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- The bremsstrahlung facility
- Photon-scattering experiments
- Data analysis and results
- QRPA and QPM calculations
- Photoactivation experiments

Supported by Deutsche Forschungsgemeinschaft
Dipole strength close to the particle-separation energy

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

- Studies for transmutation:
  - Analysis of $(n, \gamma)$ reactions.

- Open problems:
  - Precise knowledge of the $E1$ strength on the low-energy tail of the Giant Dipole Resonance.
  - Properties of the $E1$ 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
The bremsstrahlung facility at the electron accelerator ELBE

R.S. et al., NIM A 555 (2005) 211

**Accelerator parameters:**

- Maximum electron energy: 18 MeV
- Maximum average current: 1 mA
- Micro-pulse rate: 13 MHz
- Micro-pulse length: \( \approx 5 \text{ ps} \)
Detector setup
### Nuclides under investigation in photon-scattering experiments

<table>
<thead>
<tr>
<th>Z</th>
<th>Nuclide</th>
<th>$S_n$ (MeV)</th>
<th>$E_{\text{kin}}^\text{ELBE}$</th>
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<tbody>
<tr>
<td>92</td>
<td>Mo</td>
<td>12.7</td>
<td>6.0(^a), 13.2(^{b,c,d})</td>
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<tr>
<td>94</td>
<td>Mo</td>
<td>9.7</td>
<td>13.2(^d)</td>
</tr>
<tr>
<td>96</td>
<td>Mo</td>
<td>9.2</td>
<td>13.2(^d)</td>
</tr>
<tr>
<td>98</td>
<td>Mo</td>
<td>8.6</td>
<td>(3.3, 3.8)(^a,e), (8.5, 13.2)(^{b,c,d})</td>
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<tr>
<td>100</td>
<td>Mo</td>
<td>8.3</td>
<td>(3.2, 3.4, 3.8)(^a), (7.8, 13.2)(^{b,c,d})</td>
</tr>
<tr>
<td>90</td>
<td>Zr</td>
<td>12.0</td>
<td>7.0, 9.0, 13.2</td>
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<tr>
<td>89</td>
<td>Y</td>
<td>11.5</td>
<td>7.0(^f), 9.5, 13.2</td>
</tr>
<tr>
<td>88</td>
<td>Sr</td>
<td>11.1</td>
<td>6.8(^g), (9.0, 13.2, 16.0)(^h)</td>
</tr>
<tr>
<td>87</td>
<td>Rb</td>
<td>9.9</td>
<td>4.0(^i), 13.2</td>
</tr>
<tr>
<td>86</td>
<td>Kr</td>
<td>9.9</td>
<td>11.5</td>
</tr>
</tbody>
</table>

\(^a\) G. Rusev et al., PRC 73 (2006) 044308  
\(^b\) R. Schwengner et al., NPA 788 (2007) 331c  
\(^c\) G. Rusev et al., PRC 77 (2008) 064321  
\(^d\) A. Wagner et al., JPG 35 (2008) 014035  
\(^e\) G. Rusev et al., PRL 95 (2005) 062501  
\(^f\) J. Reif et al., NPA 620 (1997) 1  
\(^g\) L. Käubler et al., PRC 70 (2004) 064307  
\(^h\) R. Schwengner et al., PRC 76 (2007) 034321  
\(^i\) L. Käubler et al., PRC 65 (2002) 054315
Problem of feeding and branching

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

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

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:

$$I_{\gamma}(E_{\gamma}, \Theta) > I_s(E_x) \Phi_{\gamma}(E_x) \epsilon(E_{\gamma}) N_{at} W(\Theta) \Delta\Omega$$

Scattering cross section integral:

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Absolute efficiency of two detectors at 127° deduced from $^{22}$Na, $^{60}$Co, $^{133}$Ba, (filled circles) and simulated with GEANT3 (solid line). Relative efficiencies deduced from $^{56}$Co (open circles), $^{11}$B (open triangles) and $^{16}$O (open square).

Absolute photon flux deduced from transitions in $^{11}$B using the calculated efficiency shown in the left panel and relative photon flux calculated according to G. Roche et al. Code by E. Haug, Rad. Phys. Chem. 77 (2008) 207.
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).
Problem of feeding and branching

**Correction of the strength function by using statistical methods (G. Rusev, Dissertation):**

⇒ Monte Carlo simulations of $\gamma$-ray cascades from groups of levels in 100 keV bins over the whole energy range.

