Nuclear-structure and nuclear-astrophysics experiments at the superconducting electron accelerator ELBE

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

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Bremsstrahlung facility at the ELBE accelerator

Accelerator parameters:

- Maximum electron energy: 20 MeV
- Maximum average current: 1 mA
- Micro-pulse rate: 26 or 260 MHz
- Reduction of 26 MHz by factors of 2 to 256
- Macro pulse of 0.1 to 36 ms length with periods of 40 ms to 1 s
Electron-beam line
Simulation of the flux of photons passing the collimator

Simulations with GEANT4:

- Number of photons produced by $10^9$ electrons of $E_{e}^{\text{kin}} = 12$ MeV in a cone with an opening angle of 5 mrad as a function of the niobium-radiator thickness.

- Number of photons produced by $10^9$ electrons of $E_{e}^{\text{kin}} = 12$ MeV in niobium radiators of different thicknesses as a function of the angle between electron beam and photon.
Niobium radiators:

- Six radiator foils of 16 mm diameter mounted on a water-cooled copper rod
- Thicknesses of 2, 3, 4, 5, 7 and 12.5 μm, corresponding to $2 \cdot 10^{-4}$ to $10^{-3}$ radiation lengths
- Radiator holder can be moved by a DC motor drive to select a radiator without breaking the vacuum
Detector setup
Beam dump

$E_{\gamma} = 12$ MeV

Photon-beam dump

GEANT3 simulation with 1000 trajectories of 12 MeV photons.
About 0.3 % of the photons are scattered back towards the detectors.
Background measurements

(a) Radiator thickness 4 μm, average beam current 480 μA, $^{208}$Pb target of mass 1 g
(b) Radiator thickness 4 μm, average beam current 480 μA, no target
(c) Room background
  • Measuring time 400 min
Measurement of the electron energy via photodisintegration of deuterons

Spectra measured with Si detectors of 300 μm thickness during the irradiation of a deuterated polyethylene film with bremsstrahlung.

Spectrum of incident photons recalculated from the proton spectrum and the cross section for the disintegration of the deuteron.

σ_{dis}: H. Bethe, C. Longmire, Phys. Rev. 77 (1950) 647
Schiff: L.I. Schiff, Phys. Rev. 83 (1951) 252
Production of linearly polarised off-axis bremsstrahlung
Measurement with polarised photons

Degree of polarisation vs. photon energy as deduced from proton spectra.

Experimental asymmetries of transitions in $^{208}$Pb.
Photon scattering from $^{208}\text{Pb}$

$^{208}\text{Pb}(\gamma,\gamma')$

$E_e^{\text{kin}} = 17\ \text{MeV}$

$\Theta = 127^\circ$
Nuclear resonance fluorescence
**Photon scattering**

**Experimental needs:**
- Continuous photon spectrum of high intensity
  \[\Rightarrow\text{bremsstrahlung}\]
- Variable end-point energy
  \[\Rightarrow\text{tunable electron energy}\]

**Experimental observables:**
- Energy of the scattered photons \(\rightarrow E\)
- Intensity of the scattered photons \(\rightarrow \Gamma\)
- Angular distribution of the scattered photons \(\rightarrow J\)
- Polarisation of the scattered photons \(\rightarrow \pi\)
  \[\Rightarrow\text{Compton polarimeter (}E_\gamma < 5 \text{ MeV)}\]
  \[\Rightarrow\text{polarised bremsstrahlung for higher } \gamma \text{ energies}\]
Photon scattering

\[ I_\gamma(E_\gamma, \Theta) = \sigma_s(E_i) \cdot \Phi_\gamma(E_i) \cdot \epsilon(E_\gamma) \cdot N_{at} \cdot \frac{d\Omega}{4\pi} \cdot W(E_\gamma, \Theta) \]

\[ \frac{\sigma_s(E_i)}{\sigma_s(E_i^B)} = \frac{I_\gamma(E_\gamma, \Theta)}{I_\gamma(E_\gamma^B, \Theta)} \cdot \frac{\epsilon(E_\gamma^B)}{\epsilon(E_\gamma)} \cdot \frac{W(E_\gamma^B, \Theta)}{W(E_\gamma, \Theta)} \cdot \frac{N_{at}^B}{N_{at}} \cdot \frac{\Phi_\gamma(E_i^B)}{\Phi_\gamma(E_i)} \]

\[ \sigma_s = g \left( \frac{\pi \hbar c}{E_i} \right)^2 \frac{\Gamma_0 \Gamma_f}{\Gamma}; \quad g = \frac{2J_i + 1}{2J_0 + 1}; \quad \Gamma = \frac{\hbar}{\tau} \]

\[ B(E1)_{\uparrow} = g B(E1)_{\downarrow} = 2.866 \cdot 10^{-3} \cdot \frac{\Gamma_0/\text{meV}}{(E_\gamma/\text{MeV})^3} \cdot e^2 \text{fm}^2 \]

