Nuclear Physics

The activities of the Nuclear Physics Department during the year 2000 concentrated on the following topics:

- *The design of the Bremsstrahlung facility at the ELBE accelerator with the aim to provide us an optimized source for intense polarized gamma radiation in an envisaged energy range up to 20 MeV was completed. Particular attention was paid to achieve a low background level of scattered photons and neutrons in the experimental cave. The electron beamline in the accelerator hall including the radiator target chamber and the electron beam dump as well as the aluminum collimator with an optional photon beam hardener is now under construction.*

- *In preparing future photon scattering studies at ELBE we performed an experiment at the Bremsstrahlung beam of the Dynamitron at Stuttgart in collaboration with the groups at the Universities of Stuttgart and Köln. In this experiment the semi-magic nucleus ^{87}Rb was investigated for the first time to find indications whether the N=50 neutron core excitations can contribute to the dipole states observed in photon scattering.*

- *The extensive data taken in an EUROBALL experiment of our group in Legnaro have been analysed and evaluated. Interesting new features concerning high spin structures of the N≈Z unstable nuclei produced by the ^{40}Ca+^{40}Ca reaction were found. For instance, rotational bands identified in ^{72}Br up to high spin values manifest a striking case of signature inversion. According to the applied Nilsson-Strutinsky model this observation provides evidence for a triaxial shape of this nucleus which continuously changes with spin. In the neighboring isotope ^{73}Br rotational structures were measured which persist to the extremely high spin value I=65/2$\hbar$. The theoretical analysis has shown that one of those bands is observed up to its limiting spin where all particles of a given configuration have fully aligned their angular momenta along the nuclear symmetry axis. This is the first case of a so-called band termination in the mass region around A=80.*

- *In collaboration with the ISOL group at the GSI Darmstadt the nuclei ^{52}Fe and ^{93}Pd were studied. The detailed properties of these very neutron deficient nuclei are important for the understanding of the nucleosynthesis in rp-processes.*

- *Concerning the progress in nuclear structure theory further developments of the 3-dimensional cranking model were made to describe the chiral rotation which incorporates the highest degree of symmetry breaking occurring for the spin orientation. In fact, according to the latest experimental findings there exists an island of odd-odd isotones with N=75 around ^{134}Pr where this peculiar type of rotation shows up through the predicted signature of parallel sister bands.*

- *The integration method developed to calculate the RPA correlation energy was applied for realistic systems. These results demonstrate that quantal vibrations may considerably influence the rotational properties. Remarkably, these effects are sensitive against the specific features of the effective interaction.*

A special highlight in the year 2000 was the Workshop on Nuclear Spectroscopy and Nuclear Astrophysics held at the FZ Rossendorf from April 27 to April 29. The emphasis *of this international meeting was put on medium mass nuclei and its main goal was to discuss the new experimental possibilities for exploring nuclear structure at the limits of stability using the more intense radioactive beams being available soon. Another focus concerned the experimental nuclear physics program at the Bremsstrahlung facility of the ELBE accelerator.*

The financial support from the Federal Ministry of Education and Research (BMBF) and the Saxon State Ministry for Science and Art (SMWK) enabled us to invite the international experts to our meeting.

Collaborations

We were benefiting from the successful and permanent cooperation with the spectroscopy groups from the German universities at Stuttgart, Köln, Göttingen and Darmstadt as well as with ISOL group of the GSI Darmstadt. We acknowledge also the fruitful cooperation with the Italian colleagues which were experimenting with us at the EUROBALL Legnaro, the colleagues from the Sofia University and University of Leuven. We are also grateful to the theoretical support from our colleagues at the University of Tennessee, and Notre Dame University, both in the US.

Chiral Symmetry in Nuclear Rotation

F. DÖNAU, JING-YE ZHANG[1], S. FRAUENDORF[2], V.I. DIMITROV[3]

Recently, in rotating nuclei a new type of symmetry breaking [1,2] was predicted which is called chiral symmetry breaking. This phenomenon appears in triaxially deformed nuclei if the direction of total angular momentum (a.m.) vector $\vec{J}$ is outside all the three principal planes spanned by the intrinsic axes of the nuclear density distribution. The different principal axes form under those conditions either a left-handed or a right-handed intrinsic system with respect to the space-fixed vector $\vec{J}$ which realizes two chiral symmetry types. In the ideal case two degenerate rotational bands appear corresponding to the chirally symmetric or antisymmetric intrinsic configuration with respect to the chiral operation $\chi = \mathcal{T} R_y(\pi)$ in which the rotation $R_y(\pi)$ about the space-fixed y-axis is combined with time reversal operation $\mathcal{T}$. Following the common phase conventions of [3] one gets straightforwardly for any tensor operators $Q_{\lambda\mu}$ the invariance property

$$\chi\, Q_{\lambda\mu}\, \chi^{-1} = Q_{\lambda\mu}. \tag{10}$$

The appropriate tool for describing these new features is the 3-dimensional Tilted Axis Cranking (TAC) model which enables us to calculate self-consistently the nuclear shape in conjunction with the off-plane orientation of the total spin which is crucial for obtaining chiral symmetry breaking. The 3d-TAC mean field Hamiltonian reads

$$\begin{aligned} h'_\omega(\beta,\gamma) \;=\; & h_o - \hbar\omega_\circ\beta\,(\, cos\gamma\, Q'_0 \;+\; sin\gamma\,(Q'_2 + Q'_{-2})/\sqrt{2}\,) \\ & - \omega\,(sin\vartheta cos\varphi\, I_1 \;+\; sin\vartheta sin\varphi\, I_2 \;+\; cos\vartheta\, I_3\,) \end{aligned} \tag{11}$$

where ω is the rotational frequency, $Q'_{0,\pm 2}$ and $I_{1,2,3}$ denote the body-fixed components of the intrinsic quadrupole operator and a.m.vector, respectively. The angles (ϑ, ϕ) define the selfconsistent a.m.direction i.e. a minimum in the corresponding potential energy surface. The chiral symmetry breaking appears for $0 < \vartheta, \phi < \pi/2$ which can only happen for a triaxial shape. In fig.1 such a situation is shown as calculated for the nucleus ^{134}Pr at the frequency $\hbar\omega = 0.35$ MeV.

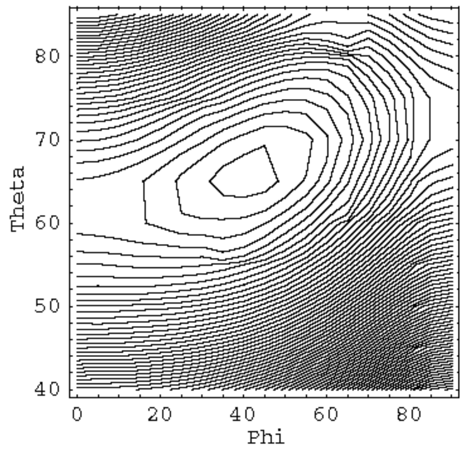

Fig. 1 *Potential energy surface $E(\vartheta, \phi)$ for ^{134}Pm which has a triaxial shape with $\gamma \approx 30^o$.*

In such a 3d-case the eigenfunctions $|\vartheta, \phi>$ of $h'_\omega(\beta,\gamma)$ become complex. The matrix elements of electromagnetic transitions can be calculated by projecting the wave function onto good chirality using the the relation

$$|\pm> = \frac{1}{\sqrt{2}}\,(1\,\pm\,\chi)\,|\vartheta,\phi> \;. \tag{12}$$

The label $\pm$ distinguishes the different chiral branches of the rotational $\Delta I = 1$ bands. Evaluating the matrix elements of an electromagnetic operator $M(\lambda, \mu)$ by means of eq.(1) and for the complex TAC eigenstates one derives

$$< \pm|M(\lambda,\mu)|\pm > = \Re e(< \vartheta,\phi|M(\lambda,\mu)|\vartheta,\phi >), \tag{13}$$

$$< \pm|M(\lambda,\mu)|\mp > = \Im m(< \vartheta,\phi|M(\lambda,\mu),|\vartheta,\phi >) \tag{14}$$

Hence, the transition amplitudes within a given chiral branch (+ or -) and in between different branches can be expressed by the real and imaginary part of the complex matrix element. One should mention, however, that these simple relations are valid only when neglecting the possible overlap between chirally reflected states, i.e. $< \vartheta,\phi|\vartheta,-\phi >= 0$.
Experimental band structures measured in the isotonic chain at N=75 are shown in fig. 2 which are suggested to be candidates for chiral doublets $|\pm >$. The lowest pair of positive parity bands in ^{134}Pr has been interpreted as a chiral doublet in [1,2]. New measurements at GAMMASPHERE extended the doublet seen for large frequency up to $\omega = 0.6\ MeV$ [4]. In order to exclude an accidental degeneracy the neighboring nuclei have been studied [5]. The systematic appearance of low-lying doublet bands of the same parity in the N=75 isotones with the disappearance of the energy difference in ^{134}Pr makes it likely that a small island of chiral rotation has been found which is surrounded by shores of soft chiral vibrations as is the case for other islands of broken symmetries, such as with quadrupole deformation, octupole deformation, and now rotational chirality. Clearly it would be interesting to study the neighboring isotone chains in order to map out the complete island.

