γ)^{56}Fe, ^{51}V(p,γ)^{52}Cr and charge exchange reactions: ^{55}Mn(p,n)^{55}Fe, ^{113}Cd(p,n)^{113}In, ^{115}In(p,n)^{115}Sn, ^{50}V(p,n)^{50}Cr. Furthermore, no shift in resonance energy for metallic relative to insulator environment was observed for the studied (p,n) and (p,γ) reactions. These results pose a question on the validity of the measurements that showed large electron screening potentials in nuclear reactions involving high Z targets [5] and might imply a dependence of the electron screening on the position of the target nuclei in a metallic lattice.

[1] H. J. Assenbaum, K. Langanke and C. Rolfs, Z. Phys. **A327**, 461 (1987).
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[5] K. U. Kettner et al., J. Phys. G **32**, 489 (2006).

Posters: Nuclear Astrophysics

Felsenkeller shallow-underground accelerator laboratory for nuclear astrophysics

Daniel Bemmerer[1] and Kai Zuber[2]

[1] Helmholtz-Zentrum-Dresden-Rossendorf, Dresden, Germany
[2] Technische Universität Dresden, Dresden, Germany

Favored by the low background in underground laboratories, low-background accelerator-based experiments are an important tool to study nuclear reactions involving stable charged particles. This technique has been used for many years with great success at the 0.4 MV LUNA accelerator in the Gran Sasso laboratory in Italy, proteced from cosmic rays by 1400 m of rock [1]. However, the nuclear reactions of helium and carbon burning and the neutron source reactions for the astrophysical s-process require higher beam energies than those available at LUNA. Also the study of solar fusion reactions necessitates new data at higher energies. As a result, in the present NuPECC long range plan for nuclear physics in Europe, the installation of one or more higher-energy underground accelerators is strongly recommended.

An intercomparison exercise using the same HPGe detector at several sites has shown that with a combination of 45 m rock overburden, as can be found in the Felsenkeller underground site in Dresden, and an active veto against the remaining muon flux, in a typical nuclear astrophysics setup a background level can be achieved that is similar to the deep underground scenario [2].

Based on this finding, a used 5 MV pelletron tandem with 250 µA upcharge current and external sputter ion source has been obtained and transported to Dresden. Work on an additional radio-frequency ion source on the high voltage terminal is underway. The project is now fully funded. The installation of the accelerator in the Felsenkeller is expected for the near future. The status of the project and the planned access possibilities for external users will be reported.

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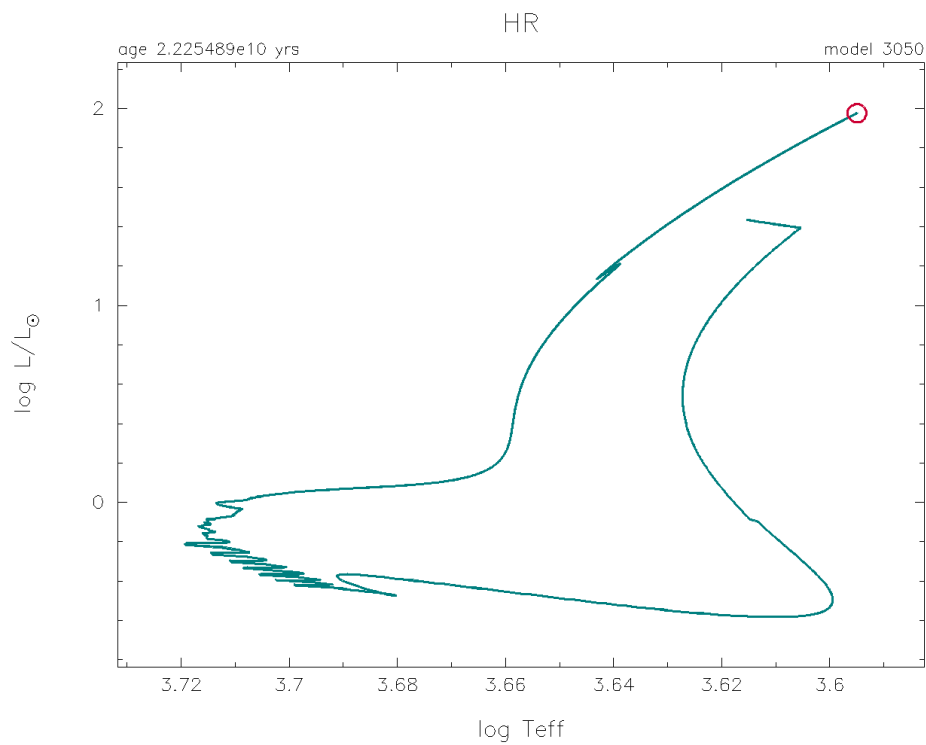[2]   T. Szücs et al., Eur. Phys. J. A 48, 8 (2012).

