Study of Dipole Strength Distributions at the ELBE Accelerator

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- Photon-scattering experiments
- Data analysis and results
- Model predictions
- Photoactivation experiments
- Photodissociation of the deuteron

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Dipole strength close to the particle-separation energy

- Modelling of astrophysical processes:
  - $(\gamma,n)$ reaction rates in the p-process.
  - $(n,\gamma)$ reaction rates in the s-process.

- Studies for future nuclear-fuel cycles:
  - improved experimental and theoretical description of $(n,\gamma)$ reactions.

- Open problems:
  - precise knowledge of the dipole strength on the low-energy tail of the Giant Dipole Resonance below the particle thresholds.
  - properties of the dipole strength functions at varying proton and neutron numbers: shell effects, deformation etc.
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The radiation source ELBE

Electron Linear accelerator of high Brilliance and low Emittance
Accelerator parameters:

- Maximum electron energy: 
  \(\approx 18\ \text{MeV}\)

- Maximum average current: 
  \(\approx 0.8\ \text{mA}\)

- Micro-pulse rate: 
  13 MHz

- Micro-pulse length: 
  \(\approx 5\ \text{ps}\)

R.S. et al., NIM A 555, 211 (2005)
Detector setup
Problem of feeding and branching

**Measured intensity of a γ transition:**

\[ I_\gamma(E_\gamma, \Theta) = I_s(E_x) \Phi_\gamma(E_x) \epsilon(E_\gamma) N_{at} W(\Theta) \Delta\Omega \]

**Integrated scattering cross section:**

\[ I_s = \int \sigma_{\gamma\gamma} \, dE = \frac{2J_x + 1}{2J_0 + 1} \left( \frac{\pi \hbar c}{E_x} \right)^2 \frac{\Gamma_0}{\Gamma} \Gamma_0 \]

**Absorption cross section:**

\[ \sigma_\gamma = \sigma_{\gamma\gamma} \left( \frac{\Gamma_0}{\Gamma} \right)^{-1} \]

**E1 strength:**

\[ B(E1) \sim \frac{\Gamma_0}{E_\gamma^3} \]
Problem of feeding and branching

Measured intensity of a $\gamma$ transition:
\[ I_\gamma(E_{\gamma}, \Theta) > I_s(E_x) \Phi_\gamma(E_x) \epsilon(E_{\gamma}) N_{\text{at}} W(\Theta) \Delta\Omega \]

Integrated scattering cross section:
\[ I_s = \int \sigma_{\gamma\gamma} \, dE = \frac{2J_x + 1}{2J_0 + 1} \left( \frac{\pi hc}{E_x} \right)^2 \frac{\Gamma_0}{\Gamma} \frac{\Gamma_0}{\Gamma_0} \]

Absorption cross section:
\[ \sigma_{\gamma} = \sigma_{\gamma\gamma} \left( \frac{\Gamma_0}{\Gamma} \right)^{-1} \]

$E1$ strength:
\[ B(E1) \sim \Gamma_0 / E_\gamma^3 \]
Absolute efficiency of two detectors at 127° deduced from $^{22}$Na (diamonds), $^{60}$Co (triangles), $^{65}$Zn (box), $^{133}$Ba (filled circles), $^{137}$Cs (circle), $^{226}$Ra (filled circles) and simulated with GEANT3 (solid line).

Absolute photon flux deduced from transitions in $^{11}$B (circles) using the calculated efficiency shown in the left panel and relative photon flux calculated according to:

Unresolved strength in the continuum

Experimental spectrum of $^{90}$Zr (corrected for room background, detector response, efficiency, measuring time) and simulated spectrum of atomic background.

Scattering cross sections in $^{90}$Zr averaged over energy bins of 0.2 MeV, not corrected for branching, derived from the difference of the experimental spectrum and the atomic background (triangles) and from the resolved peaks only (circles).
Experimental spectrum of $^{139}$La (corrected for room background, detector response, efficiency, measuring time) and simulated spectrum of atomic background.

