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

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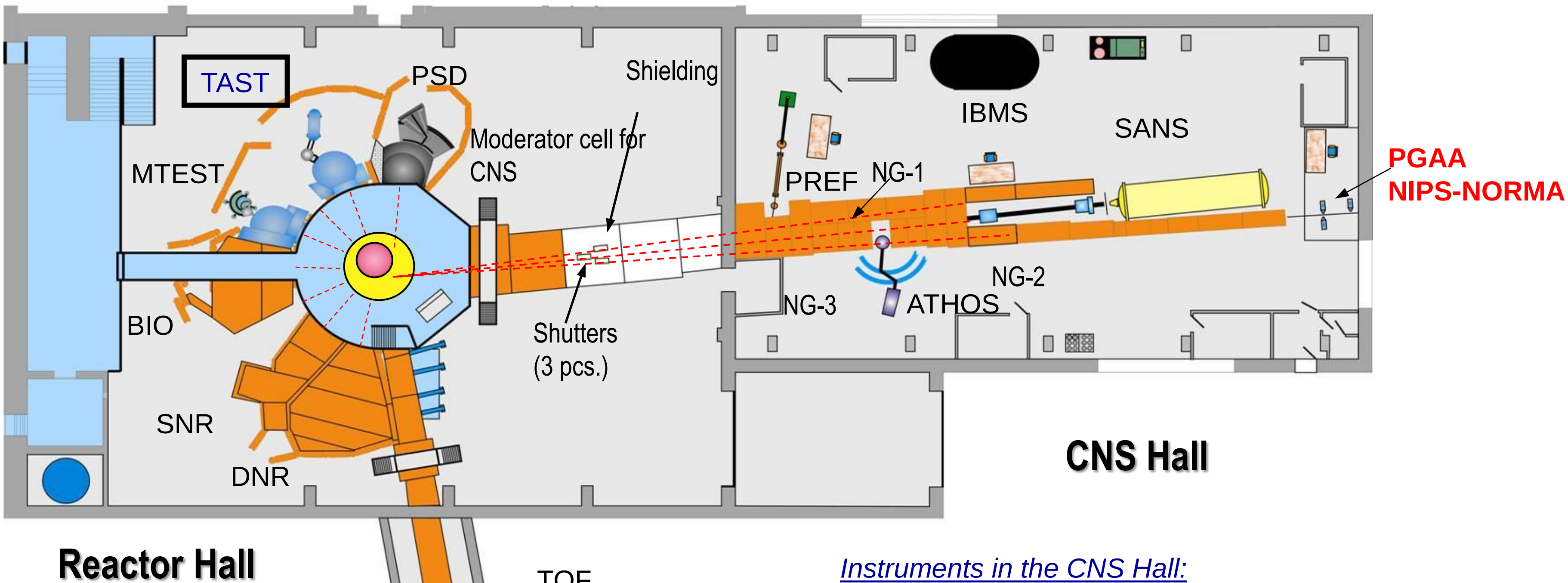
Goal of the research

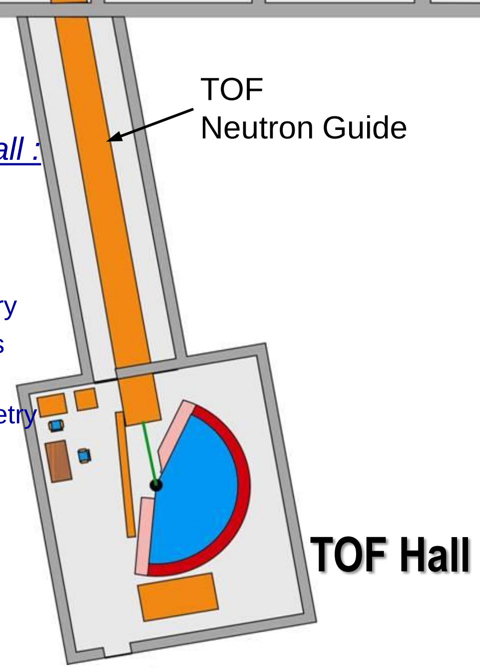
- To find out how far we can go in the description of single gamma-ray spectra and decay scheme from radiative neutron capture using the extreme statistical model
- Firestone and co-workers have already demonstrated the capabilities of extreme statistical model for decay schemes for various nuclei
- 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:

R Massarczyk, G Schramm, T Belgya, R Schwengner, R Beyer, et al. Physical Review C 93 (1), (2016) 014301

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

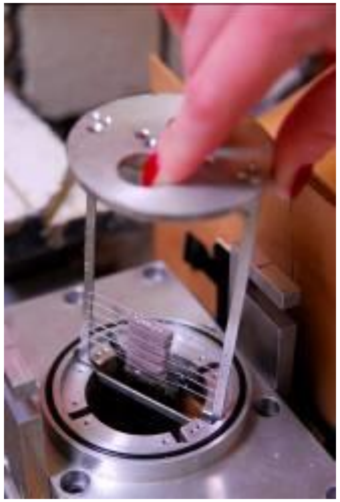
Instruments in the CNS Hall:

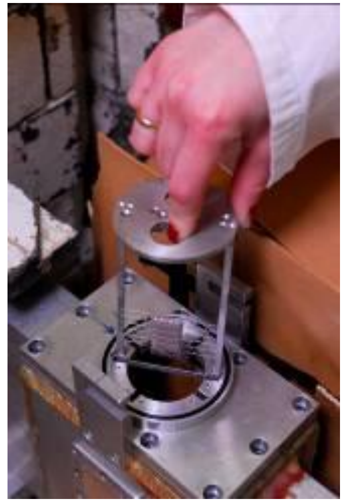
PREF: Polarized Neutron Reflectometry
ATHOS: Triple-Axis Spectrometry
SANS: Small Angle Neutron Scattering
IMBS: In-beam Mössbauer Spectrometry
PGAA: Prompt Gamma Activation Analysis
NIPS-NORMA: Neutron Induced Prompt Gamma Spectrometry / Neutron Optics and Radiography for Material Analysis
GINA: Polarized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