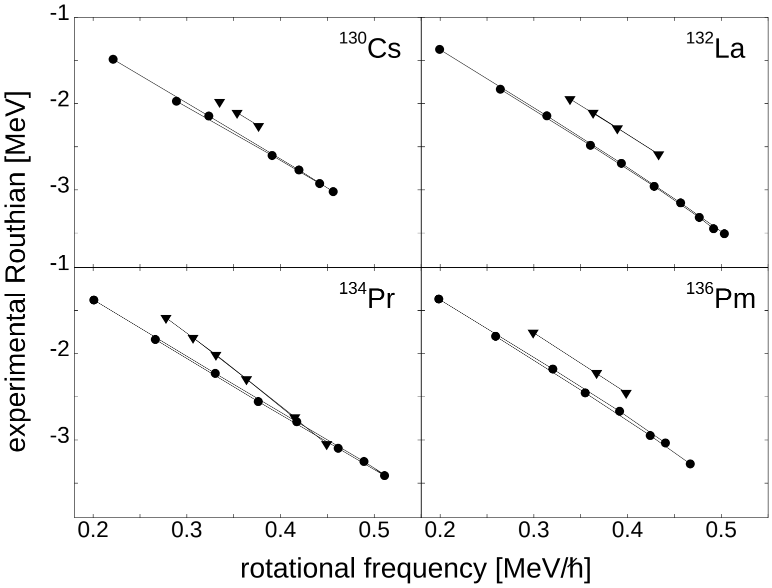

Fig. 2 *Experimental Routhians for the $\pi h_{11/2}\nu h_{11/2}$ main band (circles) and side bands (triangles) in the N=75 isotones studied. The Routhians are plotted up to a spin of I+11, where I is the bandhead spin. The distance between the two bands is the frequency of the chiral vibration. From [5].*

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Chiral Symmetry and Particle Rotor Model

JING-YE ZHANG[1], P.B. SEMMES[2], L.L. RIEDINGER[1], F. DÖNAU

The study of chiral bands in triaxially deformed nuclei [1] within the 3d-Tilted Axis cranking Model (TAC) has shown that the aplanar geometry of the angular momentum vector $< \vec{I} >$ exists only in a relatively short spin and frequency interval. This is because the energetical minimum stabilizing such an aplanar orientation is rather shallow and it can be easily driven towards a principal plane. Thus, for higher frequencies the favored a.m. direction returns to the normal (planar) tilt although the triaxial shape may still stay closely at maximal triaxiality $\gamma = 30^o$. Therefore, the question arises how sensitive is the aplanar spin orientation of the TAC model against the possible quantum interference (tunneling) in between the symmetry-related minima of the potential energy surface. This question goes beyond the TAC mean field model but can be investigated by symmetry restoration. A simple approach to it is the rotor plus particle model (RPM) in which a triaxial rotor core is coupled to two external high-j quasiparticles. The RPM is empirical with regard to the moments of inertia and the coupling to the deformed field which enter in terms of adjustable parameters. However, the above mentioned symmetry restoration of the RPM is by construction exactly carried out since the angular momentum is an exact quantum number of the model. In addition, the calculation of the important transition matrix elements is easily done and it automatically implies good a.m. states too.
Already Meng and Frauendorf [2] demonstrated in a schematic single j-shell RPM that the resulting bands have the chiral doublet pattern as predicted by the TAC model. Below we present the results from a similar calculation obtained with a more solid RPM description [3] in which both the pair and deformation field can be properly treated. This version allows one to study the energetical splitting of the chiral doublets and to calculate the inband and interband transition strength in a realistic manner. In this sense the RPM can be considered as a complementary approach to the TAC model. In Fig. 1 we show the lowest three bands calculated for the coupling of two quasiparticles ($\pi h_{11/2} \nu h_{11/2}$) to a rotor ($\gamma = 0$ and 30^o) for ^{134}Pr. Obviously, the chiral structures can not be formed with an axially deformed rotor in agreement with the prediction of TAC.

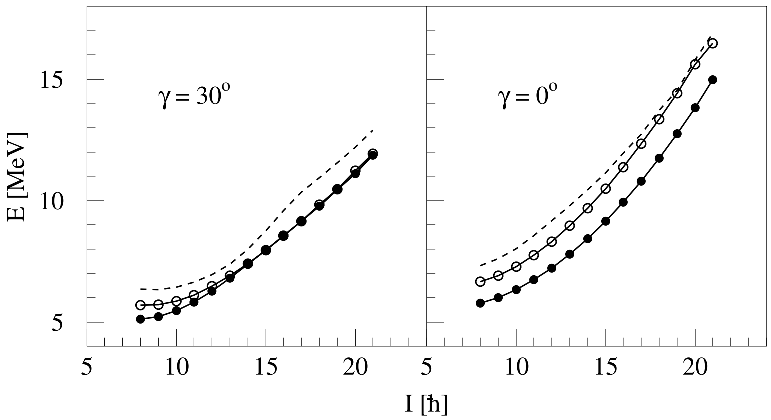

Fig. 1 *Calculated energy E vs. spin I for the three lowest bands of a rotor (left: γ=30^o, right: γ=0^o) plus two quasiparticle system. Only the triaxial rotor displays the chiral doublet structure.*

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A Hybrid Version of the Tilted Axis Cranking Model

V.I. DIMITROV[1], F. DÖNAU, S. FRAUENDORF[2]

The Tilted Axis Cranking (TAC) model [1] has turned out to be an appropriate theoretical tool for the description of the magnetic dipole bands. This model is a natural generalization of the cranking model for situations where the axis of rotation does not coincide with a principal axis of the density distribution of the rotating nucleus, and thus the signature is not a good quantum number. Since introduced, TAC has proven to be a reliable approximation for the energies and intraband transitions in both normally and weakly deformed nuclei. Hitherto the TAC calculations were based on the Nilsson Hamiltonian with the standard set of parameters [2]. This parameter set is known to have problems, for instance, in the $A = 130$ region where a better set has been suggested in [3]. On the other hand the Woods-Saxon potential with the universal parameter set [4] works very well around $A = 130$ and also in other mass regions. It is expected that this potential, which has a realistic radial profile instead of the artificial l^2- term of the Nilsson model, is more reliable when exploring mass regions where the Nilsson parameters have not been locally optimized. In addition, the l^2- dependence of the Nilsson potential is known to be problematic when the mean field is cranked at high angular velocity. In order to avoid the mentioned problems we developed an hybrid model which consists in adapting the Nilsson potential as close as possible to the Woods-Saxon one. Instead of the parameterizing the single particle levels of the spherical modified oscillator in the standard way by means of an ls- and an l^2-term, the hybrid model directly takes the energies of the spherical Woods-Saxon potential. The deformed part of the hybrid potential is an anisotropic harmonic oscillator. This compromise keeps the simplicity of the Nilsson potential, because coupling between the oscillator shell can be approximately taken into account by means of stretched coordinates [2], and it amounts to a minor modification of the existing TAC code. On the other hand, it has turned out to be quite a good approximation of the realistic flat bottom potential as long as the deformation is moderate. Another motivation for the hybrid potential is the considerably lower computation time (about a factor of 10) as compared with the full Woods-Saxon potential, which is important for the TAC calculations, which demand to achieve selfconsistency in two extra dimensions (the orientation angles).

Technically, the necessary replacements are rather simple, because the existing TAC code uses states of good l, j, m as a basis. The spherical Nilsson energies $e^{(nil)}_{N,l,j}$ are replaced by the spherical Woods - Saxon energies $e^{(ws)}_{N,l,j}$. It turns out to be unproblematic to associate the quantum numbers of the two different potentials. For a given combination l, j the third quantum number N is found by counting from the state with the lowest energy. The fact that the spherical Woods-Saxon code uses a harmonic oscillator basis permitted a check of the algorithm. The major component of the Woods-Saxon wavefunction agrees with the state found by our counting algorithm. In the high-lying part of the single-particle spectrum (three shells above the valence shell or higher) there are occasional ambiguities in assigning the states. Small errors of this kind are not expected to have any consequences at moderate or small deformation. These states do not couple strongly to the states near the Fermi surface.

