Electromagnetic excitations in nuclei: from photon scattering to photodisintegration

R. Beyer\textsuperscript{1}, F. Döna\textsuperscript{1}, M. Erhard\textsuperscript{1}, E. Grosse\textsuperscript{1,2}, A. R. Junghans\textsuperscript{1}, K. Kosev\textsuperscript{1}, C. Nair\textsuperscript{1}, N. Nankov\textsuperscript{1,3}, G. Rusev\textsuperscript{1}, K. D. Schilling\textsuperscript{1}, R. Schwengner\textsuperscript{1}, A. Wagner\textsuperscript{1}

\textsuperscript{1} Institut für Kern- und Hadronenphysik, Forschungszentrum Rossendorf, 01314 Dresden, Germany
\textsuperscript{2} Institut für Kern- und Teilchenphysik, Technische Universität Dresden, 01062 Dresden, Germany
\textsuperscript{3} Institute for Nuclear Research and Nuclear Energy, BAS, 1784 Sofia, Bulgaria

- The bremsstrahlung facility
- Photon-scattering experiments
- Photoactivation experiments

Supported by Deutsche Forschungsgemeinschaft
The bremsstrahlung facility at the radiation source 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: < 10 ps
Detector setup
Dipole strength close to the particle-separation energy

- Importance for the understanding of astrophysical processes.
  ⇒ Influence on $(\gamma,n)$ reaction rates for the production of particular neutron-deficient nuclei in the so-called p-process.

- Open problems:
  - The precise knowledge of $E1$ strength on the low-energy tail of the Giant Dipole Resonance
  - The properties of the Pygmy Dipole Resonance, a concentration of $E1$ strength in the energy range between about 5 MeV and 11 MeV.
### Nuclides under investigation in photon-scattering experiments

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>$S_n$ (MeV)</th>
<th>$E_{e}^{\text{kin}}$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{92}\text{Mo}$</td>
<td>12.7</td>
<td>6.0, 13.2</td>
</tr>
<tr>
<td>$^{98}\text{Mo}$</td>
<td>8.6</td>
<td>3.3$^a$, 3.8$^a$, 13.2</td>
</tr>
<tr>
<td>$^{100}\text{Mo}$</td>
<td>8.3</td>
<td>3.2$^a$, 3.4$^a$, 3.8$^a$, 7.8, 13.2</td>
</tr>
<tr>
<td>$^{88}\text{Sr}$</td>
<td>11.1</td>
<td>6.8$^b$, 9.0, 13.2, 16.0</td>
</tr>
<tr>
<td>$^{89}\text{Y}$</td>
<td>11.5</td>
<td>7.0$^c$, 13.2</td>
</tr>
<tr>
<td>$^{90}\text{Zr}$</td>
<td>12.0</td>
<td>7.0, 9.0, 12.8</td>
</tr>
</tbody>
</table>

**ELBE experiment**

- $^a$ Dynamitron experiment, PRL 95 (2005) 062501
- $^b$ S-Dalinac experiment, PRC 70 (2004) 064307
- $^c$ S-Dalinac experiment, NPA 620 (1997) 1
Photon scattering from $^{92}$Mo, $^{98}$Mo and $^{100}$Mo

$^{92}$Mo ($\gamma,\gamma'$) $E_e = 13.2$ MeV
$S_n = 12.7$ MeV
$S_p = 7.5$ MeV
345 transitions

$^{98}$Mo ($\gamma,\gamma'$) $E_e = 13.2$ MeV
$S_n = 8.6$ MeV
510 transitions

$^{100}$Mo ($\gamma,\gamma'$) $E_e = 13.2$ MeV
$S_n = 8.3$ MeV
535 transitions
Angular distributions of transitions in $^{92}$Mo, $^{98}$Mo and $^{100}$Mo
Linear polarisations of transitions in $^{88}$Sr

$L = 1$: $I_\gamma(90^\circ)/I_\gamma(127^\circ) = 0.73$

$L = 2$: $I_\gamma(90^\circ)/I_\gamma(127^\circ) = 2.28$

Experimental asymmetries of transitions in $^{88}$Sr.
Problem of feeding and branching

Measured intensity of a $\gamma$ transition:

$$I_\gamma(E_\gamma, \Theta) = I_s(E_x) \cdot \Phi_\gamma(E_x) \cdot \epsilon(E_\gamma) \cdot N_{\text{at}} \cdot W(E_\gamma, \Theta) \cdot d\Omega$$

Energy-integrated cross section:

$$I_s = \int \sigma_{\gamma\gamma0} \, dE$$

$$I_s = \frac{2J_x + 1}{2J_0 + 1} \left( \frac{\pi \hbar c}{E_x} \right)^2 \frac{\Gamma_0}{\Gamma} \Gamma_0; \quad \Gamma = \frac{\hbar}{\tau}$$

$E1$ strength:

$$B(E1) \sim \Gamma_0 / E_\gamma^3$$
Unresolved strength in the continuum

\[ f_1(E) = \frac{1}{\Delta} \sum_{\Delta} \frac{\Gamma_0}{E^3} \]
Correction of feeding and branching

Simulation of the intensity distribution of ground-state and branching transitions.