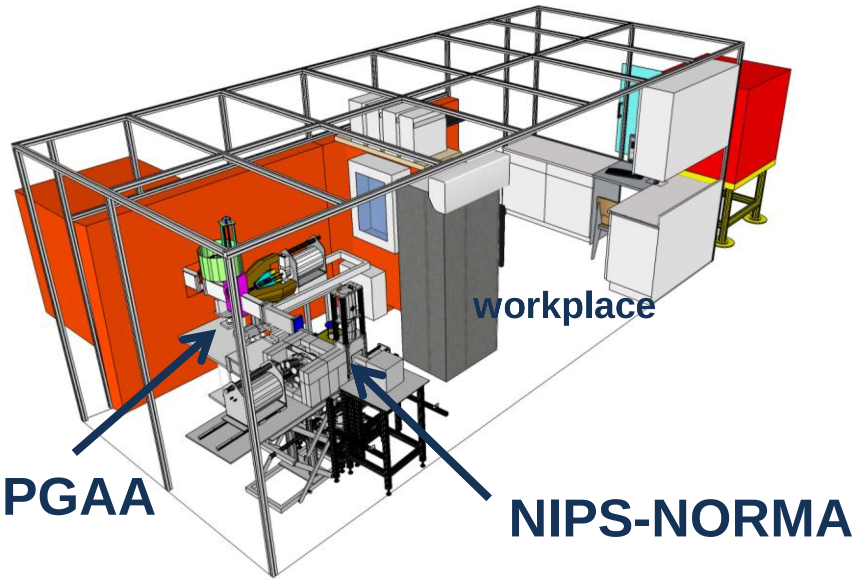
Under construction:

F-SANS: Focused Beam Small Angle Neutron Scattering

PGAA-NIPS facilities







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

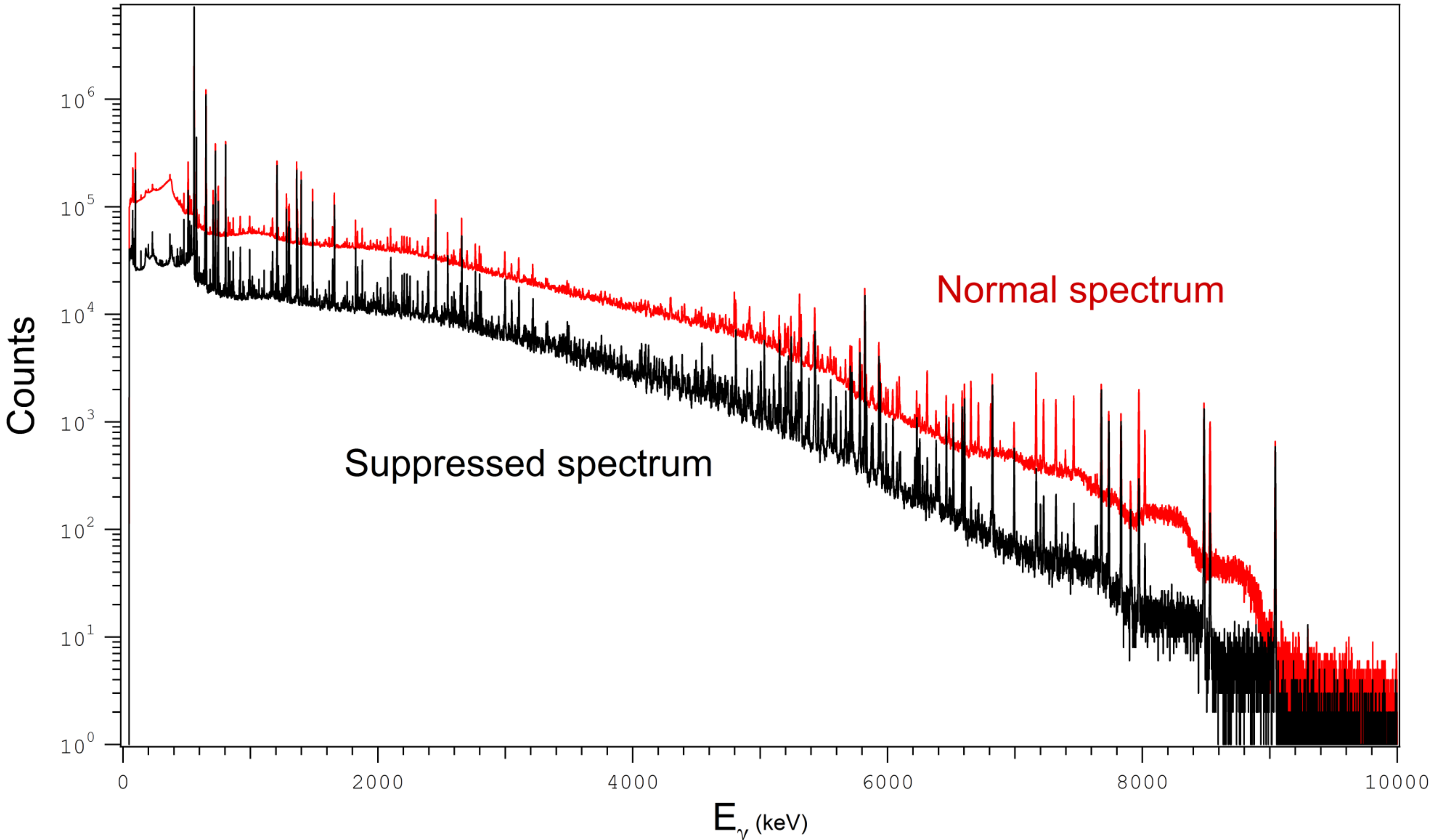
L. Szentmiklósi, T. Belgya, Zs. Révay, Z. Kis, J. Radioanal. Nucl. Chem. 286:501-505 (2010)

The $^{113}Cd(n,\gamma)$ 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 γ-spectrum was acquired for about 1 day