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Effects of Quadrupole RPA Correlations in Rotating Nuclei [B,W]

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To study the influence of quadrupole shape vibrations on the rotation we have considered the following cranked Hamiltonian implying a residual isoscalar quadrupole-quadrupole interaction:

$$\hat{H}' = \hat{h}_0 - \hbar\omega_0\tilde{\kappa}\left[2\ell\cdot\mathbf{s} + \tilde{\mu}\left(\ell^2 - \left\langle\ell^2\right\rangle_N\right)\right] - \frac{\kappa}{2}\sum_m \hat{Q}_m\hat{Q}_m^* - \omega\hat{J}_z. \tag{15}$$

The first two terms denote the common spherical oscillator part and the spin-orbit potential which are chosen such that the mean field approximation of $\hat{H}'$ leads to the Nilsson Hamiltonian with the cranking term $-\omega\hat{J}_z$. In a first step of our calculations we determine the selfconsistent values of the deformation parameters ϵ, γ of the mean field potential as a function of the rotational frequency ω. In the second step the RPA treatment of the Hamiltonian $\hat{H}'$ is performed. Using the the spectral function integration method [1] the RPA correlation energy E'_{RPA} and their dependence on ω is obtained. This correlation energy contains the effects of the zero point quantum vibrations about the selfconsistent minimum of the potential energy surface. The total angular momentum J can be derived from the canonical relation $J(\omega) = -dE'/d\omega$ which is valid on mean field as well as on RPA level. There are two different options to construct the selfconsistent mean field solutions as the basis of the subsequent RPA calculation. The mean field approximation can be done straightforwardly with normal quadrupole operators $\hat{Q}_m$ [2]. Alternatively, when imposing additionally the constraint of volume conservation then the quadrupole operators have to be taken with doubly stretched coordinates [3]. In either way it is necessary to include the the $\Delta N = \pm 2$ mixing of oscillator shells caused by the quadrupole operators $\hat{Q}_m$. The different possibilities do only slightly change the results of the mean field calculation but produce rather different effects for the RPA.
As an example of a realistic calculation for the RPA correlations we choose ^{78}Sr. This nucleus has a rather stable prolate deformation and it is situated in a region with relatively low level density. Therefore, one can expect that the neglected pairing effects are of minor importance. The resulting total angular momentum J with and without RPA correlations is given in Fig. 1.

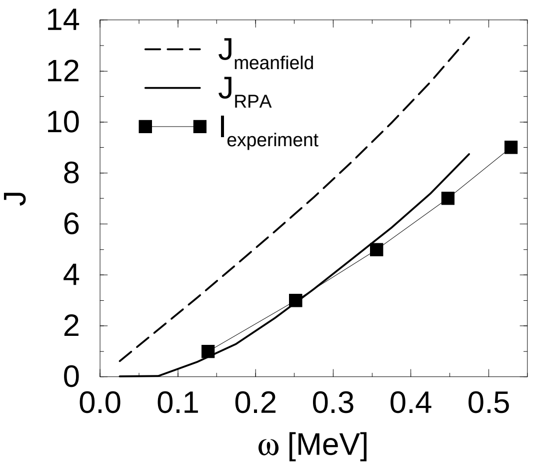

Fig. 1 *Angular momentum, in units of $\hbar$, of the ground state band in ^{78}Sr. Left panel: calculation with mean field approximation and RPA, respectively, with normal QQ force. Right panel: the same with doubly stretched QQ force. Experimental data are taken from [4].*

One notices that the mean field result for the angular momentum J is practically the same irrespectively whether the volume conservation is fulfilled or not. The moment of inertia is given by the ascent of the function $J(\omega)$. The resulting mean field value is much larger than the one seen in experiment. This is a well know result which is due to fact that ℓ^2 breaks the local

Galilean invariance. Concerning the quantum effects taken into account by the RPA there is a dramatic change when comparing the cases of normal and doubly stretched QQ-force. The RPA correlations obtained with the normal QQ-force reduce the moment of inertia by approximately 30 %. Applying the volume conservation together with doubly stretched quadrupole operators one has no reduction of the moment of inertia. There arises only a constant shift $\Delta J = \frac{1}{2}\hbar$ of the angular momentum related to its zero point motion. The better agreement of the RPA value with the experimental one, obtained for normal QQ-force is accidental.
The correlations are connected with the collective shape vibrations which is underlined by the fact that the size of these correlations is dependent on the curvature of the mean field potential.

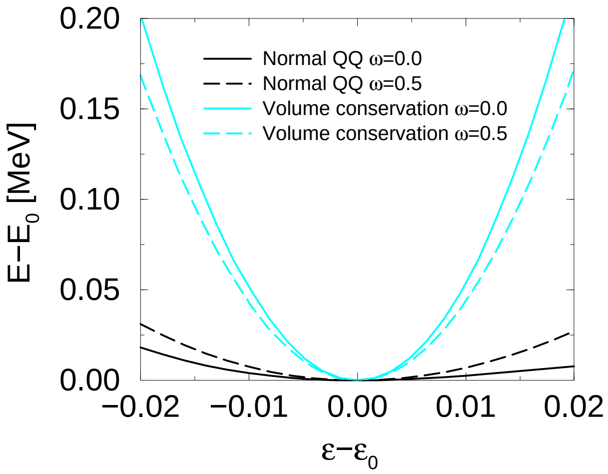

Fig. 2 *Potential energy as a function of deformation with the normal QQ-force (black lines) and with volume conservation (grey lines). The potential is plotted for the rotational frequencies $\omega = 0$ (solid lines) and 0.5 (dashed lines) MeV.*

In Fig.2 the potential energies $E(\epsilon) =< \hat{H}' >$ calculated for two frequency values ω in mean field approximation are shown as a function of the deformation parameter ϵ. The influence of the RPA correlation on the moment of inertia is determined by potential curvature with respect to ϵ and how the curvature is changing with the rotational frequency. One notices that the normal QQ-force leads to a much softer potential than the one with doubly stretched QQ-force. In addition, the stiffness of the potential increases with ω in the first case but decreases in the last case. To investigate these effects in more detail we have also considered a normal quadrupole interaction in which all $\Delta N = \pm 2$ matrix elements were neglected, i.e. the mixing between the oscillator mayor shells was omitted. In this approximation the RPA correlation effects of the normal QQ-force become similar to the one with volume conservation. This finding indicates the important role of the $\Delta N = \pm 2$ shell mixing which is known to be decisive for the formation of the Giant quadrupole resonances in nuclei. To get a more detailed understanding of the mechanism and the validity of different models in describing the effects of shape vibration in the ground state rotational band a more systematic investigation is necessary.

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The First Nuclear Resonance Fluorescence Experiment on ^{87}Rb [D,H]

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As a result of nuclear resonance investigations of N=50 nuclei [1,2] the question arises to what extent neutron degrees of freedom play a role in the structure of low-spin states in such semi-magic nuclei. Moreover, nothing is known up to now about the response of the N=50 nucleus ^{87}Rb to real photons. The first (γ,γ') experiment on ^{87}Rb was performed with bremsstrahlung of an endpoint energy of 4.0 MeV delivered by the Dynamitron at Stuttgart. Gamma-rays scattered on a 2.507 g $^{87}Rb_2CO_3$ target (^{87}Rb enriched to 99.2 %) were measured with three HPGe detectors of 100 % relative efficiency. In Fig. 1 a portion of a γ-ray spectrum is shown.

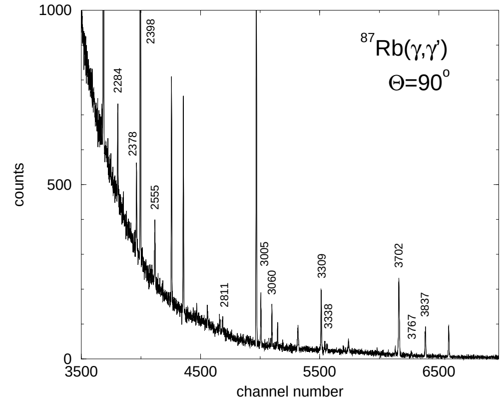

Fig. 1 *γ-ray spectrum of ^{87}Rb. Peaks denoted by their γ-ray energy belong to ^{87}Rb.*

The width Γ of 20 states could be measured for the first time. For ten levels for the first time γ-deexcitation was observed and for five for the first time γ-branchings. All observed states are dipole excitations, twelve of them M1 and six E1 excitations. For the 845 and 3837 keV transitions very large B(M1) and B(E1) values have been found, respectively. Shell model calculations [3] for ^{87}Rb have been performed. The shell model reproduces the right ordering of the experimentally observed magnetic dipole excitations and gives a fair reproduction of the excitation energies. There is a remarkable agreement of the measured B(M1) values with the calculated values (Fig. 2). The very strong 845 keV transition is the proton $p_{1/2} \rightarrow p_{3/2}$ spin-flip transition. Dominating proton $p_{3/2}$, $f_{5/2}$ and $p_{1/2}$ single particle character is found for the g.s., the 403 keV and 845 keV states, respectively. The other magnetic dipole excitations are dominated by three protons. Almost all negative parity states contain to some percent contributions of excitations of the N=50 neutron core. Even our large scale shell model calculations considering also the breakup of the N=50 core are not able to describe the electric dipole excitations.

