DIPOLE-STRENGTH FUNCTIONS STUDIED IN PHOTON-SCATTERING EXPERIMENTS AT ELBE

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- The bremsstrahlung facility
- Photon-scattering experiments
- Data analysis and results
- Comparison with model predictions

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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: \( \approx 5 \text{ ps} \)
Electron-beam line
**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
Simulation of the flux of photons passing the collimator

**Simulations with GEANT4:**

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

$\sigma_{\text{dis}}$: H. Bethe, C. Longmire, Phys. Rev. 77 (1950) 647
Schiff: L.I. Schiff, Phys. Rev. 83 (1951) 252
Absolute detector efficiency and photon flux

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

Absolute photon flux deduced from transitions in $^{11}\text{B}$ (open triangles) 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).
GEANT3 simulation with 1000 trajectories of 12 MeV photons.

About 0.3 % of the photons are scattered back towards the detectors.
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.

\[
T = 1.0 \times 10^9 \text{ K} \quad N_n = 10^{20} \text{ cm}^2
\]

\[
T = 1.5 \times 10^9 \text{ K} \quad N_n = 10^{28} \text{ cm}^2
\]

S. Goriely, PLB 436 (1998) 10
Nuclides under investigation in photon-scattering experiments

<table>
<thead>
<tr>
<th>nuclide</th>
<th>$S_n$ (MeV)</th>
<th>$E_{\text{kin}}^e$ (MeV)</th>
<th>ELBE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{92}$Mo</td>
<td>12.7</td>
<td>$6.0^a, 13.2^{b,c}$</td>
<td></td>
</tr>
<tr>
<td>$^{94}$Mo</td>
<td>9.7</td>
<td>13.2</td>
<td></td>
</tr>
<tr>
<td>$^{96}$Mo</td>
<td>9.2</td>
<td>13.2</td>
<td></td>
</tr>
<tr>
<td>$^{98}$Mo</td>
<td>8.6</td>
<td>(3.3, 3.8)$^{a,d}$, 8.5, 13.2$^{b,c}$</td>
<td></td>
</tr>
<tr>
<td>$^{100}$Mo</td>
<td>8.3</td>
<td>(3.2, 3.4, 3.8)$^a$</td>
<td></td>
</tr>
<tr>
<td>$^{90}$Zr</td>
<td>12.0</td>
<td>7.0, 9.0, 12.8</td>
<td></td>
</tr>
<tr>
<td>$^{89}$Y</td>
<td>11.5</td>
<td>7.0$^e$, 9.5, 13.2</td>
<td></td>
</tr>
<tr>
<td>$^{88}$Sr</td>
<td>11.1</td>
<td>6.8$^f$, 9.0, 13.2, 16.0$^g$</td>
<td></td>
</tr>
<tr>
<td>$^{87}$Rb</td>
<td>9.9</td>
<td>4.0$^h$, 13.2</td>
<td></td>
</tr>
<tr>
<td>$^{86}$Kr</td>
<td>9.9</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

References:
- $^a$ G. Rusev et al., PRC 73 (2006) 044308
- $^b$ G. Rusev et al., EPJA 27 (2006) s01, 171
- $^c$ R. Schwengner et al., NPA 788 (2007) 331c
- $^d$ G. Rusev et al., PRL 95 (2005) 062501
- $^e$ J. Reif et al., NPA 620 (1997) 1
- $^f$ L. Käubler et al., PRC 70 (2004) 064307
- $^g$ R. Schwengner et al., PRC 76 (2007) 034321
- $^h$ L. Käubler et al., PRC 65 (2002) 054315
Photon scattering from $^{88}\text{Sr}$

$^{88}\text{Sr}(\gamma,\gamma')$

$E_{e\text{kin}} = 13.2 \text{ MeV}$

$\theta = 127^\circ$
Measurement with polarised photons

Degree of polarisation as deduced from spectra of protons emitted in the disintegration of deuterons $d(\vec{\gamma}, p) n$.