Gamma-ray spectra



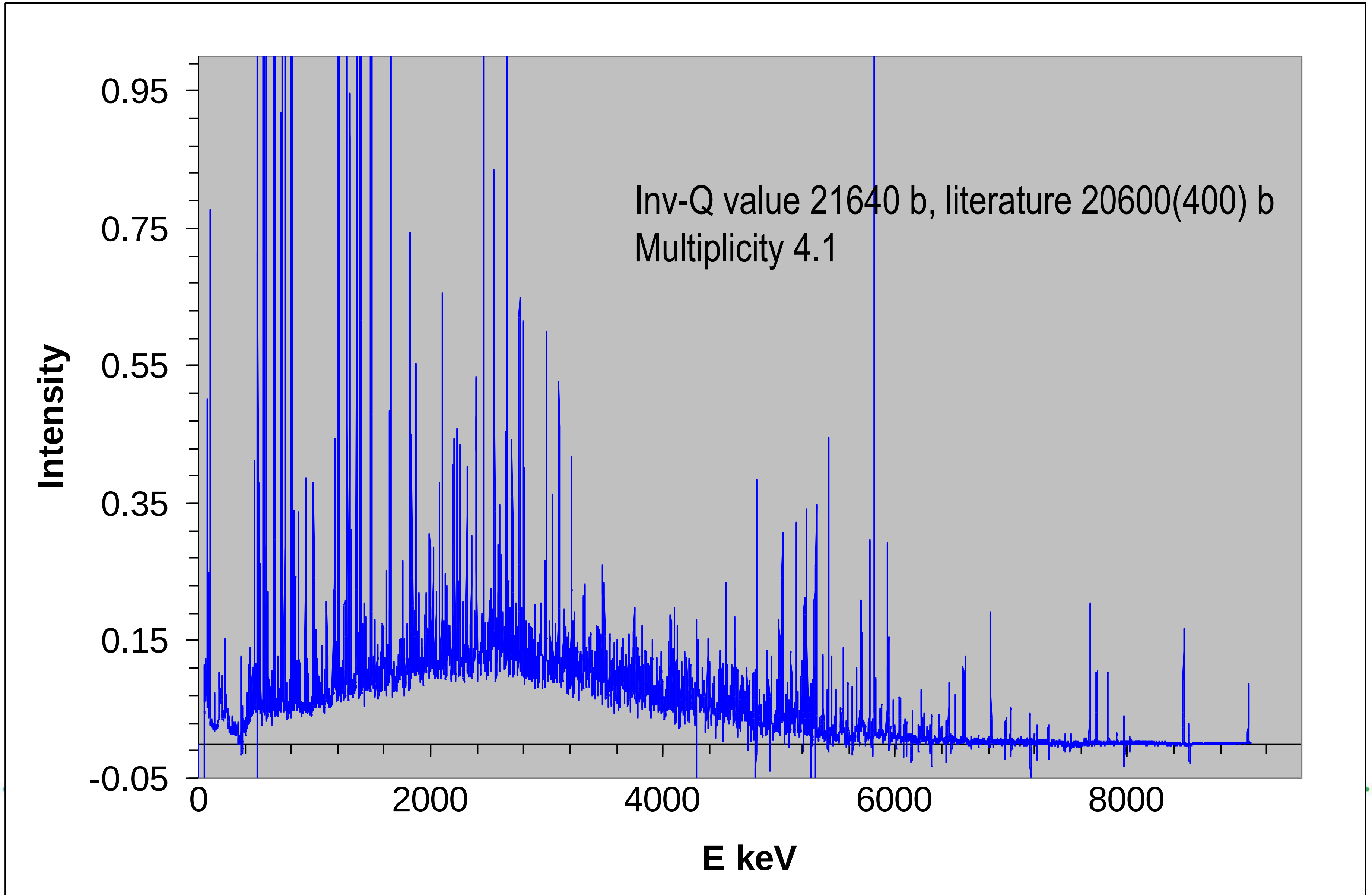
Capture Data treatment for simulation

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

M. Guttormsen et al., Nuclear Instruments and Methods **in** Physics Research A 374 (1996) 371-376
T. Belgya et al. In *Proc. ERINDA Workshop*, Geneva: CERN, 2014
https://cdsweb.cern.ch/record/1975459/files/119p.pdf.