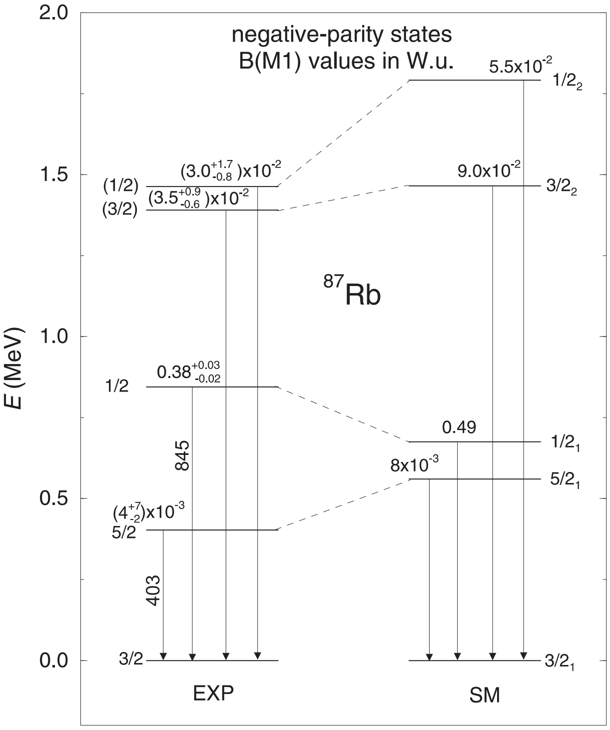

Fig. 2 *Experimental results for magnetic dipole excitations compared the results of large-scale shell model calculations.*

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A Scissors-Like State on Top of the Quadrupole Vibrational State in ^{88}Sr $^{\mathrm{D,H}}$

L. Käubler, H. Schnare, R. Schwengner, H. Prade, F. Dönau, E. Grosse, K.D. Schilling, A. Wagner

and the Köln[1] - Darmstadt[2] - Sofia[3] collaboration

A (γ,γ') experiment on ^{88}Sr was performed at the S-DALINAC accelerator of the TU Darmstadt with bremsstrahlung of 6.7 MeV endpoint energy using two EUROBALL CLUSTER detectors. In the search for the 1^- two-phonon state in the N=50 nucleus ^{88}Sr we found surprisingly $J^\pi = 1^+$ for the 4.742 MeV state [1] and a relatively large value of $B(M1)$=0.07 W.u. for the 4.742 MeV transition (Fig. 1) which is not reproduced by the quasiparticle-phonon model [2]. In order to give an interpretation for the 1^+ state at 4.742 MeV, the picture of a new excitation mode called dynamic scissors mode is proposed: a superposition of the normal scissors mode (scissors-like isovector vibration of the deformed proton and neutron systems) with the dynamically deformed quadrupole vibrational state in a spherical nucleus. This idea is suported by the following two arguments: (i) For the first 2^+ state in ^{88}Sr a deformation of $\delta = 0.11$ is obtained for the maximum elongation. Based on empirical estimates (est) [3] the normal scissors mode in ^{88}Sr would occur for $\delta = 0.11$ at the centroid of energies of $E^{est}(1^+_{sc}) = 3.17$ MeV with a total strength of $B^{est}(M1; 1^+_{sc} \rightarrow 0^+_1)$ $= 0.03$ W.u.. For the dynamic scissors mode state $E(1^+_{dsc})$ in ^{88}Sr one gets the estimate $E^{est}(1^+_{dsc}) = E^{exp}(2^+_1) + E^{est}(1^+_{sc}) = 5.01$ MeV. The estimates of 5.01 MeV and 0.03 W.u. are in fair agreement with the experimental results given above. (ii) There are many similarities of the deexcitation of the 4.742 MeV state in the spherical nucleus ^{88}Sr with that of the mixed symmetry scissors-like 1^+_{ms} state in the deformed N=52 nucleus ^{94}Mo [4], and also for the first three 2^+ states (Fig. 1). The 1^+ state in ^{94}Mo is considered to be the scissors mode in this nucleus having the structure $(2^+_1 \otimes 2^+_{ms})$, where 2^+_1 corresponds to the phonon of the isoscalar quadrupole vibration and 2^+_{ms} is the phonon of the isovector quadrupole vibration. For ^{88}Sr the energy sum of the 2^+ isoscalar quadrupole vibrational state (1.836 MeV) and the newly observed possible 2^+_{ms} isovector quadrupole vibrational state (2.935 MeV) results to 4.771 MeV in well accordance to 4.742 MeV for the 1^+ state. In summary, the 1^+ state at 4.742 MeV in the spherical $N = 50$ nucleus ^{88}Sr is a fingerprint for the existence of a scissors-like state. The picture of the dynamic scissors mode could be a schematic approach for this excitation giving a rough approximation to the real situation. The reality may be a complicated superposition of an isoscalar and isovector quadrupole vibration.

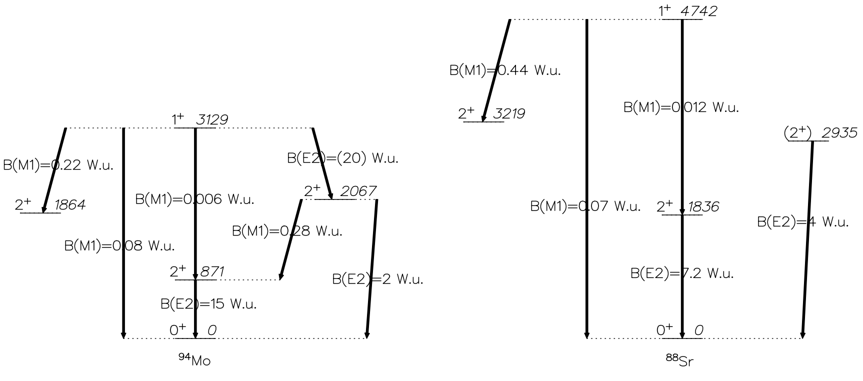

Fig. 1 *Comparison of* ^{94}*Mo and* ^{88}*Sr.*

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Transition Strengths in Magnetic Dipole Bands in ^{82}Rb, ^{83}Rb and ^{84}Rb [A,E]

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Searching for magnetic rotation in the mass region around $A = 80$ we studied the isotopes ^{82}Rb$_{45}$, ^{83}Rb$_{46}$ and ^{84}Rb$_{47}$. We found magnetic dipole ($M1$) sequences with varying properties in each nucleus. The $M1$ bands in the odd-odd nuclei ^{82}Rb and ^{84}Rb follow the regular rotational behaviour ($E \sim J(J+1)$, i.e. $J \sim \hbar\omega$) which can be seen in Fig. 1. $B(M1)/B(E2)$ ratios determined from branching ratios of transitions within the $M1$ bands reach values up to 25 $(\mu_{\mathrm{N}}/e\mathrm{b})^2$ and decrease smoothly with increasing spin in a range of $13 \leq J \leq 16$. This behaviour is typical for magnetic rotation and caused by the gradual alignment of the spins of the involved proton and neutron orbitals (shears mechanism). The regular negative-parity $M1$ bands in ^{82}Rb and ^{84}Rb are well described within the tilted-axis cranking (TAC) model [1] on the basis of the lowest-lying four-quasiparticle (4-qp) configuration: $\pi(fp)\ \pi(g_{9/2}^2)\ \nu(g_{9/2})$ [2].

