Photon strength functions in Mo region

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Outline

1. MSC spectra in $^{98}$Mo (DANCE measurement)
2. Discussion of PSF in Mo region
Part 1

MSC spectra in $^{98}$Mo

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Oslo, May 18-22, 2015
DANCE @ LANSCE

- Moderated W target gives “white” neutron spectrum, ~14 n’s/proton
- DANCE is on a 20 m flight path / ~1 cm @ beam after collimation
- repetition rate 20 Hz
- pulse width ≈ 125 ns
- DANCE consists of 160 BaF$_2$ crystals

see also talks of John Ullmann and Standa Valenta

Oslo, May 18-22, 2015
Multi-step Cascades spectra

B_n+E_n

Neutron capturing states

Energy (keV)

Intensity (arb. units)

Multiplicity = 1

Multiplicity = 2

Multiplicity = 3

Multiplicity = 4

Multiplicity > 4

E_γ^1

E_γ^2

E_γ^3

E_γ^4

Ground state

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MSC spectra

- Spectra for different multiplicities from different resonances \( J^\pi = 2^+,3^+,1^-,2^-,3^-,4^- \)

- Spectral shape and multiplicity distribution depends on resonance \( J^\pi \) - in fact, we are not able to clearly distinguish resonances with \( 2^+, 2^- \) and \( 3^+, 3^- \)

- Spectral shapes not identical due to Porter-Thomas fluctuations of individual \( \gamma \) intensities
MSC spectra

- Experimental spectra can be compared with predictions from simulations based on statistical model for different PSF and LD models – “try and error approach”
- DICEBOX code is used for simulation of $\gamma$ decay of resonances with different $J^\pi$; detector response simulated using GEANT4
- Several models describing experimental data from several experiments were tested
- One normalization coefficient for all multiplicities needed for matching experimental with simulated data
- Problem with quantitative comparison as individual points in spectra are strongly correlated
MSC spectra

- Model describing MSC and TSC spectra in $^{95}\text{Mo}(n,\gamma)$
- Temperature-dependent (GLO) model for E1 transitions in combination with spin-flip and single-particle (const.) M1 strength and BSFG NLD

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MSC spectra

- “Oslo-type model” (temperature-independent)
MSC spectra

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- Problems seen especially in the shape of $m=3$ spectra
MSC spectra

- “Rossendorf type model” – extrapolation down to low $E_\gamma$ must be assumed
MSC spectra

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- problems either
  - in the shape of spectra, especially $m=3$ or
  - in multiplicity distribution
MSC spectra

• “HI$\gamma$S model” – extrapolation down to low $E_{\gamma}$ must be assumed

• TLO Lorentzian is shown in this case
  – $E_{\gamma}$ dependence of TLO is indistinguishable from SLO below $S_n$; only difference in absolute values

• Any model with “low strength” at low $E_{\gamma}$ suffers from prediction of multiplicity distribution
  – simulated distribution is shifted to lower multiplicities
MSC spectra

- Almost the same degree of reproduction of experimental MSC spectra as with the temperature-dependent GLO-based model could be achieved also with temperature-independent GLO-based model.

- But $E_\gamma$ dependence of such a model does not reasonably match experimental data from any reaction.
MSC spectra in $^{98}$Mo - Conclusions

- Results are fully consistent with our analysis of MSC and TSC spectra in $^{95}$Mo($n,\gamma$)$^{96}$Mo reaction
- Existence of any pronounced resonance-like structures in PSFs observed previously near $E_\gamma = 2$ MeV (Oslo data) or 6 MeV (Rossendorf data) disagrees with our data but we cannot reject a presence of much weaker resonance structures in a PSF.
- A realistic E1 PSF model should be less steep than the SLO model at energies $E < 4$ MeV.
- We can not confirm/reject T-dependence of PSF
- “GLO” model underestimates $\Gamma_\gamma$ (by about 20-30%)
Part 2

What is actual PSF in $^{98}$Mo (Mo region)?

(my personal, strongly biased, view)
Where could we learn about PSFs from?
(at low-energy GDER tail, nuclei near the valley of stability)
- photoexcitation techniques
  - \((\gamma,\text{particle})\)
  - NRF experiments
- primaries from \((n,\gamma)\) reaction
- two-step cascades spectra - \((n,\gamma)\)
- spectrum fitting method
  - singles spectra
  - coincidence spectra
- inelastic scattering of charged particles
  \((e,e'), (p,p'), (\alpha,\alpha')\) ...
- sequential extraction (Oslo, \(^3\)He-induced)
- particle - \(\gamma - \gamma\) coincidence
- ...