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

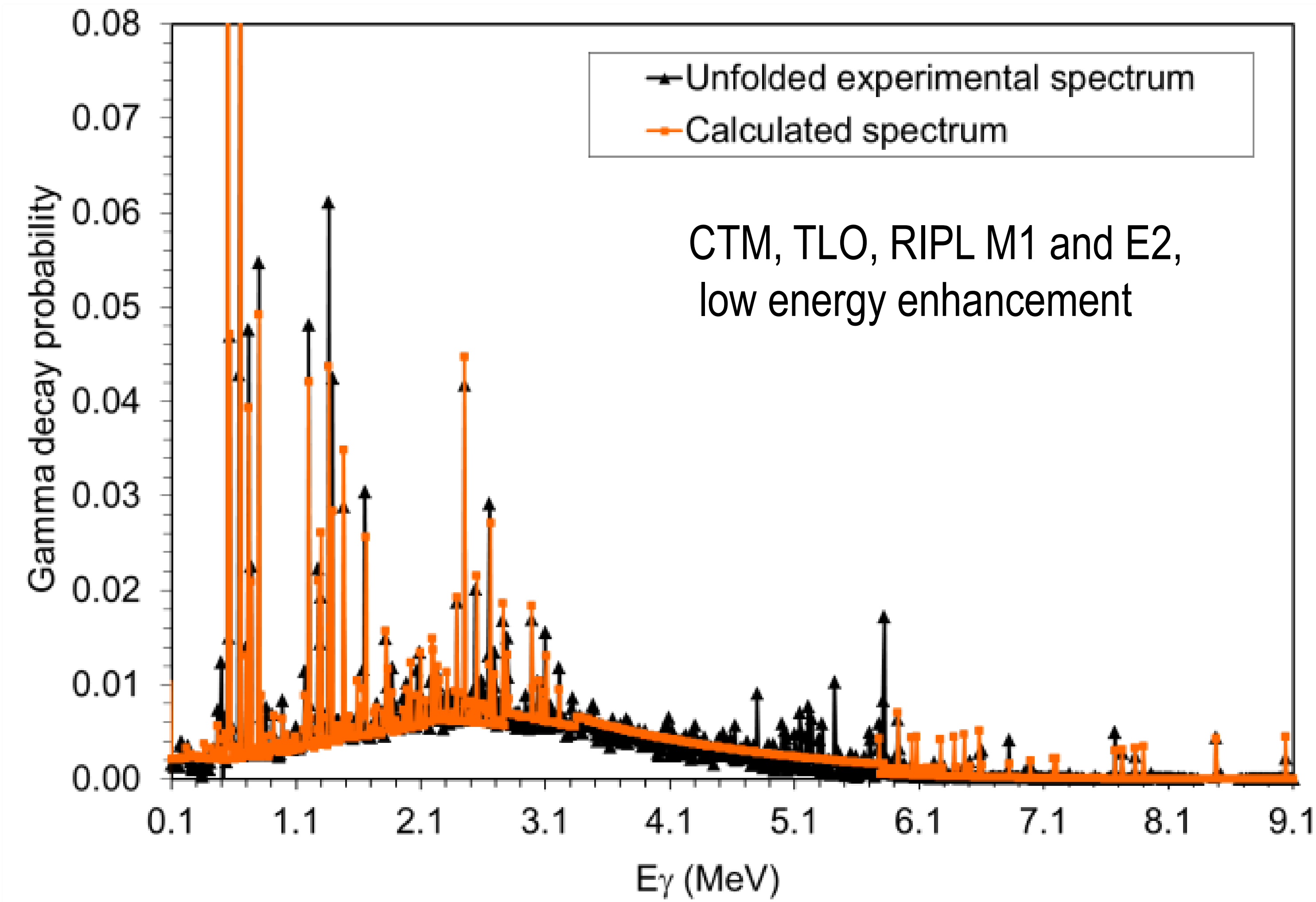


BIn Type Statistical decay program (BITS)

- 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.