MODELING THE EVOLUTION OF A HIGH-METALLICITY STAR WITH MESA

E.F. Jones and P.M. Gore

FM Research Professionals, P.O. Box 58412, Nashville, TN 37205 USA

Using MESA star [1], the one-dimensional stellar evolution program of Modules for Experiments in Stellar Astrophysics, we examined the case of the evolution of a high-metallicity one-solar-mass star. Previous studies [2] have shown that, in the cases of solar and twice solar metallicity, there is a slow blue phase beginning with the helium shell-burning phase. With three times solar metallicity, the slow blue phase begins during the helium core-burning phase, which is earlier than the other cases, so that the results differ between higher and lower metallicities in this earlier work.

Shown below is a graph of our results using Mesa star module of a one solar mass star with metallicity 0.0488:

[1] Bill Paxton et al., ApJS 192 (no.1) 3 (2011).
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S-Factor measurement of the ^{12}C(p,γ)^{13}N reaction in inverse kinematics

T. P. Reinhardt[1], K.Stöckel[2], S. Akhmadaliev[2], D. Bemmerer[2], St. Gohl[2,1], S. Reinicke[2,1], K. Schmidt[2,1], M. Serfling[2,1], T. Szücs[2], M. P. Takács[2,1] and L. Wagner[2]

[1]Technische Universität Dresden, 01069 Dresden, Germany
[2]Helmholtz-Zentrum Dresden-Rossendorf, 01328 Dresden, Germany

The ^{12}C(p,γ)^{13}N is the second slowest reaction in the CNO cycle. Hence, it determines the reaction rate in the outer parts of the solar core, where due to the lower temperature the CNO cycle has not yet reached its equilibrium [1].

The last comprehensive study of the ^{12}C(p,γ)^{13}N reaction dates back to the 1970s [2]. Recent data concentrate on $E_{CM} \geq 300$ keV [3].

The reaction was studied using ^{12}C beam at the HZDR 3 MV Tandetron, hydrogen implanted targets and a lead shielded 60% HPGe detector at an angle of 55° with respect to the beam axis. Hydrogen depth profiling with a ^{15}N beam was used for the determination of the target characterisitics.

Details of the experiment and preliminary results will be presented.

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The ^{40}Ca(α,γ)^{44}Ti reaction studied by in-beam γ-spectroscopy and activation

Konrad Schmidt[1,2], Shavkat Akhmadaliev[1], Michael Anders[1,2], Daniel Bemmerer[1], Konstanze Boretzky[3], Antonio Caciolli[4], Mirco Dietz[1,2], Zoltán Elekes[1], Zsolt Fülöp[5], György Gyürky[5], Roland Hannaske[1,2], Arnd R. Junghans[1], Michele Marta[1,3], Marie-Luise Menzel[1,2], Ronald Schwengner[1], Tamás Szücs[5], Andreas Wagner[1], Louis Wagner[1,2], Dmitry Yakorev[1], and Kai Zuber[2]

[1] *Helmholtz-Zentrum Dresden-Rossendorf (HZDR), Institute of Radiation Physics, Dresden, Germany*
[2] *TU Dresden, Institute of Nuclear and Particle Physics, Dresden, Germany*
[3] *GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany*
[4] *Istituto Nazionale di Fisica Nucleare (INFN), Padova, Italy*
[5] *Institute of Nuclear Research of the Hungarian Academy of Sciences (ATOMKI), Debrecen, Hungary*

The radioactive nuclide ^{44}Ti is believed to be produced in the alpha-rich freezeout preceding supernova explosions. The γ-rays from its decay have been observed in space-based γ-observatories for the Cassiopeia A and recently also SN 1987A supernova remnants [1]. The rates of the nuclear reactions governing the production and destruction of ^{44}Ti should therefore be known with high precision [2]. Over the last years there have been various studies of the ^{40}Ca(α,γ)^{44}Ti reaction, which is dominating the ^{44}Ti production in supernovae.