Oslo, May 18-22, 2015
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- inelastic scattering of charged particles
  - $(e,e')$, $(p,p')$, $(\alpha,\alpha')$ …
- sequential extraction (Oslo, $^3\text{He}$-induced)
- particle - $\gamma - \gamma$ coincidence
- …
Available data on PSF in Mo isotopes

• NRF data
  – HIγS data – $^{94}$Mo, $^{98}$Mo

• Oslo data

• $(n,\gamma)$ coincidence spectra from isolated resonances
  – DANCE measurement – $^{96}$Mo and $^{98}$Mo (this contribution)

• particle - $\gamma$ - $\gamma$ coincidence – $^{95}$Mo

• two-step cascades spectra following thermal neutron capture – $^{96}$Mo

• primaries from $(n,\gamma)$ reaction - $^{93}$Mo, $^{99}$Mo
  RIPL-1

• $(p,p')$ data – $^{96}$Mo

• $(\alpha,\alpha\gamma)$ data – $^{94}$Mo
Why are “PSFs” different?

- Experimental data are incorrect
- Concept of photon strength function and/or Brink hypothesis is not valid
Additional available data

PSF from intensities of primary transitions in \((n,\gamma)\) reaction

- Compilation made by Kopecky for RIPL-1
- Several data in the A=90-100 region are available

\[
\Gamma_{\alpha\gamma\beta}^{(XL)} = \frac{f^{(XL)} E_\gamma^{2L+1}}{\rho(E_\alpha, J_\alpha, \pi_\alpha)}
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Additional available data

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One of the problems is resonance spacing

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>(E_\gamma) (MeV)</th>
<th>(\langle D_0 \rangle) (eV)</th>
<th>(f_{E1} \times 10^{-8}) (MeV(^{-3}))</th>
<th>(\langle D_0 \rangle) (eV)</th>
<th>(f_{E1} \times 10^{-8}) (MeV(^{-3}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{93})Mo</td>
<td>6.6</td>
<td>1000</td>
<td>5.67(147)</td>
<td>2800(485)</td>
<td>2.02(52)</td>
</tr>
<tr>
<td>(^{95})Mo</td>
<td>7.3</td>
<td>975</td>
<td>5.38(41)</td>
<td>1690(390)</td>
<td>3.10(24)</td>
</tr>
<tr>
<td>(^{99})Mo</td>
<td>5.5</td>
<td>429</td>
<td>4.32(81)</td>
<td>970(200)</td>
<td>1.91(36)</td>
</tr>
<tr>
<td>(^{94})Nb</td>
<td>6.5</td>
<td>37.8</td>
<td>5.04(124)</td>
<td>84.8(46)</td>
<td>2.25(55)</td>
</tr>
<tr>
<td>(^{100})Ru</td>
<td>6.9</td>
<td>31.4</td>
<td>2.97(41)</td>
<td>21.7(23)</td>
<td>4.30(60)</td>
</tr>
</tbody>
</table>

Original – (Kopecky) values in RIPL-1
Recalculated – Mughabghab atlas

Data on primaries from \((n,\gamma)\) not very useful…
Oslo method

- External data needed for determination of PSF
- Uncertainty of exact slope and/or absolute PSF value – usually derived from $\Gamma_\gamma$ of s-wave resonances
- DICEBOX simulations of $\Gamma_\gamma$ for $^{98}$Mo using “Oslo-type PSF models” indicate that absolute values of Oslo PSF points should be higher (by a factor of 1.3-1.8)

- Smaller multiplication factor (1.0-1.3) was needed in $^{96}$Mo
- The difference with respect to “original Oslo” is due to the low-energy PSF shape
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- Exact value of the multiplication factor depends on exact LD shape used in simulations
- Multiplication of Oslo data by this factor probably does not bring them on top of HI$\gamma$S data – a factor of about 2 (or even slightly higher) would be needed
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NRF data

• Consistency of ELBE and HI$_\gamma$S data…
NRF with beam from “bremsstrahlung”

- “Iterative” technique used for derivation of final cross section - branching to excited states has to be “subtracted”