Scattering cross sections in $^{139}$La averaged over energy bins of 0.1 MeV, not corrected for branching, derived from the difference of the experimental spectrum and the atomic background (triangles) and from the resolved peaks only (circles).
Level densities in Mo isotopes

Experiment at $E_{e}^{\text{kin}} = 3.8$ MeV

Experiment at $E_{e}^{\text{kin}} = 13.2$ MeV

Back-shifted Fermi gas (BSFG) model

Constant-temperature (CT) approximation
Simulations of $\gamma$-ray cascades

Monte Carlo simulations of $\gamma$-ray cascades from groups of levels in 100 keV bins (G. Rusev, dissertation)

Level scheme of $J = 0, 1, 2$ states constructed by using:
- Wigner level-spacing distributions

Partial decay widths calculated by using:
- Photon strength functions approximated by Lorentz curves (www-nds.iaea.org/RIPL-2).
  - $E1$: parameters from fit to $(\gamma,n)$ data
  - $M1$: global parametrisation of spin-flip resonances
  - $E2$: global parametrisation of isoscalar resonances
  - Porter-Thomas distributions of decay widths.

Feeding intensities subtracted and intensities of g.s. transitions corrected with calculated branching ratios $\Gamma_0/\Gamma$. 
Simulations of $\gamma$-ray cascades

Wigner distribution of level spacings

Average spacing: $1/\rho(E_f, J_f^\pi)$

$$P(x) = \frac{1}{2} \pi x e^{-\pi x^2/4}$$
Simulations of $\gamma$-ray cascades

Porter-Thomas distribution of level widths

$$\Gamma_{if} = (E_i - E_f)^{2L+1} \frac{f_X^L(E_\gamma)}{\rho(E_f, J^\pi_f)}$$

$$\Gamma_{if} = y_{if} \Gamma_{if}$$

$$P(y) = \frac{1}{\sqrt{2\pi y}} e^{-y/2}$$
Simulations of $\gamma$-ray cascades

Simulated intensity distribution of transitions depopulating levels in a 100 keV bin around 9 MeV.

$\Rightarrow$ Subtraction of intensities of branching transitions.

$^{89}$Y data: N. Benouaret et al., PRC 79, 014303 (2009).

$^{139}$La data: A. Makinaga et al., PRC 82, 024314 (2010).
Distribution of branching ratios $b_0 = \Gamma_0/\Gamma$ versus the excitation energy as obtained from the simulations of $\gamma$-ray cascades.

⇒ Estimate of $\Gamma_0$ and $\sigma_\gamma$.

$^{89}\text{Y}$ data: N. Benouaret et al., PRC 79, 014303 (2009).

$^{139}\text{La}$ data: A. Makinaga et al., PRC 82, 024314 (2010).
Test of simulated branching ratios - Measurements at HI$\gamma$S

Measurement with monochromatic photons at HI$\gamma$S ($\Delta E \approx 200$ keV).
*Black:* Population of $0_2^+$ neglected.
*Red:* Assumption that $b_{0_2^+} = b_{2_1^+}$.
G. Rusev, A.P. Tonchev et al., priv. comm.

Distribution of branching ratios $b_0 = \Gamma_0/\Gamma$ versus the excitation energy as obtained from the simulations of $\gamma$-ray cascades for $^{90}$Zr.
R.S. et al., PRC 78, 064314 (2008)
Absorption cross section in $^{89}$Y

$^{89}$Y

$E_e = 13.2$ MeV

Present $(\gamma, \gamma)$ data
Absorption cross section in $^{89}\text{Y}$

$^{89}\text{Y}$

$E_e = 13.2$ MeV

$\sigma_\gamma$ (mb)

$E_x$ (MeV)

$\langle\gamma,\gamma'\rangle_{\text{corr}}$

$\langle\gamma,\gamma'\rangle_{\text{uncorr}}$

$S_n$

Present ($\gamma, \gamma$) data
Absorption cross section in $^{89}$Y

$E_e = 13.2$ MeV

Present ($\gamma, \gamma$) data
($\gamma, p$) calculated
Talys

$\sigma_\gamma$ (mb)

