Update on (n,γ) studies of photon strength functions at Budapest

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Goal of the research

- To find out how far we can go in the description of single gamma-ray spectra and decay scheme from radiative neutron capture using the extreme statistical model
- Firestone and co-workers have already demonstrated the capabilities of extreme statistical model for decay schemes for various nuclei
- If good agreement could be achieved then gamma-strength functions and level density models can be tested with higher confidence
- Results with low resolution study has already been published:
  
The Budapest PGAA-NIPS Facility
Instruments in the Experimental Halls

**Instruments in the Reactor Hall:**
- TOF: Time of Flight Diffractometry
- BIO: Biological Irradiation Channel
- RAD: Dynamic Radiography
- MTEST: Material Test Diffractometry
- TAST: Thermal Neutron Three-Axis Spectrometry
- PSD: Position Sensitive Diffractometry

**Instruments in the CNS Hall:**
- PREF: Polarized Neutron Reflectometry
- ATHOS: Triple-Axis Spectrometry
- SANS: Small Angle Neutron Scattering
- IMBS: In-beam Mössbauer Spectrometry
- PGAA: Prompt Gamma Activation Analysis
- NIPS-NORMA: Neutron Induced Prompt Gamma Spectrometry / Neutron Optics and Radiography for Material Analysis
- GINA: Polarized Neutron Reflectometry

**Under construction:**
- F-SANS: Focused Beam Small Angle Neutron Scattering
PGAA-NIPS facilities

Two independent neutron beams:
Upper for PGAA
Lower for NIPS-NORMA

The $^{113}\text{Cd}(n,\gamma)$ Measurements
Samples and measurements

- Two samples were used:
  - High purity Natural Cd sheet of 50 um thickness
  - Enriched $^{113}$Cd powder of 0.3 mm thickness, packed in quartz glass bottle
- Cold neutron beam was collimated to 1 mm$^2$
- Standard BGO shielded HPGe detector was used in the data taking with and without Compton suppression
- Internal calibration of partial cross section was used
- Beam background was measured
- Efficiency were measured in the 50 keV – 12 MeV range with relative uncertainty around 1%
- Each beam on $\gamma$-spectrum was acquired for about 1 day
Gamma-ray spectra

Counts

$E_\gamma$ (keV)

Normal spectrum

Suppressed spectrum
Capture Data treatment for simulation
Unfolding normal spectra

• Node spectra and list mode were calculated using GEANT4 from 250 keV to 11 MeV with steps of 250 keV and with 1 keV binning
• Further treatment is according to Oslo description
  • Full spectra were normalized to 1
  • Full energy, SE, DE and Annihilation peaks were removed and stored separately for later use
  • Interpolation were calculated using the scattering angular space rather than the energy space
  • Interpolation of peak heights were obtained from Cardinal spline interpolations for SE & DE peaks
  • Above Compton edge stretching and constriction were used

Efficiency corrected unfolded $^{113}\text{Cd}(n,\gamma)$ spectrum

Inv-Q value 21640 b, literature 20600(400) b
Multiplicity 4.1
BIn Type Statistical decay program (BITS)

- BITS is an EXCEL VBA based extreme statistical gamma-decay simulation program
  - Up to the critical number of levels it reads in an experimental decay scheme and from this it models the decay scheme with bins of 100 keV width in which several levels are described with their density functions.
  - In deciding the decay pattern from the excited states the average decay widths are used for the bins. From the critical number of levels the decays are modelled with their branching ratios taking into the account of conversion electron decay.
  - The program is flexible to accommodate any kind of strength functions and level densities.
- The program output
  - BITS provides a 10 keV resolution output for gamma spectrum
  - It calculates the incoming and outgoing gamma intensities to compare it with the experimental one.
Results
Simulated $^{114}$Cd $\gamma$-spectrum

Decay scheme is under development, 71 levels included
Low energy simulated $^{114}$Cd $\gamma$-spectrum
Feeding of $^{114}$Cd levels vs. level energy

Positive parity level feedings
- LEE E1

Negative parity level feedings
- LEE M1

Positive parity level feedings
- LEE E1

Negative parity level feedings
- LEE M1
Feeding of $^{114}$Cd levels from capture state

Positive parity levels' feeding from capture state

Negative parity levels' feeding from capture state
$^{114}$Cd capture level gamma-ray emission

Capture state emitted gamma-rays

Emission probability

$E_\gamma$ (MeV)

Limiting the emission of gamma-rays

$^{114}$Cd capture level gamma-ray emission

Diagram showing the emission probability of gamma-rays as a function of energy ($E_\gamma$) for $^{114}$Cd capture state.
Simulated properties of $^{114}$Cd level feeding