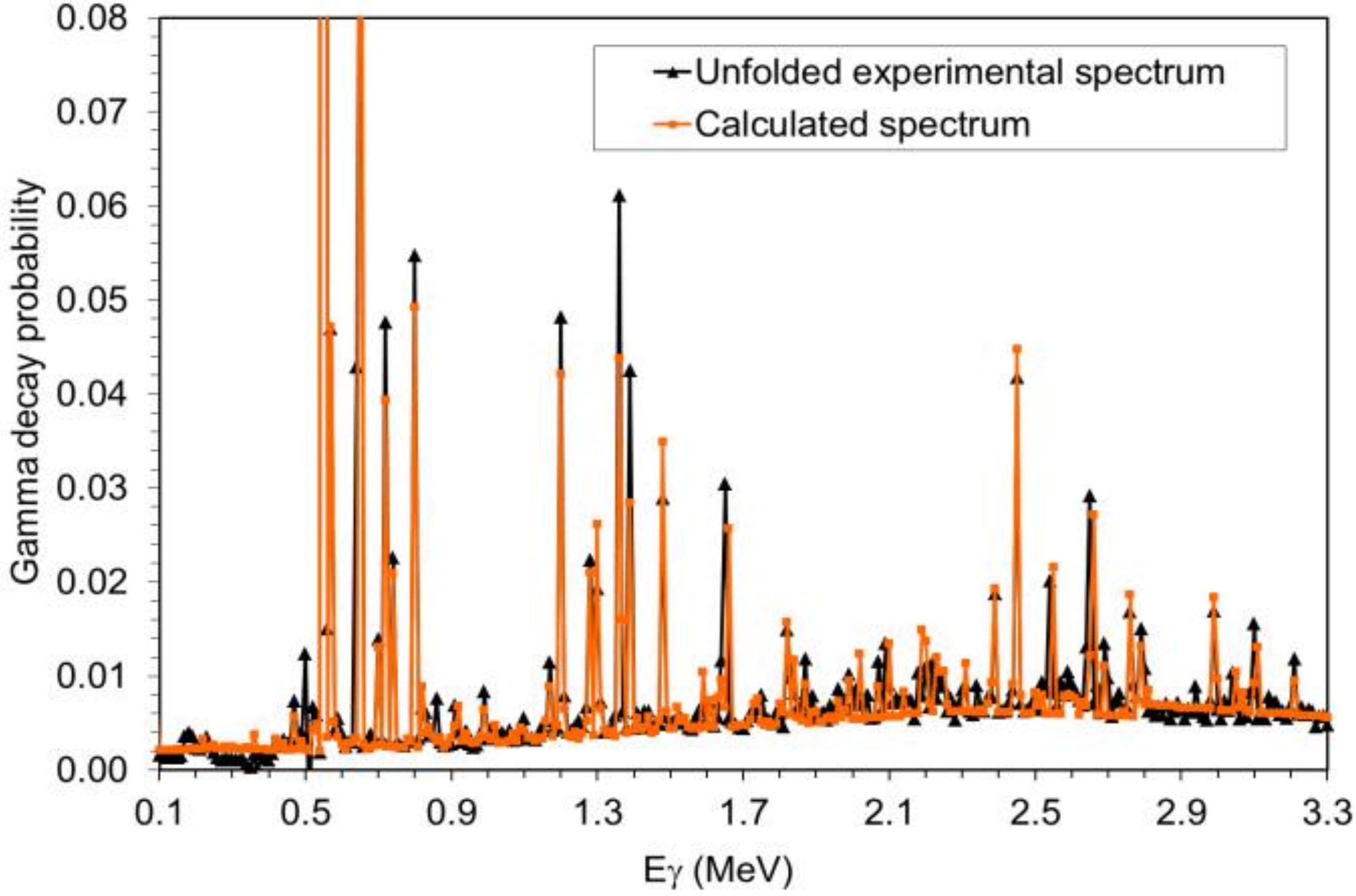
Results

Simulated ^{114}Cd γ-spectrum

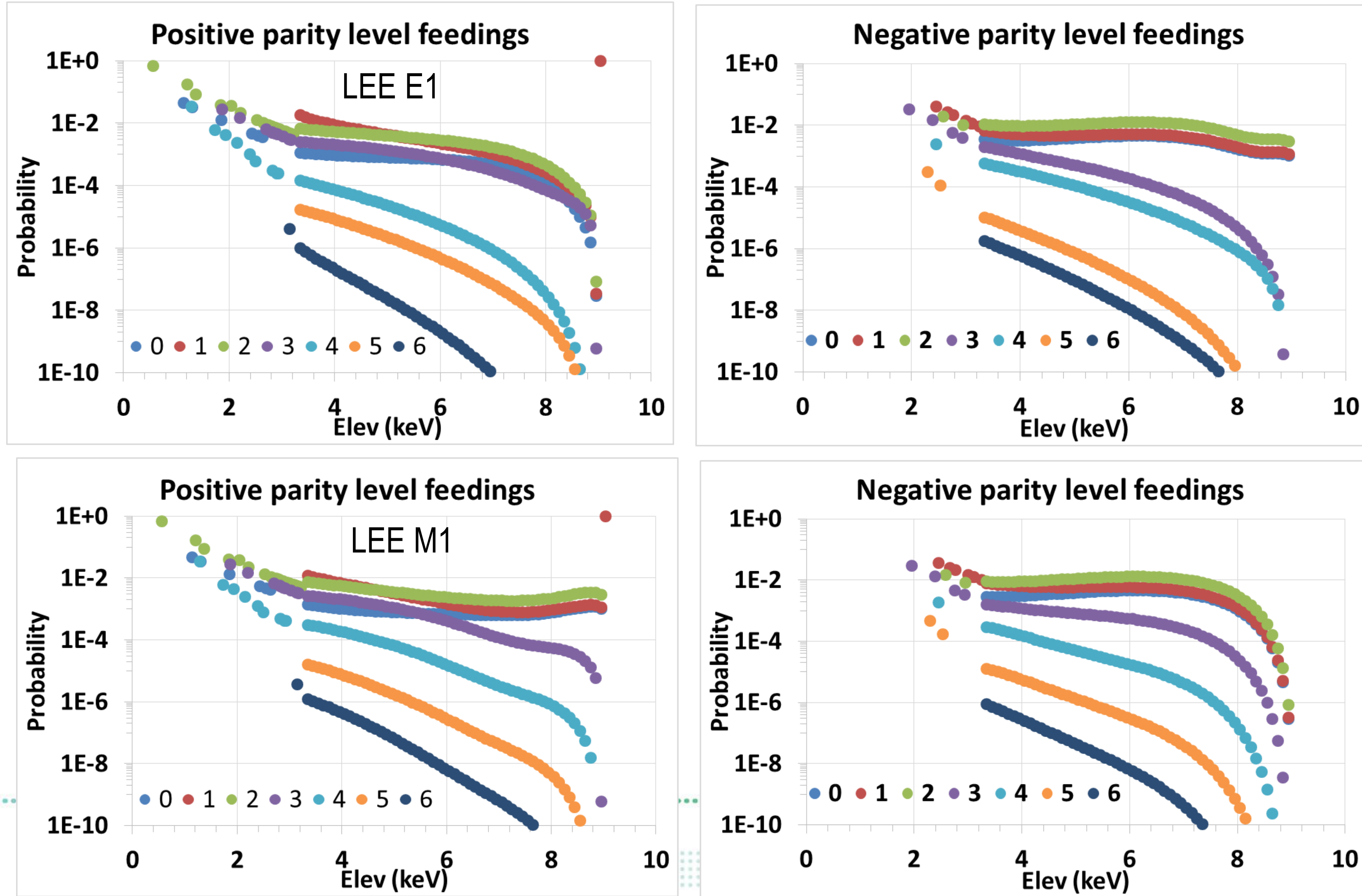


Decay scheme is under development, 71 levels included

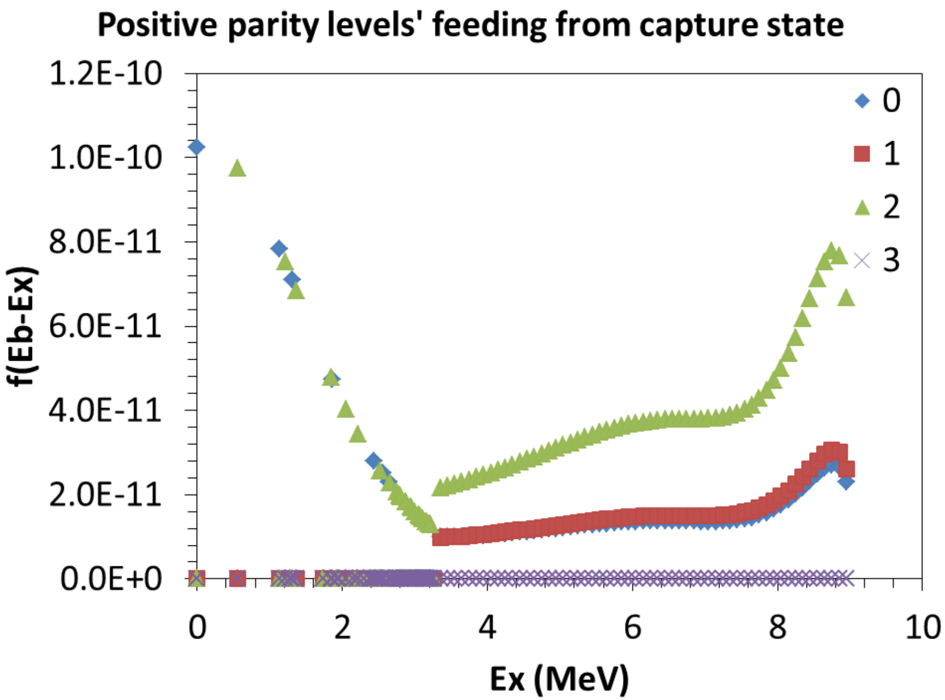
Low energy simulated ^{114}Cd γ-spectrum