Intensity distribution of ground-state transitions after correction for branchings and feedings.

ground-state transitions
branchings
continuum
branchings and feedings corrected continuum

$E_\gamma$ / MeV

Photon / (100 keV*sr)

$^{98}$Mo

Forschungszentrum
Rossendorf

Institut für Kern- und Hadronenphysik
Correction of feeding and branching

Simulated distribution of branching ratios $B_0 = \Gamma_0 / \Gamma$.

Absorption cross section $\sigma_\gamma \sim \Gamma_0 / E_\gamma^2$.
Absorption cross sections in $^{92}\text{Mo}$, $^{98}\text{Mo}$ and $^{100}\text{Mo}$

$(\gamma,n)$ - experiment: H. Beil et al., NPA 227 (1974) 427
$(\gamma,p)$ - theory: T. Rauscher and F.-K. Thielemann, ADNDT 88 (2004) 1
RPA calculations for deformed nuclei

Energy-weighted sum rule from experiments and RPA calculations:

\[ EWSR(E_x) = \sum_{i}^{E_x} \sigma(\gamma_i) \Delta E \]
RPA calculations for deformed nuclei

Hamiltonian for $1^-$ states:
- Nilsson mean field plus monopole pairing
- isoscalar and isovector dipole-dipole and octupole-octupole interactions
F. Dönau, PRL 94 (2005) 092503

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

$^{92}\text{Mo}_{50}$
$\varepsilon_2 = 0.0$

$^{94}\text{Mo}_{52}$
$\varepsilon_2 = 0.02$

$^{96}\text{Mo}_{54}$
$\varepsilon_2 = 0.10$
$\gamma = 60^\circ$

$^{98}\text{Mo}_{56}$
$\varepsilon_2 = 0.18$
$\gamma = 37^\circ$

$^{100}\text{Mo}_{58}$
$\varepsilon_2 = 0.21$
$\gamma = 32^\circ$

TAC model with shell-correction method
Summary

- Dipole-strength distributions of even-even Mo isotopes studied up to neutron-separation energies at the photon-scattering facility of the ELBE accelerator.
- Simulations of $\gamma$ cascades from excited levels:
  - Estimate of branchings and feedings.
- The reconstructed dipole-strength distributions connect smoothly with the low-energy tails of the Giant Dipole Resonances.
- RPA calculations in a deformed basis reproduce the dipole-strength distributions in the series of Mo isotopes.
P-nuclei and the \( \gamma \)-process

- 35 p-nuclei from \( ^{74}\text{Se} \) to \( ^{196}\text{Hg} \) cannot be produced in the s- or r-processes.
- They are produced and destroyed by the p- or \( \gamma \)-process at temperatures of \( T \approx (2 - 3) \cdot 10^9 \) K.
- The \( \gamma \)-process comprises \((\gamma,n)\), \((\gamma,p)\) and \((\gamma,\alpha)\) reactions starting from s- and r-process seed nuclei.
- Abundances of p-nuclei are 10 to 1000 times smaller than those of their neutron-rich isotopes - except for Mo and Ru.
Calculation of abundances of p-nuclei

- The abundances of Mo and Ru are underestimated by network calculations.
- Are the reaction rates correct?

$\Rightarrow$ Study of the photodisintegration of $^{92}$Mo

M. Arnould, S. Goriely,
PR 384 (2003) 1
Setup for photoactivation experiments
Setup for photoactivation experiments
**Activation yield**

Activation yield of the $^{197}$Au($\gamma$, n) reaction. The yield is normalised to the number of $^{197}$Au atoms and to the absolute photon flux at $E_x = 8921$ keV.

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

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

- Endpoint energy derived from the photodisintegration of $^2$H.
- Photon-flux distribution from known widths in $^{11}$B.
- Determination of the photon flux in the electron-beam dump by means of the $^{197}$Au($\gamma$, $n$) reaction.
- Rough agreement of the activation yield with theoretical predictions.
- $^{92}$Mo($\gamma$, $\alpha$)$^{88}$Zr observed for the first time.