\[ B(M1)_{\uparrow} = g B(M1)_{\downarrow} = 0.2598 \cdot \frac{\Gamma_0/\text{meV}}{(E_\gamma/\text{MeV})^3} \cdot \mu_N^2 \]

\[ B(E2)_{\uparrow} = g B(E2)_{\downarrow} = 6201 \cdot \frac{\Gamma_0/\text{meV}}{(E_\gamma/\text{MeV})^5} \cdot e^2 \text{fm}^4 \]
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>13.2</td>
</tr>
<tr>
<td>$^{100}\text{Mo}$</td>
<td>8.3</td>
<td>7.8, 13.2</td>
</tr>
<tr>
<td>$^{88}\text{Sr}$</td>
<td>11.1</td>
<td>3.2, 3.4, 3.8</td>
</tr>
<tr>
<td>$^{90}\text{Zr}$</td>
<td>12.0</td>
<td>7.0, 9.0</td>
</tr>
</tbody>
</table>

* $^{a}$ Dynamitron experiment, PRL 95 (2005) 062501
* $^{b}$ S-Dalinac experiment, PRC 70 (2004) 064307
M1 strength in even-even Mo isotopes up to 4 MeV

$^{92}$Mo$_{50}$

$\Sigma B(M1) = 0.56(4) \mu_N^2$

$^{94}$Mo$_{52}$

$\Sigma B(M1) = 0.67(7) \mu_N^2$

$^{96}$Mo$_{54}$

$\Sigma B(M1) = 0.47(2) \mu_N^2$

$^{98}$Mo$_{56}$

$\Sigma B(M1) = 0.74(3) \mu_N^2$

$^{100}$Mo$_{58}$

$\Sigma B(M1) = 0.98(4) \mu_N^2$

$^{94}$Mo: C. Fransen et al.,
PRC 67 (2003) 024307

$^{96}$Mo: C. Fransen et al.,
PRC 70 (2004) 044317
Deformation of even-even Mo isotopes

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

- $^{92}$Mo$_{50}$
  - $\varepsilon_2 = 0.0$
- $^{94}$Mo$_{52}$
  - $\varepsilon_2 = 0.02$
- $^{96}$Mo$_{54}$
  - $\varepsilon_2 = 0.10$
  - $\gamma = 60^\circ$
- $^{98}$Mo$_{56}$
  - $\varepsilon_2 = 0.18$
  - $\gamma = 37^\circ$
- $^{100}$Mo$_{58}$
  - $\varepsilon_2 = 0.21$
  - $\gamma = 32^\circ$

TAC model with shell-correction method
M1 strength in even-even Mo isotopes up to 4 MeV

\[ \Sigma B(M1)_{\text{EXP}} = 0.56(4) \mu_N^2 \]
\[ \Sigma B(M1)_{\text{RPA}} = 0.21 \mu_N^2 \]

\[ \Sigma B(M1)_{\text{EXP}} = 0.67(7) \mu_N^2 \]
\[ \Sigma B(M1)_{\text{RPA}} = 0.19 \mu_N^2 \]

\[ \Sigma B(M1)_{\text{EXP}} = 0.47(2) \mu_N^2 \]
\[ \Sigma B(M1)_{\text{RPA}} = 0.58 \mu_N^2 \]

Deformed-RPA calculations
Spin-spin interaction
Suppression of spurious modes
F. Dönau, PRL 94 (2005) 092503
Photon scattering from $^{92}\text{Mo}$, $^{98}\text{Mo}$ and $^{100}\text{Mo}$

$^{92}\text{Mo} (\gamma,\gamma^\prime) E_e = 13.2 \text{ MeV}$

$S_n = 12.7 \text{ MeV}$

$S_p = 7.5 \text{ MeV}$

345 transitions

$^{98}\text{Mo} (\gamma,\gamma^\prime) E_e = 13.2 \text{ MeV}$

$S_n = 8.6 \text{ MeV}$

510 transitions

$^{100}\text{Mo} (\gamma,\gamma^\prime) E_e = 13.2 \text{ MeV}$

$S_n = 8.3 \text{ MeV}$

535 transitions
Detection limits

\[ p_{DL} = 3 \sqrt{\frac{\eta_P}{\eta_B}} B \]

Angular distributions of transitions in $^{92}\text{Mo}$, $^{98}\text{Mo}$ and $^{100}\text{Mo}$

Expected values:

$L = 1$:

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

$L = 2$:

$I_\gamma(90^\circ)/I_\gamma(127^\circ) = 2.28$
E1 strength in $^{92}$Mo, $^{98}$Mo and $^{100}$Mo

The summed $B(E1)$ strength decreases with increasing $N/Z$. 
E1 strength in even-even Mo isotopes and in even-even N = 50 isotones

The summed $B(E1)$ strength decreases with increasing $N/Z$.

The summed $B(E1)$ strength increases with increasing $N/Z$. 

$\begin{align*}
\sum B(E1) / (e^2 fm^2) \\
\end{align*}$
Unresolved strength in the continuum

\[ f_L(E) = \frac{1}{\Delta} \sum \frac{\Gamma_0}{E^3} \]
The summed $B(E1)$ strength decreases with increasing $N/Z$. The summed $B(E1)$ strength increases with increasing $N/Z$. 