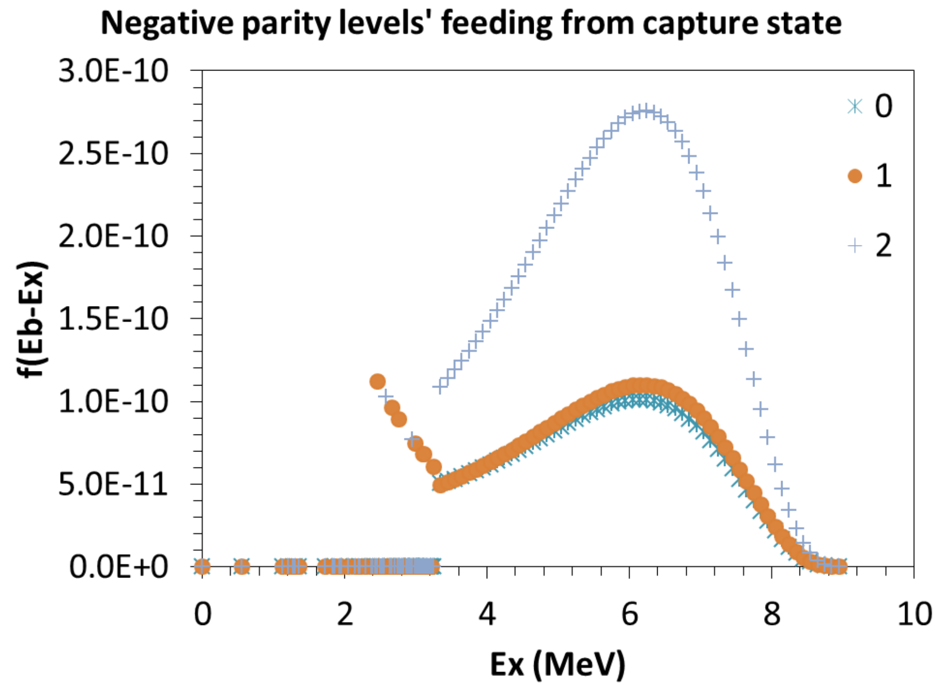


Feeding of ^{114}Cd levels vs. level energy

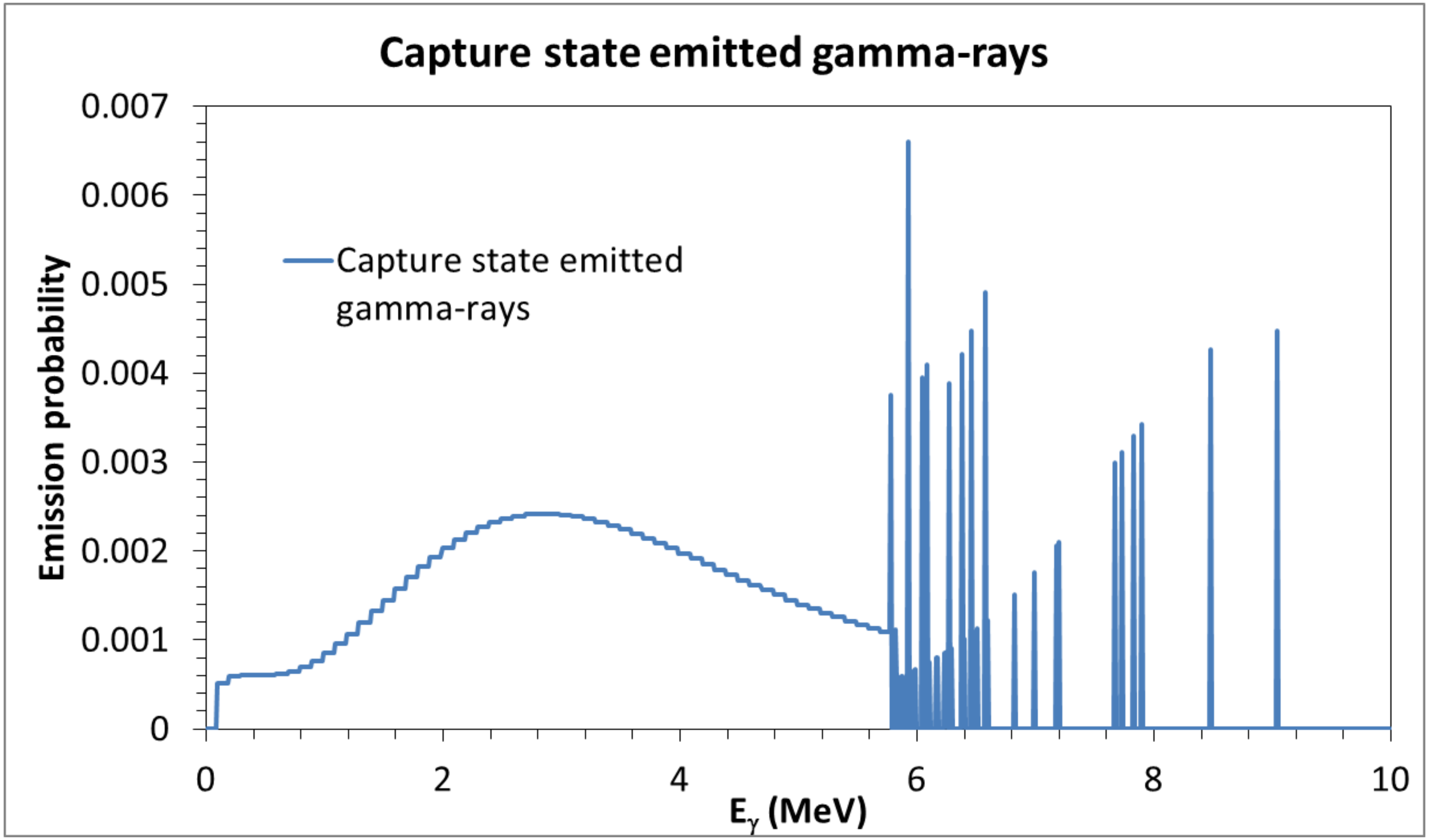


Feeding of ^{114}Cd levels from capture state





^{114}Cd capture level gamma-ray emission