$E_x$ (MeV)

$^{89}$Y

$(\gamma, \gamma')_{corr}$

$(\gamma, \gamma')_{uncorr}$

$S_n$
Absorption cross section in $^{89}$Y

$^{89}$Y

$E_e = 13.2$ MeV

Present ($\gamma, \gamma$) data

($\gamma, p$) calculated

Talys

($\gamma, n$) data

NPA 175 (1971) 609
Absorption cross section in $^{89}$Y

Present ($\gamma$, $\gamma$) data
+ ($\gamma$, $p$) data
+ ($\gamma$, $n$) data

Lorentz curve:
$E_0 = 16.8$ MeV
\( \Gamma = 4.1 \) MeV
\( \frac{\pi}{2} \sigma_0 \Gamma = 60 \frac{N Z}{A} \) MeV mb
Absorption cross section in $^{139}$La

Present data for $^{139}$La
A. Makinaga et al., PRC 82, 024314 (2010)

HIGS data for $^{138}$Ba
A. Tonchev et al., PRL 104, 072501 (2010)
Absorption cross section in $^{89}$Y

Present $(\gamma, \gamma)$ data
+ $(\gamma, p)$ data
+ $(\gamma, n)$ data

Lorentz curve:

$E_0 = 16.8$ MeV
$\Gamma = 4.1$ MeV

$\frac{\pi}{2} \sigma_0 \Gamma = 60 \frac{NZ}{A}$ MeV mb
Absorption cross section in $^{89}\text{Y}$

Present ($\gamma, \gamma$) data
+ ($\gamma, p$) data
+ ($\gamma, n$) data

Lorentz curve

Axel-Brink + M1
Absorption cross section in $^{89}$Y

**Graph:**
- Present ($\gamma, \gamma$) data
  - + ($\gamma, p$) data
  - + ($\gamma, n$) data
- Lorentz curve
- Axel-Brink + M1
- Kopecky-Uhl + M1
Absorption cross section in $^{89}$Y

Present ($\gamma, \gamma$) data + ($\gamma, p$) data + ($\gamma, n$) data

Lorentz curve

Axel-Brink + M1

Kopecky-Uhl + M1

QRPA
Woods-Saxon basis
$\Gamma = 3.2$ MeV

PRC 79, 014303 (2009)
Absorption cross sections in Mo isotopes

G. Rusev et al., PRC 79, 061302(R) (2009)
Absorption cross sections in Mo isotopes

\[ \sigma_\gamma(E_x) = \frac{2S_{TRK}}{3\pi} \sum_{i=1}^{3} \frac{E_x^2 \Gamma_i(E_x)}{(E_i^2 - E_x^2)^2 + E_x^2 \Gamma_i^2(E_x)} \]

\[ \Gamma_i(E_x) = \Gamma_S \cdot (E_x/E_i)^\delta; \quad \Gamma_S = 4 \text{ MeV}; \quad \delta \approx 0 \]

\[ S_{TRK} = \int_0^\infty \sigma_\gamma(E) \, dE = 60 \frac{NZ}{A} \text{ MeV mb} \]

\[ E_i = h\omega_0 \left( 1 - \frac{2}{3} \epsilon_2 \cos \left( \gamma - \frac{2\pi i}{3} \right) \right) \]
Hamiltonian for $1^-$ states:
- Nilsson or Woods-Saxon mean field plus monopole pairing
- isoscalar and isovector dipole-dipole and octupole-octupole interactions

F. Dönauf, PRL 94, 092503 (2005), F. Dönauf et al., PRC 76, 014317 (2007)

Total energy as a function of the quadrupole deformation $\varepsilon_2$ and the triaxiality $\gamma$:

TAC model with shell-correction method:
Absorption cross sections in Mo isotopes

Present \((\gamma, \gamma)\) data + \((\gamma, p)\) data + \((\gamma, n)\) data

QRPA, folded with Lorentzian, \(\Gamma = 0.1\) MeV
Shape fluctuations much slower than dipole vibrations \(\Rightarrow\) adiabatic approximation.