Using the α-beam of the 3.3 MV Tandetron at Dresden, the strengths of ^{40}Ca(α,γ)^{44}Ti resonance triplet at 4.5 MeV laboratory alpha-energy has been studied by in-beam gamma-spectroscopy and activation [3]. In addition, preliminary results of resonance strengths between 3.5 and 3.8 MeV will be presented.

The irradiated samples have been analyzed in the underground laboratory Dresden Felsenkeller. The target stoichiometry has been determined by nuclear reactions and by elastic recoil detection analysis (ERDA), whereby the strength of the $E_p = 1.842$MeV resonance in the ^{40}Ca(p,γ)^{41}Sc reaction could be restudied [4].

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Determination of level widths in ^{15}N using nuclear resonance fluorescence

T. Szücs[1,2], D. Bemmerer[1], A. Caciolli[3], Zs. Fülöp[2], R. Massarczyk[1,4], C. Michelagnoli[5], T. P. Reinhardt[4], R. Schwengner[1], M. P. Takács[1,4], C. A. Ur[6], A. Wagner[1], L. Wagner[1,4]

[1] *Helmholtz-Zentrum Dresden-Rossendorf (HZDR), Dresden, Germany*
[2] *Institute for Nuclear Research (MTA Atomki), Debrecen, Hungary*
[3] *INFN Sezione di Padova, Padova, Italy*
[4] *Technische Universität Dresden, Dresden, Germany*
[5] *Grand Accélérateur National d'Ions Lourds (GANIL), Caen, France*
[6] *Extreme Light Infrastructure - Nuclear Physics (ELI-NP), Magurele, Romania*

The stable nucleus ^{15}N is the mirror of the astrophysically important ^{15}O, the product of the slowest reaction in the hydrogen burning CNO cycle, which therefore determine the production rate of the cycle.

Most of the ^{15}N level widths below the nucleon emission thresholds are known from just one nuclear resonance fluorescence (NRF) measurement published more than 30 years ago, with limited precision in some cases [1]. A recent experiment with the AGATA demonstrator array aimed to determine level widths using the Doppler Shift Attenuation Method (DSAM) in ^{15}O and ^{15}N populated in the ^{14}N + ^{2}H reaction. In order to set a benchmark value for the upcoming AGATA demonstrator data, the widths of several ^{15}N levels have been studied with high precision using the bremsstrahlung facility γELBE [2] at the electron accelerator of Helmholtz-Zentrum Dresden-Rossendorf (HZDR). The precision of our new dataset are on a 10% level for the weak transitions, which have 60% and 100% error bars in the old dataset. The preliminary data seem to confirm the earlier NRF data.

[1] R. Moreh *et al.*, Phys. Rev. C **23**, 988 (1981).
[2] R. Schwengner *et al.*, Nucl. Inst. Meth. A **555**, 211 (2005).

Solar ^{7}Be and ^{8}B neutrino fluxes, the ^{3}He(α,γ)^{7}Be reaction rate, and the production of ^{7}Li during the Big Bang

M.P. Takács[1,2], D. Bemmerer[1], K. Zuber[2]

[1] *Helmholtz-Zentrum Dresden-Rossendorf, Dresden, Germany*
[2] *Technische Universität Dresden, Dresden, Germany*

The ^{3}He(α,γ)^{7}Be reaction plays an important role both in determining the predicted fluxes of ^{7}Be and ^{8}B neutrinos from our Sun, and in the calculation of primordial ^{7}Li production. In light of the highly precise determination of the baryon-to-photon ratio from the cosmic microwave background data [1], it is necessary to re-determine primordial ^{7}Li production.