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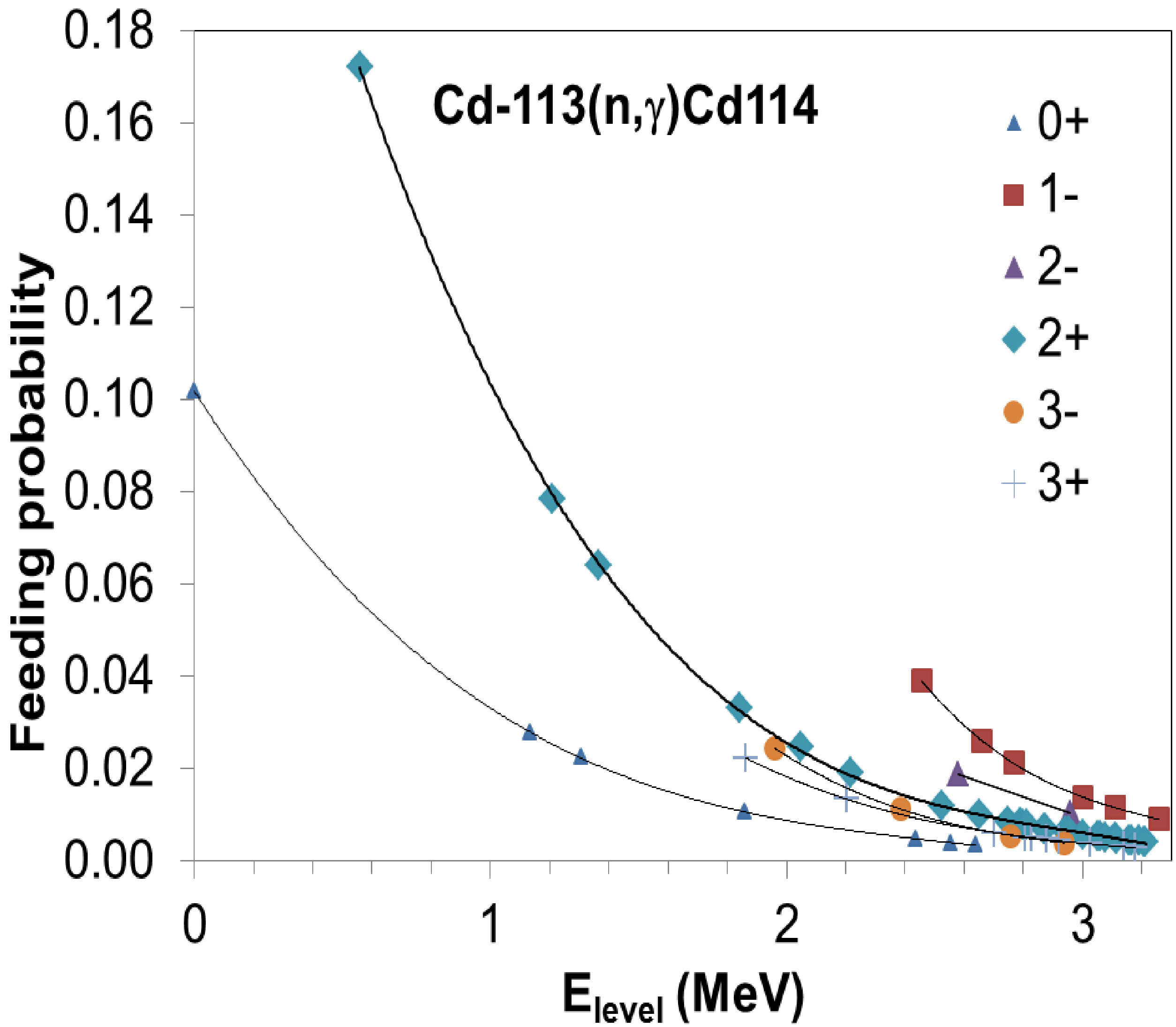
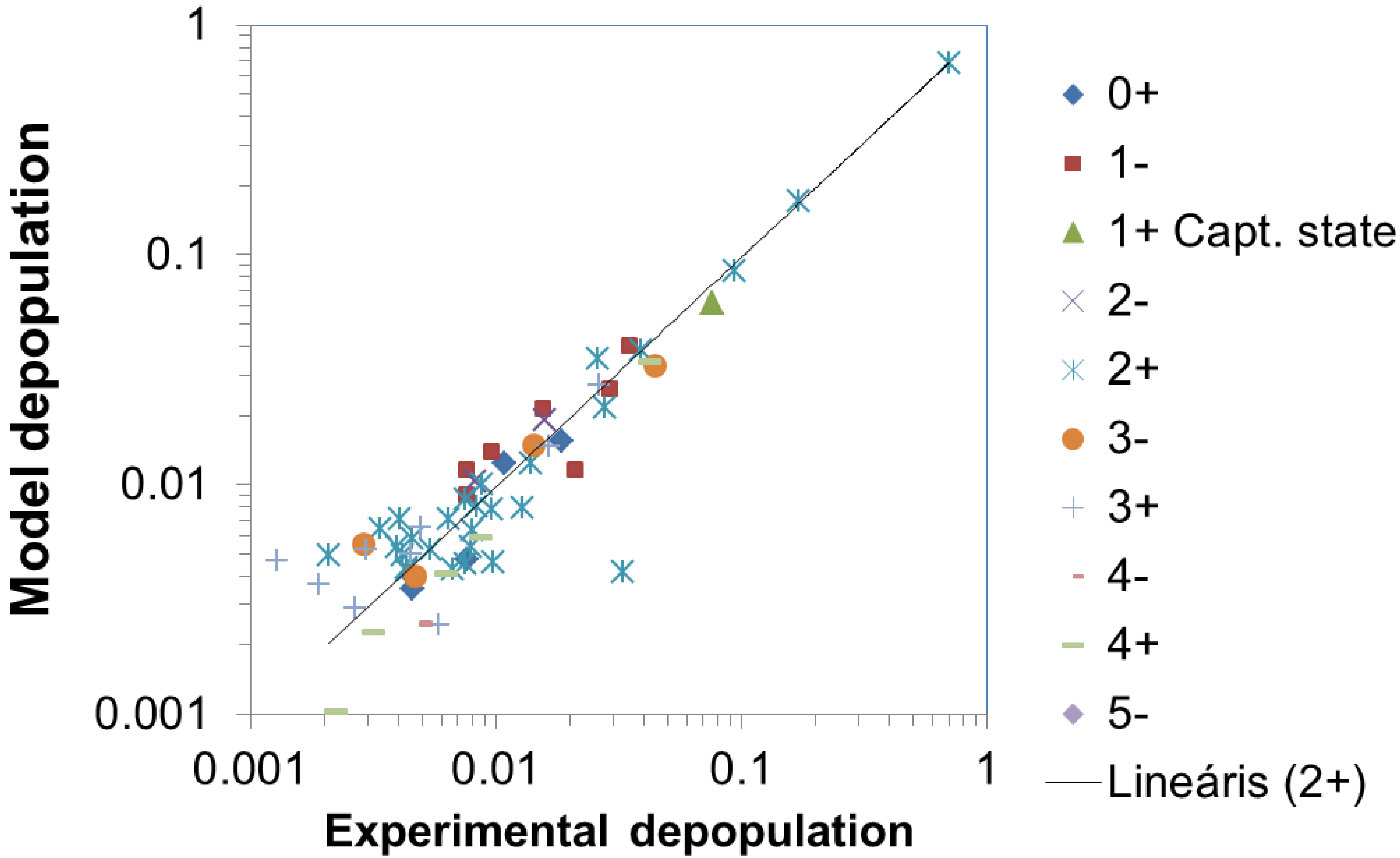
Simulated properties of ^{114}Cd level feeding