Calculation of absorption cross sections for a set of instantaneous deformation parameters \(\{\beta_{2,n}, \gamma_n\}\) of the mean field by means of QRPA:

\[
\sigma_\gamma(E, \beta_{2,n}, \gamma_n).
\]

Probabilities for particular shapes present in the ground state determined as the projections of the ground state \(|0^+_1\rangle\) on the eigenstates \(|n\rangle\) by means of IBA:

\[
P(\beta_{2,n}, \gamma_n) = |\langle 0^+_1 | n \rangle|^2.
\]

Calculation of the total cross section as the incoherent sum of the instantaneous cross sections:

\[
\sigma_\gamma(E) = \sum_n P(\beta_{2,n}, \gamma_n) \sigma_\gamma(E, \beta_{2,n}, \gamma_n).
\]

S.Q. Zhang et al., PRC 80, 021307(R) (2009)
Probability distributions $P(\beta_2, n, \gamma_n)$ of instantaneous nuclear shapes in the $\beta_2 - \gamma$ plane. Distributions of coexisting shapes are shown in blue and red.
Absorption cross sections in Mo isotopes

Present $(\gamma, \gamma)$ data + $(\gamma, p)$ data + $(\gamma, n)$ data

QRPA, folded with Lorentzian, $\Gamma = 0.1$ MeV

ISS-QRPA, folded with Lorentzian, $\Gamma = 0.1$ MeV
Absorption cross sections in Mo isotopes

Present ($\gamma, \gamma$) data + ($\gamma, p$) data + ($\gamma, n$) data

QRPA, folded with Lorentzian, $\Gamma = 0.1$ MeV

ISS-QRPA, folded with Lorentzian, $\Gamma = 0.1$ MeV

ISS-QRPA, folded with Lorentzian, $\Gamma = 0.014/\text{MeV } E^2$

S.Q. Zhang et al., PRC 80, 021307(R) (2009)
Dipole strength in $^{208}$Pb within the shell model

Photon-scattering at ELBE 
$(\gamma,n)$ data from NPA 159, 561 (1970)
Shell-model calculations including (2p-2h) excitations by B.A. Brown

R.S. et al., PRC 81, 054315 (2010)
Summary

- Study of dipole-strength distributions at high excitation energy and high level density via photon scattering.

- Simulations of statistical $\gamma$ cascades: Estimate of intensities of inelastic transitions and correction of intensities of elastic transitions:
  - Reliable determination of $\sigma_\gamma$ up to the neutron-separation energy $S_n$ including unresolved strength.
  - Combination with ($\gamma,p$) and ($\gamma,n$) data gives information on $\sigma_\gamma$ over the whole energy range from low excitation energy up to the giant dipole resonance.
  - Observation of extra strength in the range from 6 to 12 MeV – not described in phenomenological approximations of dipole-strength functions.

- Instantaneous-shape sampling combined with QRPA improves the description of the dipole strength around $S_n$ in transitional nuclei.

- Shell-model calculations including (2p-2h) excitations describe the spreading of the GDR in $^{208}$Pb.

- Further developments are necessary to reproduce the extra strength below $S_n$.

- Consequences of the extra strength for reaction rates need to be studied.
Photodissociation reactions:

- \((\gamma, n)\)
- \((\gamma, p)\)
- \((\gamma, \alpha)\)

Method: photoactivation

- \((A, Z) + \gamma \Rightarrow (A, Z - 1) + p\)
- Measure decay rate of \((A, Z - 1)\)

\[
N_{\text{act}}(E_e) = N_{\text{tar}} \cdot \int_{E_{\text{thr}}}^{E_e} \sigma_{(\gamma,x)} \Phi_{\gamma}(E, E_e) \, dE
\]

\[
N_{\text{act}}(E_e) = I_{\gamma}(E_{\gamma}) \cdot \varepsilon^{-1}(E_{\gamma}) \cdot p^{-1}(E_{\gamma}) \cdot \kappa_{\text{corr}}
\]
Photoactivation of $^{92}\text{Mo}$