Curves are 3$^{rd}$ order polynomial fittings
Simulated properties of $^{114}$Cd level feeding
### Simulation parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Temperature (MeV)</td>
<td>0.62</td>
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<tr>
<td>E0 backshift (MeV)</td>
<td>0.50</td>
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<tr>
<td>Emax (MeV)</td>
<td>9</td>
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<tr>
<td>a at binding energy 1/MeV</td>
<td>12.39</td>
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<tr>
<td>Capture spin</td>
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<tr>
<td>Capture parity</td>
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<td>Critical level number</td>
<td>71</td>
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<tr>
<td>beta for TLO</td>
<td>0.2</td>
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<tr>
<td>gamma for TLO (deg)</td>
<td>27</td>
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<tr>
<td>Number of total levels</td>
<td>72</td>
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<tr>
<td>Tot capt. Cross section (b)</td>
<td>20600</td>
</tr>
<tr>
<td>D0 (eV)</td>
<td>24.8</td>
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<tr>
<td>Bn</td>
<td>9.042701</td>
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<tr>
<td>SF E1 type</td>
<td>TLO</td>
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<tr>
<td>SF M' type</td>
<td>M1_V1</td>
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<tr>
<td>Low energy enh. (0.005,2.6,Eg)</td>
<td>E1</td>
</tr>
<tr>
<td>Egidy's Odd-even effect included</td>
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<tr>
<td>No special parity distr applied</td>
<td></td>
</tr>
<tr>
<td>ILL data up to 2000 keV used</td>
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<tr>
<td># of combined ILL &amp; Budapest gamma</td>
<td>1369</td>
</tr>
<tr>
<td># of placed gamma-rays</td>
<td>381</td>
</tr>
</tbody>
</table>
Simulation gamma-strength functions

![Graph showing simulation gamma-strength functions. The x-axis represents $E_\gamma$ (MeV) and the y-axis represents strength function $1/\text{MeV}^{(2L+1)}$. Different curves represent various models and their corresponding labels.](image_url)
Coincidence experiments using $^{113}\text{Cd}(n, \gamma\gamma)$ reactions in collaboration with Rez, Czech

- **Purpose:**
  - To check and improve the low lying decay scheme
  - To calculate two step cascade distributions for improving spectrum modelling PSFs

- **Measurements:**
  - Ivo Tomandl at the $(n,\gamma\gamma)$ facility of the Prague (Rez) Research Reactor
  - Natural Cd metal
Shell model calculations of $^{114}$Cd B(M1) transitions in collaboration with Ronald Schwengner

- **Purpose:**
  - To understand Low Energy Enhancement (LEE)
- **Calculations NuShellX code:**
  - The first calculations were done using $^{78}$Ni core to calculate B(M1) values are of the type $\pi[(pf) g_{9/2}^{-2}] \nu[g_{7/2}^{6} d_{5/2}^{6} d_{3/2}^{3} s_{1/2}^{1}] (\pi= +)$ and $\pi[(pf)^{-1} g_{9/2}^{-1}] \nu[g_{7/2}^{6} d_{5/2}^{6} d_{3/2}^{3} s_{1/2}^{1}] (\pi = -)$
  - The calculation yielded about 23000 transitions, particle space should be increased
\(^{238}\text{U}(n,\gamma)\) unfolded spectrum

- **Purpose:**
  - To obtain spectrum for extreme statistical modeling
  - **Inv-Q value** 3340 mb, literature 2683 (12) mb
    - Highly enriched target. Measured \(^{238}\text{U}\) enrichment 99.96\%, 18 times less \(^{235}\text{U}\) than in natural uranium
    - It is still not enough, more measurements are needed
Summary

• Radiative capture spectrum modelling continuously improving with better decay-scheme
• Comparison with model about 15 levels had to be removed
• Continuum feeding is very sensitive for certain spins and is decreasing smoothly with increasing level energy
• Low Energy Enhancement was needed to get better fit for the low energy continuum of the unfolded experimental spectrum
• Further improvement of the decay scheme is needed, required coincidence experiment that was performed
• $^{239}$U unfolded spectrum has 25% more cross section which proves the presence of $^{236}$U capture and $^{235}$U fission gamma-ray spectra, thus either subtraction or more depleted sample should be measured
THANK YOU FOR YOUR ATTENTION!
Node spectra

![Graph showing node spectra with probability on the y-axis and E keV on the x-axis.](image-url)
Interpolation and calculated GEANT4 spectra

- Interpolated continuum
- Monte_carlo_1332
Unfolding of Co-60 spectrum
Unfolding of Eu-152 spectrum

Probability vs. Energy (E keV) graph.
Unfolding of enriched $^{113}\text{Cd}(n,\gamma)$ spectrum