Recent experimental nuclear astrophysics work has led to an improved determination of the ^{3}He(α,γ)^{7}Be cross section, with several experiments clustered at $E = 0.5$ MeV center-of-mass energy and above [2, and references therein]. On the other hand, precisely calibrated ^{7}Be and ^{8}B neutrino fluxes from the Sun are now available [3, 4]. Assuming the accepted solar central temperature to be correct, the neutrino flux data can be used to determine the ^{3}He(α,γ)^{7}Be cross section [5] at the solar Gamow peak, $E = 0.03$ MeV.

The energy range relevant for Big Bang ^{7}Li production lies just between 0.03 and 0.5 MeV. The poster aims to use the two above described levels in order to improve the precision of the predicted primordial abundance of ^{7}Li. It updates a previous work [6] that appeared before the new cross section, solar neutrino and microwave background data were available.

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The ^{14}N(p, γ)^{15}O S factor at 0.4 - 1.5 MeV

<u>L. Wagner</u>[1,2], D. Bemmerer[1], A. Caciolli[4], A. Junghans[1], M. Marta[3], T. P. Reinhardt[2], S. Reinicke[1,2], M. Röder[2], K. Schmidt[1,2], R. Schwengner[1], M. Serfling[1,2], K. Stöckel[1,2], T. Szücs[2], M. P. Takács[1,2], A. Wagner[1] and K. Zuber[2]

[1] *Helmholtz-Zentrum Dresden-Rossendorf (HZDR), Dresden, Germany*
[2] *TU Dresden, Dresden, Germany*
[3] *GSI Helmholtz-Zentrum für Schwerionenforschung, Darmstadt, Germany*
[4] *INFN Sezione di Padova, Padova, Italy*

The ^{14}N(p,γ)^{15}O reaction rate determines the rate of the CNO cycle of hydrogen burning. For a precise cross section extrapolation to low energies one needs accurate knowledge of the excitation function over a wide range of energy. The non-resonant ^{14}N(p,γ)^{15}O cross section was studied at beam energies of 0.4 - 1.5 MeV at the 3 MV Tandetron of Helmholtz-Zentrum Dresden-Rossendorf (HZDR). The preliminary new cross section data will be presented. Combined with data of experiments at other proton energies [1,2] an R-Matrix fit is performed to achieve a more accurate extrapolation to the astro-physically relevant cross section at the Gamow-window of the reaction.

[1] A. Formicola *et al*, Phys. Letters B 591 (2004)
[2] R. C. Runkle *et al*, Phys. Rev. Letters 94, 082503 (2005)

Posters: Nuclear Data & Applications

High-flux PGAA for milligram-weight samples

Z. Révay[1], P. Kudejova[1], K. Kleszcz[1]
C. Genreith[2], M. Rossbach[2],
[1] *Heinz Maier-Leibnitz Zentrum, Technische Universität München, 857 47 Garching, Germany*
[2] *Institute for Energy and Climate Research, IEK-6, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany*

With the high-intensity cold neutron flux available at the Prompt Gamma Activation Analysis (PGAA) instrument [1] of the research reactor Heinz Maier-Leibnitz (FRM II), samples with a weight of 1 mg or even less can be investigated for their elemental compositions using a (n,γ) capture reaction. In that case, the typical sample packing material or sample holder for PGAA made of PTFE can be of order of magnitude higher weight than the sample itself. We measured and analysed few challenging samples like micro-meteorites with the weight of 0.2 – 3 mg [2], 1.2 mg Zircaloy foil doped with190 ppm hydrogen or 2 mg of FePt nanoparticles doped with W.

Another challenge came in a form of a project for validation of thermal neutron capture cross section data of actinides like ^{241}Am, ^{237}Np or ^{242}Pu [3]. Only 30 – 40 µg were available for some isotopes and a proper sample holder had to be invented to pack vacuum-tightly the radioactive material and at the same time produce as low background signal for PGAA measurement as possible.

Examples of diverse measurement, their motivation and results of the analysis will be presented together with the proper choice of the packing material and/or sample holder.

[1] L. Canella, P. Kudejova, R. Schulze, A. Türlel, J. Jolie, Nucl. Instrum. Meth. A 636,108 (2011).