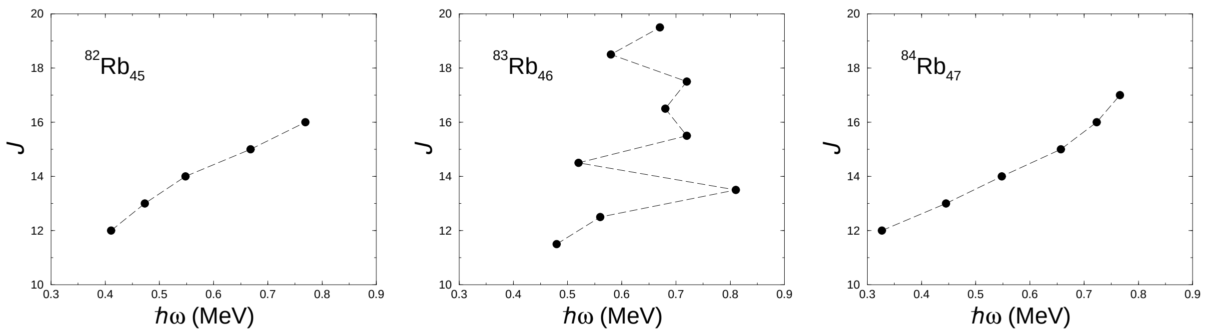

Fig. 1 *Spin as a function of rotational frequency in the $M1$ bands of ^{82}Rb (left panel), ^{83}Rb (middle panel) and ^{84}Rb (right panel). Lines are drawn to guide the eye.*

So far, the interpretation of the $M1$ bands was based on $B(M1)/B(E2)$ ratios deduced from γ-ray intensities. However, a detailed test of the predictions of the tilted-axis cranking model requires the knowledge of absolute $M1$ and $E2$ transition strengths. Therefore, we carried out a measurement of level lifetimes using the reaction ^{11}B + ^{76}Ge ($E = 45$ MeV) at the XTU tandem accelerator of the LNL Legnaro. Gamma rays were detected with the spectrometer GASP. A thick target was used to stop the recoil nuclei. Level lifetimes were deduced from a lineshape analysis applying the Doppler-shift-attenuation method.

Absolute experimental transition strengths within the $M1$ band of ^{84}Rb derived from the present lifetime measurement are compared with predictions of TAC calculations [2] in Fig. 2. The experimental $B(M1)$ values show a smooth decrease with increasing rotational frequency which may indicate the shears mechanism, but is not as pronounced as the calculated behaviour. The experimental $B(E2)$ values increase up to $\hbar\omega \approx 0.6$ MeV and decrease strongly towards higher frequency which may indicate a loss of collectivity due to a change of the structure. However, the calculated $B(E2)$ values stay almost constant over the considered frequency range.

In contrast to the odd-odd isotopes, the negative-parity $M1$ sequence in the odd-even nucleus ^{83}Rb is not regular, which can be seen in Fig. 1. Moreover, the $B(M1)/B(E2)$ ratios reveal a pronounced staggering that is not compatible with the shears mechanism [3] and cannot be described in the TAC model. Based on the present lifetime measurement we deduced absolute transition strengths within the negative-parity $M1$ sequence of ^{83}Rb which are shown in Fig. 3.

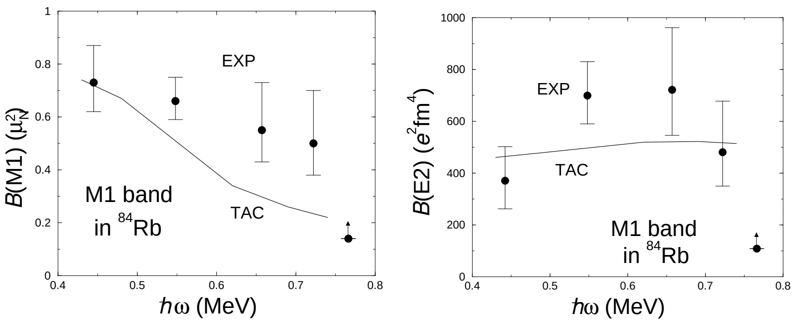

Fig. 2 *Experimental and calculated $B(M1)$ (left panel) and $B(E2)$ (right panel) transition strengths versus the rotational frequency in the $M1$ band of ^{84}Rb.*

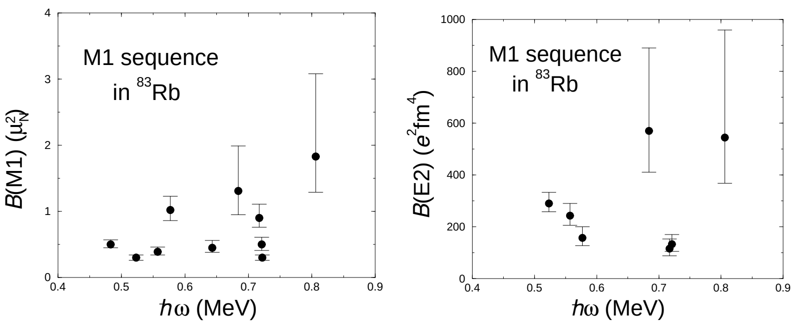

Fig. 3 *Experimental and calculated $B(M1)$ (left panel) and $B(E2)$ (right panel) transition strengths versus the rotational frequency in the negative-parity $M1$ sequence of ^{83}Rb.*

The experimental $B(M1)$ as well as the $B(E2)$ values show an irregular behaviour which is considered as the consequence of the even neutron number of this isotope in difference to the two odd-odd neighbours $^{82}\text{Rb}_{45}$ and $^{84}\text{Rb}_{47}$. In ^{83}Rb, the breakup of a neutron pair is necessary to generate excitations that include unpaired nucleons of both kinds. A possible configuration of negative parity is the 3-qp configuration $\pi(g_{9/2})\ \nu(g_{9/2})\ \nu(fp)$. This configuration has one $g_{9/2}$ particle less than the 4-qp configuration assumed for the odd-odd isotopes and, therefore, less possibilities to generate high spins. This and the specific neutron orbitals obviously lead to a spin coupling which cannot realize the shears mechanism. A further possible configuration similar to the one in the odd-odd isotopes is the 4-qp configuration $\pi(fp)\ \pi(g_{9/2}^2)\ \nu(g_{9/2}^2)$ which may occur at higher energy.

The different behaviour of the isotopes with odd numbers of $N = 45, 47$ on the one hand and an even number of $N = 46$ on the other hand demonstrates the delicate balance between irregular and coherent collective motion in this mass region.

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Shape Coexistence at High Spin in the N = Z + 2 Nucleus ^{70}Se [A,B,E]

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The structure of nuclei in the vicinity of $N = Z$ in the mass region $A \approx 70 - 80$ reveals a rich variety of structural phenomena and provides a good test for nuclear models. The competition between proton and neutron shell gaps occurring at large oblate and prolate deformations near the nucleon numbers 36 and 38 results in a coexistence of different nuclear shapes [1]. The purpose of the present study is to extend the knowledge about the structure of nuclei close to $N = Z$ in the mass region $A \approx 70 - 80$. In particular, the information about high-spin states in such nuclei is scarce, since they can be produced in heavy-ion fusion reactions with small cross sections only. With the advent of large highly-efficient spectrometers as EUROBALL there are new prospects for the study of nuclei close to $N = Z$ which are populated in weak reaction channels.

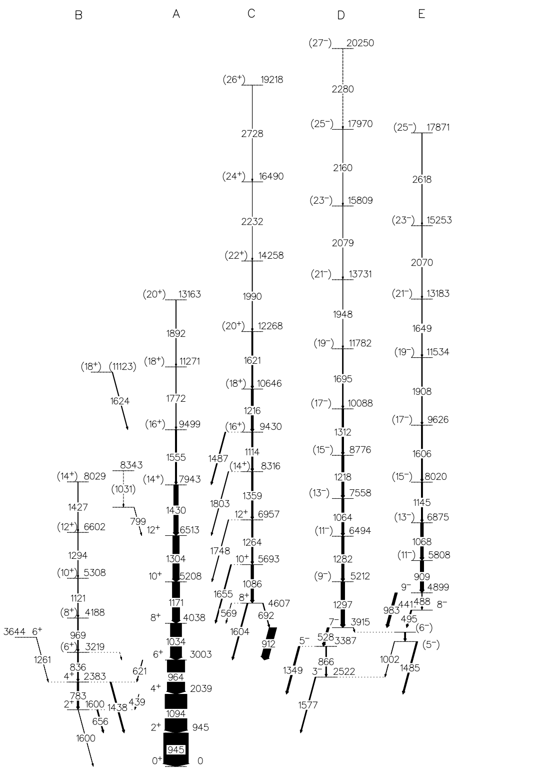

Fig. 1 *Level scheme of ^{70}Se deduced from the present experiment.*

Excited states in ^{70}Se were populated via the $2\alpha 2p$ exit channel of the reaction ^{40}Ca + ^{40}Ca at a beam energy of 185 MeV. The ^{40}Ca beam was provided by the XTU tandem accelerator at the Laboratori Nazionali di Legnaro. Gamma rays were measured with the EUROBALL III array consisting of 15 Cluster and 26 Clover detectors. Charged particles were detected with the silicon ball ISIS consisting of 40 $\Delta E - E$ telescopes. In the forward hemisphere, 50 neutron detector units filled with liquid scintillator BC501A were mounted.