⇒ Level scheme of $J = 0$, 1 and 2 states constructed using:
  ○ Backshifted Fermi-Gas Model with level-density parameters given in:
  ○ Wigner level-spacing distributions

⇒ Partial decay widths calculated by using:
  ○ Photon strength functions approximated by Lorentzian parametrisations.
    – $E1$: parameters determined from a fit to ($\gamma$, $n$) data
    – $M1$: global parametrisation of $M1$ spin-flip resonances
    – $E2$: global parametrisation of $E2$ isoscalar resonances
      (www-nds.iaea.org/RIPL-2)
  ○ 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

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

$^90\text{Zr}$

Ground–state transitions

Branching transitions

$E_\gamma$ (MeV)

$I_\gamma$ (arb. units)

$E_x$ (MeV)

$b_0^\Delta$ (%)

Distribution of branching ratios $b_0 = \Gamma_0/\Gamma$ versus the excitation energy as obtained from the simulations of $\gamma$-ray cascades for $^90\text{Zr}$. ⇒ Estimate of $\Gamma_0$ and $\sigma_\gamma$. 
Test of simulated branching ratios

Measurement with monochromatic photons at H1γS (ΔE ≈ 200 keV).
Black: Population of 0_2^+ neglected.
Red: Assumption that b_0^+ = b_2_1^+.
G. Rusev, A.P. Tonchev et al., priv. comm.

Distribution of branching ratios b_0 = Γ_0/Γ versus the excitation energy as obtained from the simulations of γ-ray cascades for ^{90}Zr.
Test of E1 strength functions

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

\[ \Gamma_i(E_x) = \Gamma_S \cdot \left(\frac{E_x}{E_i}\right)^\delta; \quad \Gamma_S = 4 \text{ MeV}; \]

\[ f_1 = \sigma_\gamma / [3(\pihc)^2E_\gamma] \]

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

\[ E_i = \hbar\omega_0 \left(1 - \frac{2}{3} \epsilon_2 \cos \left(\gamma - \frac{2\pi i}{3}\right)\right) \]
Absorption cross section in $^{90}$Zr

Present ($\gamma, \gamma$) data
Absorption cross section in $^{90}$Zr

Present ($\gamma, \gamma$) data
Absorption cross section in $^{90}$Zr

Present ($\gamma$, $\gamma$) data

($\gamma$, $p$) calculated

ADNDT 88 (2004) 1
Absorption cross section in $^{90}$Zr

Present $(\gamma, \gamma)$ data
$(\gamma, p)$ calculated
ADNDT 88 (2004) 1
$(\gamma, n)$ data
PR 162 (1967) 1098
Absorption cross section in $^{90}$Zr

Present ($\gamma$, $\gamma$) data + ($\gamma$, $p$) + ($\gamma$, $n$) data
Absorption cross section in $^{90}$Zr

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

Lorentz curve:

$E_0 = 16.8$ MeV

$\Gamma = 4.0$ MeV

$\frac{\pi}{2} \sigma_0 \Gamma = 60 \frac{N_Z}{A}$ MeV mb

$E_x$ (MeV)

$\sigma_\gamma$ (mb)
Absorption cross section in $^{90}$Zr

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

Lorentz curve:
$E_0 = 16.8$ MeV
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$\frac{\pi}{2}\sigma_0\Gamma = 60 \frac{N_Z}{A}$ MeV mb

RIPL-2
(S. Goriely, E. Khan, NPA 706 (2002) 217)
Absorption cross section in $^{90}$Zr

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

Lorentz curve:
$E_0 = 16.8$ MeV
$\Gamma = 4.0$ MeV
$\frac{\pi}{2} \sigma_0 \Gamma = 60 \frac{N Z}{A}$ MeV mb

RIPL-2
(S. Goriely, E. Khan, NPA 706 (2002) 217)

QRPA
Woods-Saxon basis
$\Gamma = 3.2$ MeV
Absorption cross section in $^{88}\text{Sr}$

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

Lorentz curve:
$E_0 = 16.8$ MeV
$\Gamma = 4.0$ MeV

$\frac{\pi}{2} \sigma_0 \Gamma = 60 \frac{N_Z}{A} \text{ MeV mb}$

RIPL-2
(S. Goriely, E. Khan, NPA 706 (2002) 217)

QRPA
Woods-Saxon basis:
$\Gamma = 3.2$ MeV
Absorption cross section in $^{89}$Y

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

Lorentz curve:
$E_0 = 16.8$ MeV
$\Gamma = 4.0$ MeV
$\frac{\pi}{2} \sigma_0 \Gamma = 60 \frac{NZ}{A}$ MeV mb

RIPL-2
(S. Goriely, E. Khan, NPA 706 (2002) 217)

QRPA
Woods-Saxon basis:
$\Gamma = 3.2$ MeV
One-phonon QPM calculations for $^{88}\text{Sr}$ and $^{90}\text{Zr}$

Transition densities of neutrons and protons:

Energy range below 9 MeV:

⇒ Oscillations at the surface by neutrons only

⇒ Indication for a PDR
Absorption cross sections in Mo isotopes

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

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

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

\[ E_i = \hbar \omega_0 \left(1 - \frac{2}{3} \epsilon_2 \cos \left(\gamma - \frac{2\pi i}{3}\right)\right) \]
Absorption cross sections in Mo isotopes

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\[ E_i = \hbar \omega_0 \left( 1 - \frac{2}{3} \epsilon_2 \cos \left( \gamma - \frac{2\pi i}{3} \right) \right) \]
Comparison with other experiments

Present $(\gamma, \gamma)$ data

$(\gamma, n)$ data
H. Beil et al., NPA 227 (1974) 427

$(^3\text{He}, ^3\text{He}'\gamma)$ data
M. Guttormsen et al., PRC 71 (2005) 044307

$(n, \gamma)$ data
J. Kopecky and M. Uhl, Bologna 1994
Hamiltonian for $1^{-}$ states:
- Nilsson or Woods-Saxon mean field plus monopole pairing
- isoscalar and isovector dipole-dipole and octupole-octupole interactions
F. Döbau, PRL 94 (2005) 092503
F. Döbau et al., PRC 76 (2007) 014317

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

\[ \begin{align*}
92\text{Mo}_{50} & : \varepsilon_2 = 0.0 \\
94\text{Mo}_{52} & : \varepsilon_2 = 0.02 \\
96\text{Mo}_{54} & : \varepsilon_2 = 0.10, \gamma = 60^\circ \\
98\text{Mo}_{56} & : \varepsilon_2 = 0.18, \gamma = 37^\circ \\
100\text{Mo}_{58} & : \varepsilon_2 = 0.21, \gamma = 32^\circ 
\end{align*} \]

TAC model with shell-correction method:
QRPA calculations in a deformed basis for Mo isotopes

\[ \Sigma(E_x) = \sum_i \sigma_\gamma(E_i) \Delta E \]

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

- Study of dipole-strength distributions at high excitation energy and high level density via photon scattering.
- Comparison of measured spectrum with calculated atomic background: 30 – 40% of the total dipole strength in resolved peaks and 70 – 60% in continuum.
- Simulations of statistical $\gamma$ cascades: Estimate of intensities of inelastic transitions.
- Deduced $\sigma_\gamma$ connect smoothly with $(\gamma,n)$ data.

$\Rightarrow$ (i) Correct determination of $\sigma_\gamma$ up to the $(\gamma,n)$ threshold.
(ii) Information on the photoabsorption cross section over the whole energy range from low excitation energy up to the GDR.
(iii) Observation of extra strength in the range from 6 to 12 MeV – not described in current approximations of dipole-strength functions.

$\Rightarrow$ QPM calculations:
(i) Qualitative description of the observed extra strength.
(ii) Extra strength below 9 MeV caused by oscillations of the excessive neutrons.
(iii) Increase of dipole strength below the neutron-threshold toward the heavier Mo isotopes is correlated with increasing deformation.
Photodissociation

Photodissociation reactions:

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

Method: photoactivation

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

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

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

$^{92}$Mo

$^{91}$Mo

$^{91}$Nb

$^{91}$Zr

$^{41}$Zr

$^{41}$Nb

$^{42}$Zr

$^{42}$Nb

$^{42}$Sn

$^{42}$Mo

$^{41}$Sn

$^{41}$Mo

$^{40}$Zr

$N_{act}(E_e) = N_{tar} \cdot \int_{E_{thr}}^{E_e} \sigma(\gamma,x) \cdot \Phi_\gamma(E, E_e) \ dE$

$N_{act}(E_e) = I_\gamma(E_\gamma) \cdot \varepsilon^{-1}(E_\gamma) \cdot p^{-1}(E_\gamma) \cdot \kappa_{corr}$
Setup for photoactivation experiments

Accelerator hall

Bremsstrahlung cave

Low-level counting setup

Electron beam

Graphite

Steel

Iron

Electron beam dump (rotated by 90°)

Photoactivation target

Aluminium collimator

Photo-activation target

Lead wall

PE blocks

Photon beam dump

Lead housing

HPGe detectors

Photoactivated target

Pneumatic delivery

Lead castle

Dewar Depot

HPGe detector

Lead

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


Activation yield

Solid lines: NON-SMOKER,
T. Rauscher and F.-K. Thielemann,
ADNDT 88 (2004) 1

Dashed lines: TALYS,
A. Koning et al.,

Activation yields of $^{144}\text{Sm}$ normalised to the activation yield of the $^{197}\text{Au}(\gamma, n)$ reaction.
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
Summary

- 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.