[2] Ted E. Bunch, et al, Proc. Nat. Acad. Sci. 109 (2012) E1903

[3] C. Genreith, M. Rossbach, Z. Révay und P. Kudejova, *Determination of (n,γ) cross sections of 241-Am by PGAA,* Nuclear Data Sheets, accepted in April 2013

Determination of trace concentration in TMD detectors using PGAA

I. Tomandl[1], L. Viererbl[2], P. Kudějová[3], Z. Lahodová[2], V. Klupák[2] , M. Fikrle[1]

[1]*Nuclear Physics Institute, 250 68 Řež, Czech Republic*
[2] *Research Centre Řež, 250 68 Řež, Czech Republic*
[3] *Heinz Maier-Leibnitz Zentrum, TU München, 857 48 Garching, Germany*

The recently proposed transmutation detector (TMD) method could be alternative to traditional   activation detector method for neutron fluence dosimetry at power nuclear reactors [1]. However, this new method requires an isotopically highly-sensitive, non-destructive in sense of compactness as well as isotopic content, precise and standardly used analytical method for trace concentration determination. Prompt Gamma-ray Activation Analysis (PGAA) seems to be a very promising method for this task.

 The capability of PGAA for determination of trace concentrations of transmuted stable nuclides in the metallic foils of Ni, Au, Cu and Nb, which were irradiated for 21 days in the reactor core   at the LVR-15   research reactor in Řež, will be reported.   The PGAA measurements of these activation foils were performed at the PGAA facility at Forschungs-Neutronenquelle Heinz Maier-Leibnitz (FRMII) in Garching [2]. Beside the feasibility of the combination of TMD and PGAA the necessity of the new data on the partial cross sections for transmuted nuclides will be discussed.

[1] L. Viererbl, Z. Lahodová, V. Klupák, F. Sus, J. Kučera, P. Kůs, M. Marek, Nucl. Instrum. Meth. A 632, 209 (2011).

[2] L. Canella, P. Kudějová, R. Schulze, A. Türlel, J. Jolie, Nucl. Instrum. Meth. A 636, 108 (2011).

Experimental Nuclear Reaction Data Library EXFOR - Recent Developments

V. Semkova, N. Otuka, S. Simakov, V. Zerkin

Nuclear Data Section, International Atomic Energy Agency, A-1400 Wien, Austria

The International Network of Nuclear Reaction Data Centres (NRDC) that constitutes of worldwide cooperation of nuclear data centres under the auspices of the International Atomic Energy Agency collaborate in collection, compilation and dissemination of experimental nuclear reaction data in EXFOR data library.

The database contains about 20500 references that report experimental nuclear reaction data. The main goal of the Network is to provide completeness for all data compulsory for compilation including neutron-, charged-particle- and photon- induced reaction data for projectile energies up to 1 GeV and incident projectiles up to A=12. However, data for heavier projectiles and higher energies are compiled in EXFOR on voluntary bases as well. More than 60 journals are scanned on a regular basis and compiled in a timely manner. In parallel completeness of the database is verified by comparison with references included in the comprehensive compilations of specific nuclear reaction data. Such EXFOR completeness checking was recently performed against Mughaghab's "Atlas of Neutron Resonances". The content of the database is also constantly improving following the discussions and recommendations of the experts participating in the meeting organized by IAEA-NDS [1,2].

The scope of the data compiled in EXFOR is revised in order to respond to the new developments / needs of the nuclear science and technology. Recently the NRDC community agree to compile Nuclear Resonance Fluorescence (NRF) data under discussion are compilations of beta-delayed neutron spectra and emission probabilities and consider for future discussions are the compilations of antineutrino spectra etc.

EXFOR database is available online. Users are provided with sophisticated search options and retrieval interface for downloading data in different formats and additional output options such as expensive plotting capabilities.

The paper will present recent EXFOR developments.

[1] F. Gunsing, P. Schillebeeckx, V. Semkova, "EXFOR Data in Resonance Region and Spectrometer's Response Function", INDC(NDS)-0647.

[2] A. Trkov, L.R. Greenwood, S. Simakov, „Testing and Improving the International Reactor Dosimetry and Fusion File (IRDFF)", INDC(NDS)-0639.