The level scheme of ^{70}Se based on the present work is presented in Fig. 1. Excited states known from previous studies [2] were confirmed in our experiment. The positive-parity bands labelled A and C in Fig. 1 were considerably extended and a new positive-parity band (labelled B) was observed. Two new negative-parity bands (labelled D and E) were established on top of the irregular low-spin sequences.

The bands C, D and E are interpreted in terms of the configuration-dependent cranked Nilsson-Strutinsky model [3]. The potential energy surfaces show different minima that develop from configurations with the same numbers of nucleons lifted from the fp shell to the $g_{9/2}$ orbital. The newly observed negative-parity bands are thought to belong to such different minima. Thus, they represent a coexistence of different nuclear shapes at high spin.

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Signature Inversion Caused by Triaxiality in the ^{72}Br Nucleus ^{B,E}

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Rotational structures in nuclei can be characterized by the signature quantum number α which defines the admissible spin sequence for a band through the relation $I = \alpha + 2n$ $(n = 0, 1, \ldots)$. This is a consequence of the well-known $D2$-symmetry of deformed intrinsic shapes reflected by the appearance of two signature partner bands with $\alpha = 0$ or 1 in even-mass nuclei. By investigating the relative position of the signature partners, important information about the structural changes ocurring in the nucleus with the increasing spin can be gained.

A peculiar feature of the negative-parity bands in ^{72}Br is the signature splitting that can be seen in the upper panel of Fig. 1. The $\alpha = 1$ branch is favoured up to $I \approx 16$ where a crossing of the branches takes place such that the $\alpha = 0$ branch is favoured at higher spins. This signature inversion in the negative-parity bands is unique in the chain of the odd-odd Br isotopes. In contrast, the ^{74,76,78}Br nuclei display signature inversions in the positive-parity bands at lower spin values of 9,10,11, respectively.

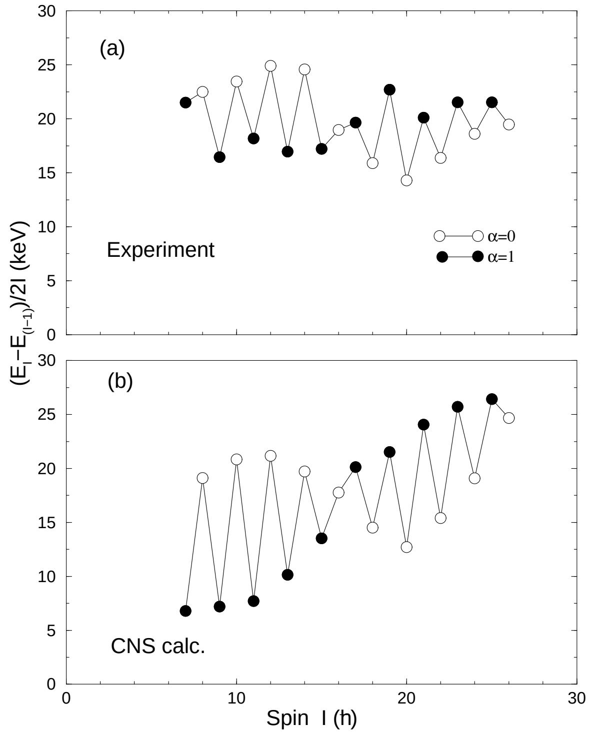

Fig. 1 *Energy difference between the states with spin I and spin (I - 1), divided by 2I, for the observed (upper panel) and calculated (lower panel) negative-parity bands in ^{72}Br.*

To understand the microscopic origin of the signature inversion in the negative-parity bands of ^{72}Br we performed calculations using the configuration-dependent cranked Nilsson-Strutinsky (CNS) [1] approach. A fully consistent calculation was performed, where the equilibrium deformation in the potential energy surface was searched for at each spin value separately. A comparison of the calculated signature splitting with the experimental one is presented in Fig. 1. This comparison shows that the main features, especially the energetic order of the signature partners and the spin, where the crossing takes place, are correctly reproduced. However, it should be mentioned that the signature inversion can not be reproduced in calculations with a fixed γ deformation [2]. The equilibrium deformation at low spin corresponds to negative γ deformation and gradually changes with increasing spin to positive values at the highest observed spins. This shows that the signature inversion is a consequence of changing triaxial deformation.

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Band Termination in the ^{73}Br Nucleus [B,E]

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The structure of the ^{73}Br isotope was investigated by using the EUROBALL spectrometer and the level scheme was published in [1].
To interpret the data, the configuration-dependent Cranked Nilsson-Strutinsky (CNS) approach was applied [2]. The calculations minimize the total energy of a specific configuration for a given spin with respect to the deformation parameters $(\varepsilon_2, \varepsilon_4, \gamma)$. The configurations are specified with respect to a $^{56}_{28}\mathrm{Ni}_{28}$ core as having 7 active protons and 10 active neutrons. They are labelled by the shorthand notation $[p_1p_2, n_1n_2]$, where $p_1(n_1)$ stands for the number of protons (neutrons) in the $(p_{3/2}, f_{5/2})$ orbitals and $p_2(n_2)$ stands for the number of protons (neutrons) in $g_{9/2}$ orbitals. In addition, the sign of the signature of the last occupied orbital is given as a subscript, if the number of occupied orbitals in the specific group is odd. The calculated energies of the energetically lowest configurations are compared with experimental energies in Fig. 1, where a rigid rotor reference was subtracted. Based on this comparison the configurations $[43_+,64]$ and $[5_+2,64]$ were assigned to bands A and C, respectively. Band B is observed up to I = (63/2). The calculations suggest that the $[5_-2,64]$ configuration can be assigned to this band at low and medium spin. It is the signature partner of the $[5_+2,64]$ configuration assigned to band C. The $[5_-2,64]$ configuration is crossed at spin 57/2 by the $[43_+,7_+3_+]$ configuration. The predicted crossing is indeed observed in band B at spin $(55/2^-)$. The latter configuration can be related to band B above the band crossing. In the calculations, the $[43_+,7_+3_+]$ configuration (empty triangles in Fig. 1) undergoes a shape change from a collective shape (triaxiality parameter $\gamma \approx +30°$) to a non-collective oblate shape ($\gamma = +60°$) between spins 55/2 and 63/2. This means that collective rotation is no longer possible and the corresponding band terminates at spin 63/2. Since this is the highest spin observed for band B, we conclude that we observed band B up to its termination.

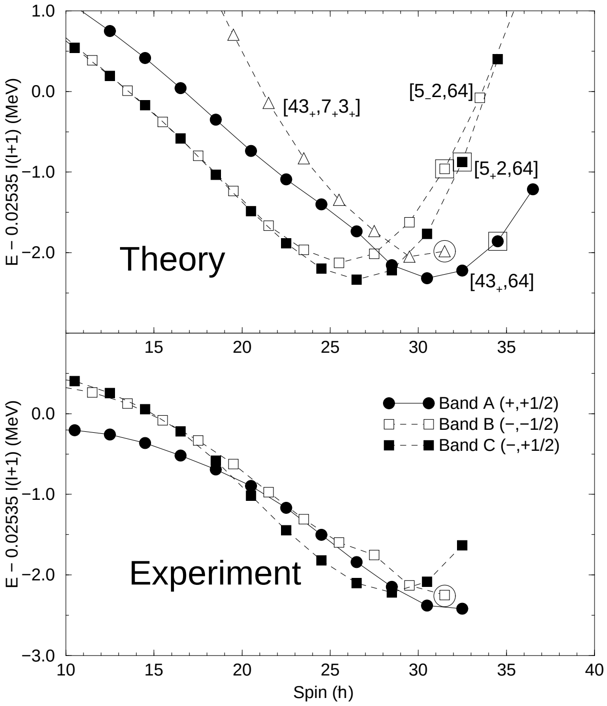

Fig. 1 *Comparison of experimental with calculated energies with respect to a rigid rotor reference.*

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Influence of Neutron-Core Excitations on High-Spin States in ^{88}Sr S

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High-spin states of the $N = 50$ nucleus ^{88}Sr were studied via the reaction ^{80}Se(^{11}B,$p2n$) at a beam energy of 45 MeV with the six-detector array OSIRIS CUBE at the University of Cologne. The level scheme of ^{88}Sr deduced from this experiment is shown in Fig. 1. On the basis of the analysis of directional correlations of coincident γ rays emitted from oriented states (DCO), spin assignments for all observed states were made. Mean lifetimes of three levels were determined using the Doppler-shift-attenuation method. They correspond to strong $M1$ transitions with $B(M1)$ values of about 0.3 to 1.4 W.u. Shell-model calculations in the model space $(0f_{5/2}, 1p_{3/2}, 1p_{1/2}, 0g_{9/2})$ for the protons and $(1p_{1/2}, 0g_{9/2}, 1d_{5/2})$ for the neutrons were performed. Experimental and calculated level energies of states in ^{88}Sr are compared in Fig. 2. Neutron-core excitations are predicted for the lowest 6^+ and 7^+ states in agreement with results of previous (d,p) experiments (e.g. [1]). Proton configurations of seniority $v = 4$ are predicted for the positive-parity states with $J^\pi = 8^+$, 10^+, 11^+ and 12^+. The calculations describe experimental high-spin level sequences with $J^\pi > 7^-$ and $J^\pi \geq 12^+$ linked by strong M1 transitions as $v = 4$ and 6 multiplets, respectively, which include proton excitations coupled to neutron-core excitations. A detailed description of this work is given in Ref. [2].