Asymmetries $(N_{\gamma\parallel} - N_{\gamma\perp})/(N_{\gamma\parallel} + N_{\gamma\perp})$ of intensities of $\gamma$ rays in $^{88}$Sr.
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:

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

Scattering cross section integral:

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

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

**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:
  - 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 $\Gamma_0/\Gamma$. 
Unresolved strength in the continuum

Experimental spectrum of $^{88}$Sr (corrected for room background, detector response, efficiency, measuring time) and simulated spectrum of atomic background.

Dipole strengths in $^{88}$Sr, not corrected for branching and averaged over energy bins of 0.2 MeV, as derived from the difference of the experimental spectrum and the atomic background (triangles) and from the isolated peaks only (circles).
Correction for feeding and branching by using statistical methods

Simulated intensity distribution of transitions de-populating levels in a 100 keV bin around 11 MeV.

Distribution of branching ratios $b_0 = \Gamma_0/\Gamma$ versus the excitation energy as obtained from the simulations of $\gamma$-ray cascades for $^{88}$Sr. Solid line: mean values of $b_0$. Dashed lines: maximum uncertainties of $b_0$ resulting from the various nuclear realizations.
Absorption cross section in $^{88}\text{Sr}$

Present $(\gamma, \gamma')$ data
Absorption cross section in $^{88}\text{Sr}$

$\sigma_\gamma (\text{mb})$ vs $E_x (\text{MeV})$

Present ($\gamma, \gamma$) data
Monoenergetic photons
PRC 8 (1973) 1421
Absorption cross section in $^{88}\text{Sr}$

Present $(\gamma, \gamma)$ data
$(\gamma, n)$ data
NPA 175 (1971) 609
$(\gamma, n)$ data
VTYF 8 (1982) 121
Absorption cross section in $^{88}\text{Sr}$

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

$\frac{\pi}{2}\sigma_0\Gamma = 60 \frac{NZ}{A}$ MeV mb
**Absorption cross section in $^{88}$Sr**

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

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

QRPA

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

$\sigma_\gamma$ (mb) vs. $E_x$ (MeV)

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

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

QRPA
Woods-Saxon basis:
$\Gamma = 3.2$ MeV
Absorption cross section in $^{90}$Zr

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

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

QRPA
Woods-Saxon basis:
$\Gamma = 3.2$ MeV
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
**Hamiltonian for $1^-$ states:**
- Nilsson or Woods-Saxon mean field plus monopole pairing
- Isoscalar and isovector dipole-dipole and octupole-octupole interactions

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

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

![Graphs](image)

- $^{92}$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:**
Experiments and QRPA calculations for deformed Mo isotopes

\[
\Sigma(E_x) = \sum_i \sigma_\gamma(E_i) \Delta E \\
\Sigma_{TRK} = 60 \frac{NZ}{A} \text{ MeV mb}
\]
Deformed and spherical QRPA calculations for Mo isotopes

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

\[ \Sigma_{\text{TRK}} = 60 \frac{NZ}{A} \text{ MeV mb} \]
Summary

- Study of dipole-strength functions of $N=50$ isotones and of even-even Mo isotopes up to the neutron-separation energies at the photon-scattering facility of ELBE.

- Measurement with polarised photons for $^{88}\text{Sr}$: Multipolarity $E1$ deduced for 50 g.s. transitions above 6 MeV including 63% of the total $E1$ strength of all g.s. transitions.

- 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 branching transitions.

- The reconstructed $\sigma_\gamma$ connect smoothly with $(\gamma,n)$ data.

⇒ For the first time in photon-scattering experiments:
  (i) Correct determination of the dipole-strength function at high excitation energy.
  (ii) Information on the photoabsorption cross section over the whole energy range up to the GDR.

- QRPA calculations:
  (i) Reproduction of observed extra strength in the energy range from 6 – 12 MeV.
  (ii) The increase of the dipole strength towards the heavier Mo isotopes is correlated with increasing deformation.