Performance Measurements for the Ge tracking array AGATA on the way to Isomeric Ratios

N. Lalovic[1,2], R. Perez[3], C. Louchart-Henning[4]

[1]*Lund University, S-22100 Lund, Sweden*
[2]*GSI Helmholtzzentrum für Schwerionenforschung GmbH, D64291 Darmstadt, Germany*
[3]*Instituto de Fisica Corpuscular, CSIC-Universitat de Valencia, Valencia E-46920, Spain*
[4]*Technische Universität Darmstadt, D-64289 Darmstadt, Germany*

From 2012 to 2014 the pan-European Advanced GAmma-ray Tracking Array (AGATA) is placed at the German accelerator research centre GSI Darmstadt. Within the PreSPEC collaboration, AGATA is used to perform high-resolution γ-ray spectroscopy of relativistic radioactive ions to obtain unique nuclear structure information of exotic nuclei far away from the line of stability.

One of the experiments performed successfully within the PreSPEC-AGATA campaign was the relativistic Coulomb excitation in the vicinity of doubly-magic nucleus ^{208}P. Since almost all nuclei of interest have isomeric states, determining isomeric composition of the beam via isomeric ratios is of great importance. This would then allow for deduction of transition strengths. However, to quantify all aforementioned, the efficiency of our array is needed.

In order to evaluate the performance of AGATA array and compare with Monte-Carlo simulations, a series of gamma-ray source measurements were conducted at GSI.

We present the results of source analysis measurement with 21 AGATA crystals coupled with a single EUROBALL encapsulated detector used as a coincidence trigger. The absolute efficiency and P/T ratio and the effect of tracking in these performance figures will be evaluated. Different sources have been used such as 60-Co, 56-Co, 152-Eu and 166m-Ho.

Simulations of the modified SIMBA array for the determination of Q_β values

N. Warr[1], A. Blazhev[1], K. Moschner[1]

[1]*Institute for Nuclear Physics, University of Cologne, Germany*

In the RIBF83 experiment to measure the N = Z nuclei ^{94}Ag, ^{96}Cd, ^{98}In at RIKEN, projectile fragmentation of 345 MeV/u ^{124}Xe on a ^{9}Be target, followed by the selection of the ions of interest by the BigRIPS fragment separator, was used in the framework of EURICA [1]. The ions were then implanted in the active stopper, *SIMBA*, in which the position of the ions was determined by a thin double-sided 60x40 silicon-strip detector and then the beam was implanted in a stack of three 1-mm thick double-sided 60x40 silicon-strip detectors. A stack of twenty additional 1-mm thick single-sided 7x1 silicon-strip detectors was used to perform beta calorimetry. Gamma rays were detected by 12 Euroball clusters, giving a total of about 9 % efficiency at 1.3 MeV.

A primary focus of this experiment was the decays of the metastable states in ^{94}Ag, especially the exotic one- and two-proton decay channels of the (21$^+$) isomer. For such odd-odd N = Z nuclei, there is the possibility of super-allowed Fermi β transitions, which are an important test of the weak interaction. There are also additional strong Gamow-Teller decay channels. Thus, besides decay half-lives, a key goal for this experiment was to determine the Fermi and Gamow-Teller strengths, for which Q_β values are needed. In this region, close to the proton dripline, some very high Q_β values (> about 10 MeV) are expected, meaning that the energy of the β particles is not always detected.

Thus, in order to extract reliable Q_β values from the experimental data, it is crucial to determine the instrument response of *SIMBA* as a function of the beta end-point energy. To do this, detailed Geant4 calculations have been performed. Although a previous configuration of *SIMBA* used at GSI Darmstadt has already been simulated, it was not possible to adapt this code to the new configuration, so a new code based on Geant4 was written from scratch.

This contribution will report on these simulations, which includes a detailed simulation of the silicon detectors and their support structures and housing, as well as the Euroball clusters. A comparison of these simulations with the experimental data will provide the Fermi and Gamow-Teller strengths [2]. These simulations will also be required for the analysis of other data from the same campaign, such as ^{96}Cd.

[1] P.-A. Söderström *et al.*, Nucl. Instr. Meth. B 317, 649-652 (2013).
[2] K. Moschner *et al.*, abstract submitted to CGS15.