- One can process data in a different way – simulations of $\gamma$ decay with DICEBOX code should be able to produce spectra comparable to measured ones

- Deduced NRF data seems not to reproduce the measured spectrum

Results are preliminary
NRF with beam from “bremsstrahlung”

Oslo, May 18-22, 2015

Experiment:
- \((\gamma, x)\)
- Oslo
- NRF

PSF:
- E1
- M1
- E1 + M1

Gamma-Ray Energy (MeV)

Intensity (arb. units)

Gamma-Ray Energy (MeV)
NRF with beam from “bremsstrahlung”

- Spectra cannot be reproduced also using PSF from Oslo measurement
NRF with beam from “bremsstrahlung”

• Better agreement between experimental data and simulations can be achieved
NRF with beam from “bremsstrahlung”

- Better agreement between experimental data and simulations can be achieved

PSF used in simulations
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NRF with beam from “bremsstrahlung”

• Absolute cross section is determined for the “highest” ELBE experimental point – the data should be renormalized
• Renormalized ELBE data seem to match HI$_\gamma$S as well as ($\gamma$,n) data
• More detailed study of this “disagreement” from two different approaches to data processing is needed
Consistency of data?

- These “corrections” - renormalization of Oslo data and correction of ELBE shape at high energies - would give a reasonable agreement of all data for $E_\gamma > 4$ MeV ...

But problems remain

1. Total radiation width reproducing “HI\gamma S normalization”
2. NRF point at 3.5 MeV – temperature dependence of PSF?
3. Problem with reproduction of feeding low-lying excited levels in NRF
Total cross section given by

\[ \sigma_{\gamma T} = \sigma_{\gamma \gamma} + \sigma_{\gamma \text{LL}} + \sigma_{\gamma \text{cont}} \]

Negligible at low excitation energies, several per cent in PDR region – must be corrected from “simulations”

\[ ^{142}\text{Nd} \]
seven 2\(^+\) levels below 3.5 MeV; almost all intensity goes via the first excited state

Fit to data

C.T. Angell et al., PRC 86, 051302(R) (2012)
In addition to total cross section we can look at “GS branching”

\[ <b_0> = \frac{\sigma_{\gamma\gamma}}{\sigma_{\gamma T}} \text{ or } <b_0> = \frac{\sigma_{\gamma\gamma}}{\sigma_{\gamma LL}} \]
\[ ^{142}\text{Nd}(\gamma,\gamma') \oplus \text{HI\gamma S} \]

- In addition to total cross section we can look at “GS branching”
  \[ <b_0> = \frac{\sigma_{\gamma\gamma}}{\sigma_{\gamma T}} \text{ or } <b_0> = \frac{\sigma_{\gamma\gamma}}{\sigma_{\gamma LL}} \]

- Experimental values of \( <b_0> \) can be compared with results of simulations assuming the validity of the statistical model (DICEBOX code)

- Extrapolation of PSFs down to low \( \gamma \) energies is needed

C.T. Angell et al., PRC 86, 051302(R) (2012)
\( ^{142}\text{Nd}(\gamma,\gamma') \) @ HI\( \gamma \)S

\[
\langle b_0 \rangle = \frac{\sigma_{\gamma\gamma}}{\sigma_{\gamma LL}}
\]
None of tested models is able to reproduce $\langle b_0 \rangle$ at all energies

Problem with the shape of $\langle b_0 \rangle$, especially at 6-8 MeV ⇒ assumptions in simulations are not correct

Virually no influence of NLD, many PSFs models tested ⇒ problem with Brink hypothesis (at least for PDR region)
NRF data from HI\(\gamma\)S

Similar results obtained also for several other nuclei

- \(^{130}\)Te
- \(^{94}\)Mo

Brink hypothesis seems to be violated for „pygmy“ resonance transitions

\[ \Rightarrow \text{PSF from NRF data (probably excitation data in general) must differ from PSF from Oslo, (n,\(\gamma\)}, \ldots \]
PSFs in $^{98}$Mo according to MK

- At least some states in the PDR region does not follow the Brink hypothesis – they are strongly connected to the ground state ⇒ “PSF” from NRF is not the same as “PSF” for decay
- PSF for decay is “temperature-dependent”

- This solution would be consistent with
  - NRF data
  - Oslo data
  - $(n,\gamma)$ data (including $\Gamma_\gamma$)