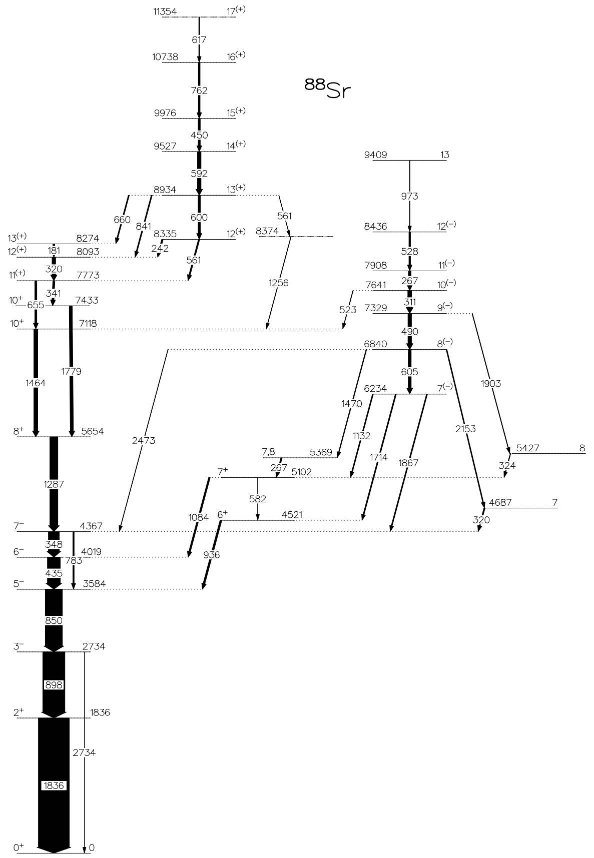

Fig. 1 *Level scheme of ^{88}Sr deduced from the present experiment.*

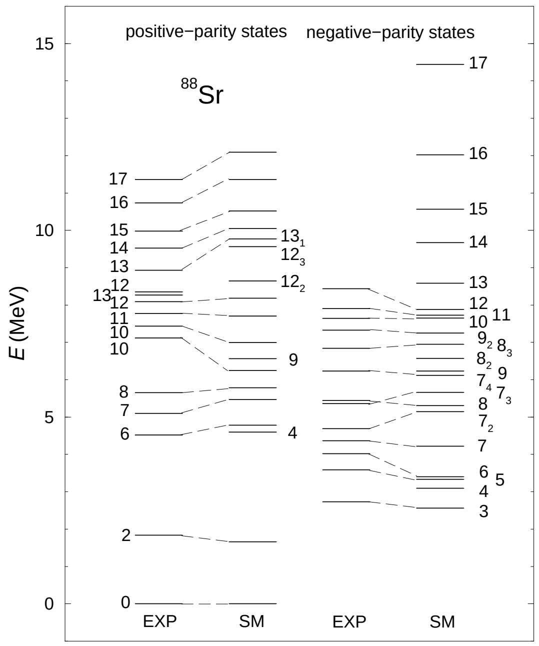

Fig. 2 *Comparison of experimental with calculated level energies in ^{88}Sr.*

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Gamma and Beta Decay of the 12^+ Yrast Trap in ^{52}Fe [E,G]

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The spectroscopy of $1f_{7/2}$-shell nuclei provides a good test for shell-model calculations and the associated effective interactions. Recent advances in experimental techniques [1,2] have enabled detailed in-beam studies of high-spin states in many of the $N \approx Z$ nuclei in the $1f_{7/2}$ shell, and a similarly impressive progress has been made in large-scale shell-model (LSSM) calculations [3,4]. The high-spin spectrum of ^{52}Fe ($N = Z = 26$) represents a particular experimental challenge due to the presence of a 12^+ isomer which acts as a "trap" for the de–exciting γ–ray flux. In a recent work [5] performed with the γ–ray detector array GASP, the level scheme of ^{52}Fe has been extended up to the 10^+ state lying above the yrast 12^+ isomer. In the present report, preliminary results on the γ and β decays of the 12^+ state are presented. The experiment was performed at the GSI on-line mass separator, where a 2.5 mg/cm^2 thick ^{nat}Si target was bombarded by a 209 MeV ^{36}Ar beam. The mass 52 secondary beam was implanted in a tape which moved away every 80 s. The implantation position was viewed by a plastic scintillator with a β-detection efficiency of 85%, two composite germanium detectors of the Cluster and Clover type, and a 60% single germanium crystal. The absolute efficiency of the germanium detectors was 3.9% for a γ-ray energy of 1332 keV, which improves the detection sensitivity limit by a factor of 100 compared to that achieved in the previous study [6].

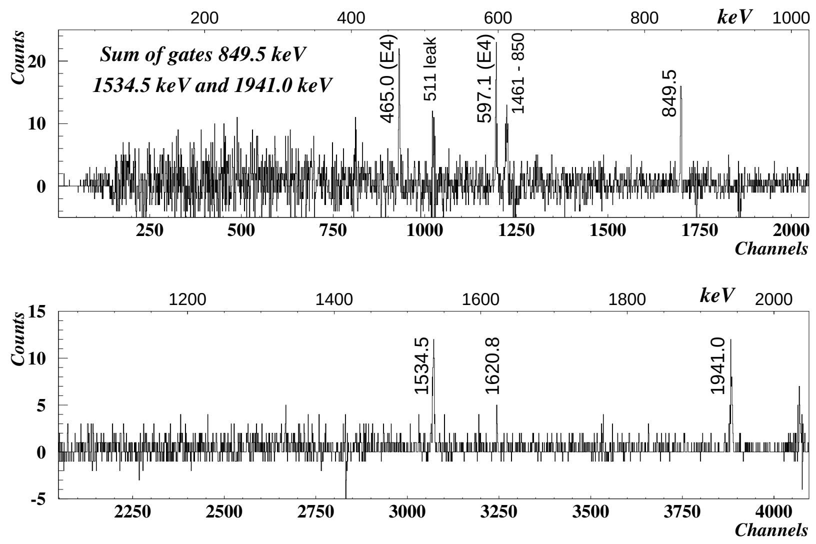

Fig. 1 *Spectrum gated on the main transitions in ^{52}Fe and in anti-coincidence with the β-counter.*

Events with β-γ-γ and γ-γ coincidences were recorded and afterwards sorted into 3D-cubes and 2D-matrices. The analysis of the γ-γ coincidences, including the "add-back" of the composite detectors and a veto condition derived from the β counter (see Fig. 1), allowed us for the first time to observe the γ de-excitation of the 12^+ isomer to the two 8^+ states via E4 transitions of 597.1 and 465.0 keV, thus giving the excitation energy of the isomer as 6957.5(4) keV (see Fig. 2). This value is significantly more accurate than the previous result deduced from β decay measurements [6] and yields better agreement with the LSSM predictions [5]. The intensities per total isomer decay have been estimated to be $1.3(4) \times 10^{-4}$ for the 597.1 keV $12^+ \rightarrow 8_1^+$ and

$0.9(3) \times 10^{-4}$ for the 465.0 keV $12^+ \rightarrow 8_2^+$ transition. We have also observed the second 11^+ state of ^{52}Mn populated in ^{52}Fe 12^+ β-decay (see Fig. 2) with an apparent feeding of 0.5%, which is in good agreement with the theoretical value of 0.3% predicted by the LSSM calculation.