$^{91}\text{Mo}$

- Photoactivation process
- $\gamma$ transitions
- Electron capture (EC) and $\beta^+$ decay

\[ N_{\text{act}}(E_e) = N_{\text{tar}} \cdot \int_{E_{\text{thr}}}^{E_e} \sigma(\gamma,x) \cdot \Phi(\gamma,E_e) \cdot dE \]
\[ N_{\text{act}}(E_e) = I(\gamma) \cdot \varepsilon^{-1}(E_\gamma) \cdot p^{-1}(E_\gamma) \cdot \kappa_{\text{corr}} \]
Setup for photoactivation experiments

- Bremsstrahlung cave
  - Aluminium collimator
  - Photo-activation target

- Low-level counting setup
  - Lead wall
  - PE blocks
  - Photon beam dump
  - Lead housing

- Accelerator hall
  - Electron beam
  - Graphite
  - Steel
  - Iron

- Photoactivation target
  - Electron beam dump (rotated by 90°)

- Pneumatic delivery
  - Photoactivated target
  - HPGe detectors
  - Lead castle
  - Dewar depot

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Activation yields of Mo isotopes normalised to the activation yield of the $^{197}$Au($\gamma$, $n$) reaction.


C. Nair et al., PRC 78, 055802 (2008)
M. Erhard et al., PRC 81, 034319 (2010)
Activation yields of $^{144}\text{Sm}$ normalised to the activation yield of the $^{197}\text{Au}(\gamma, n)$ reaction.


C. Nair et al., PRC 78, 055802 (2008)
C. Nair et al., PRC 81, 055806 (2010)
Activation yield – low-background measurement

Spectra of the decay of $^{140}\text{Nd} \rightarrow ^{140}\text{Pr} \rightarrow ^{140}\text{Ce}$ following the $^{144}\text{Sm}(\gamma, \alpha)$ reaction.

Measured in ELBE building

Measured in underground lab “Felsenkeller” in Dresden
Photodissociation of Mo isotopes and of $^{144}$Sm studied via photoactivation at the ELBE accelerator.

Determination of the photon flux in the electron-beam dump by means of the $^{197}$Au$(\gamma, n)$ reaction.

Measurement of weak decay rates in an underground lab.

$^{92}$Mo$(\gamma, \alpha)^{88}$Zr and $^{144}$Sm$(\gamma, \alpha)^{140}$Nd reactions observed for the first time at astrophysically relevant energies.

Rough agreement with predictions of Hauser-Feshbach models for $(\gamma, n)$ and $(\gamma, p)$ reactions. Predictions differ for $(\gamma, \alpha)$ reactions.
Precision Measurement of the Photodissociation of the Deuteron at Energies relevant to Big Bang Nucleosynthesis*

Principal investigators
• Dr. Arnd R. Junghans (project leader)
• Roland Hannaske (PhD student)

Motivation
• experimental p(n,γ)d data are scarce at energies relevant to Big Bang nucleosynthesis (T_{CMS} = 10 - 300 keV)
• nuclear network calculations use p(n,γ)d reaction rates based on theoretical models, nucleon-nucleon scattering data & d(γ,n)p data
• exp. d(γ,n)p data have uncertainties > 10 %

Figure: exp. and theo. cross section data (not complete)
  [Rupak NPA 678 (2000) 405, Arenhövel, priv. com. (2005), Bishop PR 80 (1950) 211,

* This work is supported by the Deutsche Forschungsgemeinschaft under Contract No. JU2705/1-1.
Precision Measurement of the Photodissociation of the Deuteron at Energies relevant to Big Bang Nucleosynthesis*

Setup

- bremsstrahlungs facility at ELBE [Schwengner NIM A555 (2005) 211]
- neutron time-of-flight measurement with fast, low-threshold plastic scintillation detectors [Beyer NIM A575 (2007) 449]
- photon scattering on $^{27}$Al for intensity normalization

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Preliminary results

- energy resolution 3 – 4 
- estimated unc. at 150 keV: 5 % systematic + 5 % statistical

Objective

- differential cross sections (after all systematic effects are analyzed)

Publications


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