E1 strength in even-even Mo isotopes and in even-even N = 50 isotones
Statistical analysis

Level-spacing distributions for levels with $E > 4$ MeV. The drawn lines represent Wigner distributions.

Distributions of reduced level widths for levels with $E > 4$ MeV. The drawn lines represent Porter-Thomas distributions.
Problem of feeding and branching

Feeding from high-lying states:
→ Determination of the widths $\Gamma$ from measurements at various energies

Branching to low-lying states:
→ Correction of the strength distribution $f_L$ by using statistical methods:
The branching ratios $\Gamma_f/\Gamma$ are calculated by means of Monte Carlo simulations of the decays. Intensities are corrected with calculated branching ratios.

A level scheme of $J = 1$ and 2 states is constructed with a model using the Wigner level-spacing distribution and level densities given by the backshifted Fermi-gas model. The partial decay width is given by:

$$
\Gamma_{if} = \sum_{X,L} y_{XL}^2 (E_i - E_f)^{2L+1} \frac{f_{XL}(E_i - E_f)}{\rho(E_i, J_i^\pi)}
$$
Reconstructed dipole-strength distributions in $^{92}$Mo, $^{98}$Mo and $^{100}$Mo

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

$(\gamma, n)$ and $(\gamma, p)$ - theory:
T. Rauscher and
F.-K. Thielemann,
ADNDT 88 (2004) 1

$$E < S_n : \quad f_L(E) = \frac{1}{3(\pi hc)^2} \sum_i \int \frac{\sigma_i^{\text{corr}}}{E_i} dE$$

$$E > S_n : \quad f_L(E) = \frac{1}{3(\pi hc)^2} \left\langle \frac{\sigma_{\gamma,n}(E)}{E} \right\rangle$$
Accumulative E1 strength

$\sum f / 10^{-6} \text{MeV}^3$

$E_x / \text{MeV}$

$^{98}\text{Mo}$

$^{100}\text{Mo}$

(\gamma,\gamma) - not corrected
(\gamma,\gamma) - corrected
RPA
Photon scattering from $^{88}$Sr and $^{90}$Zr

$^{88}$Sr($\gamma$,$\gamma'$) $E_e^{\text{kin}} = 9$ MeV $\theta = 127^0$

$^{90}$Zr($\gamma$,$\gamma'$) $E_e^{\text{kin}} = 9$ MeV $\theta = 127^0$
Summary

- Dipole-strength distributions of even-even Mo isotopes have been studied up to the respective neutron-separation energies at the photon-scattering facility of the ELBE accelerator.
- The $M1$ strength distributions up to $E_x < 4$ MeV fragment with increasing deformation, which is qualitatively described by deformed-RPA calculations.
- The total $E1$ strength above 5 MeV decreases with increasing $N/Z$ of the Mo isotopes, which is reproduced by deformed-RPA predictions.
- The total $E1$ strength above 5 MeV increases with increasing $N/Z$ for $N = 50$ isotones.
- The high level density above 5 MeV in connection with feeding by high-lying states and branchings to low-lying states require new techniques in order to reconstruct the original dipole-strength distributions.
- Simulations of the decay of excited levels deliver an estimate of the branchings. The reconstructed dipole-strength distributions fit the low-energy tails of the giant dipole resonances.
P-nuclei and the $\gamma$-process

- 35 p-nuclei from $^{74}$Se to $^{196}$Hg cannot be produced in the s- or r-processes.
- They are produced and destructed 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?

⇒ Study of the photodissociation of $^{92}$Mo

M. Arnould, S. Goriely,
PR 384 (2003) 1
Setup for photoactivation experiments
Photoactivation of $^{92}\text{Mo}$

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

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

\[
N_{act}(E_e) = I_\gamma(E_\gamma) \cdot \varepsilon^{-1}(E_\gamma) \cdot p^{-1}(E_\gamma) \cdot \kappa_{corr}
\]
Activation yield of the $^{197}\text{Au}(\gamma, n)$ reaction. The yield is normalised to the number of $^{197}\text{Au}$ atoms and to the absolute photon flux at $E_{\gamma} = 8917$ keV.

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

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

- Endpoint energy derived from the photodissociation of $^2\text{H}$.
- Photon-flux distribution deduced from photon scattering from states with known widths in $^{11}\text{B}$.
- Determination of the photon flux in the electron-beam dump by means of gold targets.
- Determination of the activation yield of the $^{92}\text{Mo}(\gamma, p)^{91m}\text{Nb}$ reaction up to $S_n(^{92}\text{Mo})$ via the decay $^{91m}\text{Nb(EC)} \rightarrow ^{91}\text{Zr} (E_\gamma = 1205 \text{ keV})$.
- Good agreement of the activation yield with theoretical predictions.
- $^{92}\text{Mo}(\gamma, \alpha)^{88}\text{Zr}$ observed for the first time.