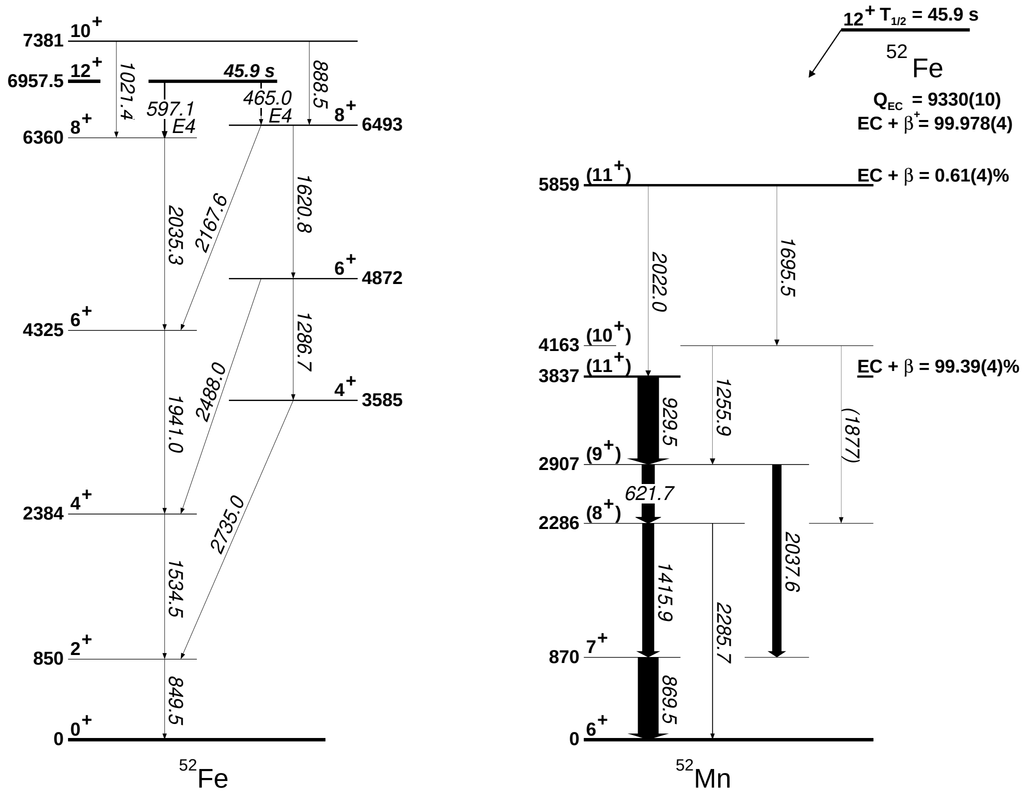

Fig. 2 *γ-decay (left) and β-decay (right) level schemes.*

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Decay Properties of ^{93}Pd [A,G]

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Neutron-deficient isotopes in the vicinity of the $N = Z$ line have attracted considerable experimental and theoretical attention over the last years. Among the key points of interest are investigations in the framework of the astrophysical rp-process [1] and studies of the residual proton-neutron interaction [2]. Reaction network calculations of the rp-process [3] identified, along with other isotopes such as ^{92}Pd and ^{96,97}Cd, the very proton-rich nucleus ^{93}Pd ($Z = 46, N = 47$) as a probable waiting point in the reaction path in X-ray burst scenarios. Calculations of this kind require, amongst other nuclear properties, β-decay half-lives as input parameters.

The nucleus ^{93}Pd was produced in the fusion-evaporation reaction ^{58}Ni(^{40}Ca,αn)^{93}Pd at a beam energy of 188 MeV. The reaction products were collected and ionised in a FEBIAD-E ion source. The mass-separated $A = 93$ beam collected from the GSI Online Mass Separator was implanted in a thin carbon foil in front of a $\Delta E - E$ silicon telescope which served as a detector for β-delayed protons. Figure 1 shows the energy spectrum containing 205 events, obtained within a measuring time of 14.3 hours. For part of the time, the beam was flipped between the collection position on the carbon foil and a beam dump, thus allowing for the recording of time-differential data. A comparison of the number of β-delayed protons registered during beam-on and beam-off periods yielded a half-life of $T_{1/2} = 0.7^{+0.2}_{-0.1}$ s.

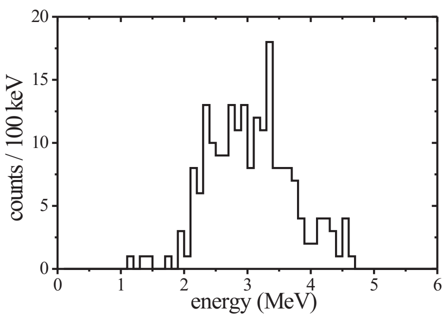

Fig. 1 *Energy spectrum of β-delayed protons recorded at mass A = 93.*

In addition to the measurement of β-delayed protons, β-delayed γ-rays were investigated by using an array of 13 germanium detectors and a plastic scintillator, mounted at a separate beamline. Gamma transitions of 239.7 keV, 381.7 keV, 621.7 keV, and 864.1 keV were identified in measurements of mass-separated $A = 93$ sources and preliminarily assigned to the decay of ^{93}Pd. The time characteristics of these γ-lines yield a half-life of $T_{1/2} = (1.0 \pm 0.3)$ s in good agreement with the value deduced from the proton data. Shell model calculations in the mass range $A = 86 - 100$ [4] predict a ground-state spin of either $7/2^+$ or $9/2^+$ for the isotope ^{93}Pd, while a low-lying $1/2^-$ isomer can not be excluded. The calculated disintegration mode of the ground-state is an allowed Gamow-Teller β-decay with a half-life of $T_{1/2} = 1.4$ s. Due to the good agreement with the calculations, we attribute the observed activity of β-delayed protons and γ-rays to the ground-state decay of ^{93}Pd. ^{93}Ag, on the other hand, is predicted [4,5] to be unbound with respect to direct proton emission from its ground state. The search for direct protons at mass $A = 93$ was unsuccessful.

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Static Quadrupole Moment of Five-Quasiparticle $K = \frac{35}{2}$ Isomer in ^{179}W Studied with the LEMS Method [B]

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This study addresses the following question: is there a difference between the deformation of the nuclei in their ground states and in their high-seniority multi-quasiparticle excitations often observed as isomeric states. The importance of this question is related to the question of the quenching of the pairing correlations in atomic nuclei. The nuclear deformations are present as a parameter in many calculations, which requires that they should be determined experimentally. Prior to this experiment [1], only the quadrupole moments of the high-K isomers in ^{182}Os ($K^\pi = 25^+$), ^{178}Hf ($K^\pi = 16^+$) and ^{177}Lu ($K^\pi = \frac{23}{2}^-$) were known. For the latter two isomers the deformation which was deduced is similar to the ground-state deformation. In the case of ^{182}Os there is a considerable difference between the ground state and isomeric quadrupole moment.

The spectroscopic quadrupole moment of the high-spin, high-K five-quasiparticle isomer ($K^\pi = \frac{35}{2}^-$, $T_{1/2} = 750(80)$ ns, $E_i = 3349$ keV) in ^{179}W has been determined using the Level Mixing Spectroscopy (LEMS) method [1]. A value $Q_s = 4.00(^{+0.83}_{-1.06})eb$ was derived, which corresponds to an intrinsic quadrupole moment $Q_0 = 4.73(^{+0.98}_{-1.25})eb$ and to a quadrupole deformation $\beta_2 = 0.185(^{+0.038}_{-0.049})$. These values differ significantly from the deduced ground-state quadrupole moments and are in disagreement with the current theoretical predictions in this mass region.

Hartree-Fock-Bogolyubov calculations within the framework of the Tilted Axis Cranking (TAC) theory [2] permit us to take into account possible mixing between bands with different K values. Such effects were found to be small. TAC yields a value for the quadrupole moment of this isomer $Q_s = 6.223$ eb if pairing is treated with the particle number projection technique [3] and $Q_s = 6.343$ eb without it (the neutron pairing is zero in this case). These values of the quadrupole moment correspond to an axially symmetric nucleus with deformations $\epsilon_2 = 0.228$ and $\epsilon_4 = 0.038$, which coincide practically with the calculated ground-state deformations for ^{179}W: $\epsilon_2 = 0.226$ and $\epsilon_4 = 0.039$ but contradict with the measured quadrupole moment for the isomer.

In conclusion, we have measured the quadrupole moment of the $K = \frac{35}{2}$, $E_i = 3349$ keV isomer in ^{179}W. The deduced deformation of this state is smaller, compared to the systematic trend of the ground-state deformations of the nuclei in the region, and smaller than the theoretically predicted values. Further improvement of the experimental accuracy is probably needed. At the same time the exploration of other theoretical aspects is necessary, since it seems impossible to explain these differences within the well established schemes to calculate nuclear deformations in this mass region.

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