Curves are 3rd order polynomial fittings

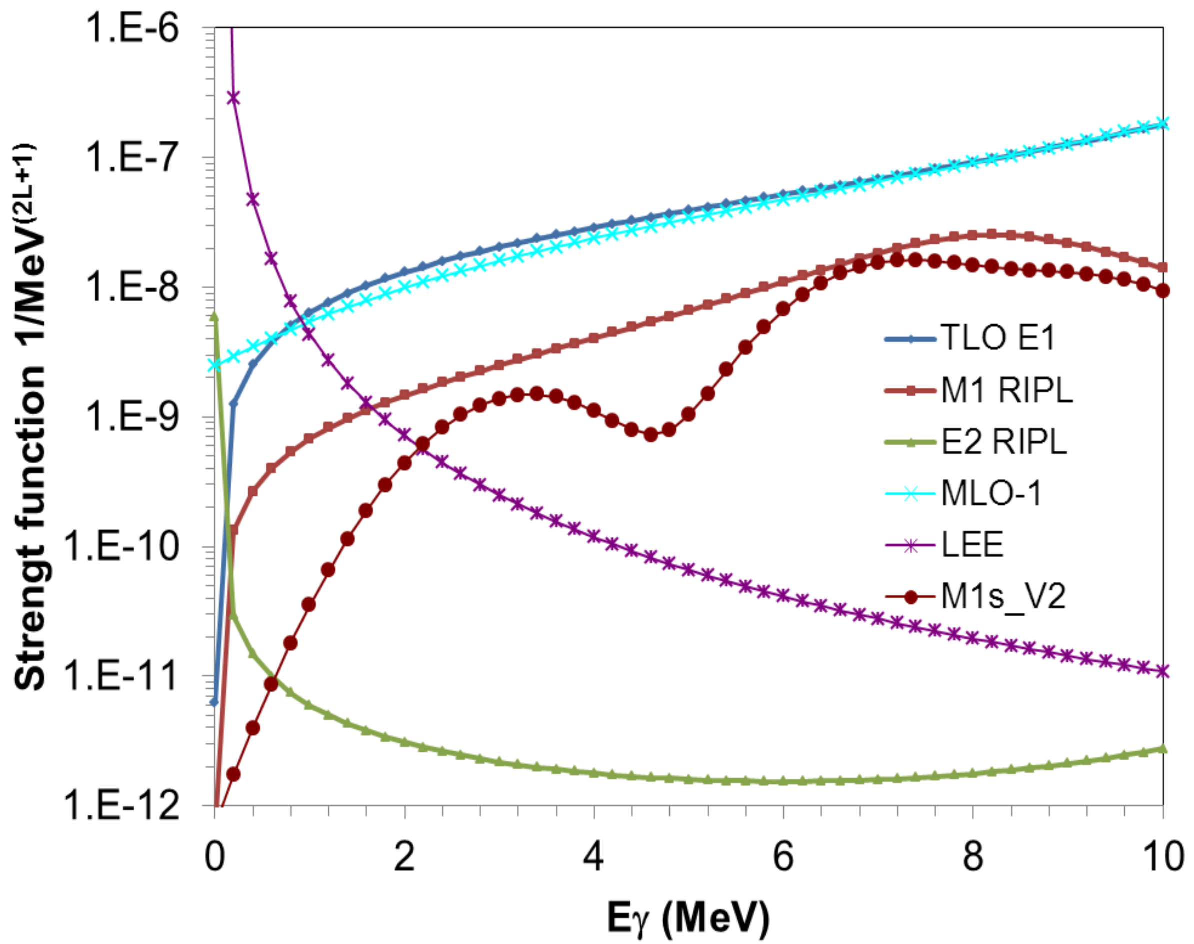
Simulated properties of ^{114}Cd level feeding



Simulation parameters

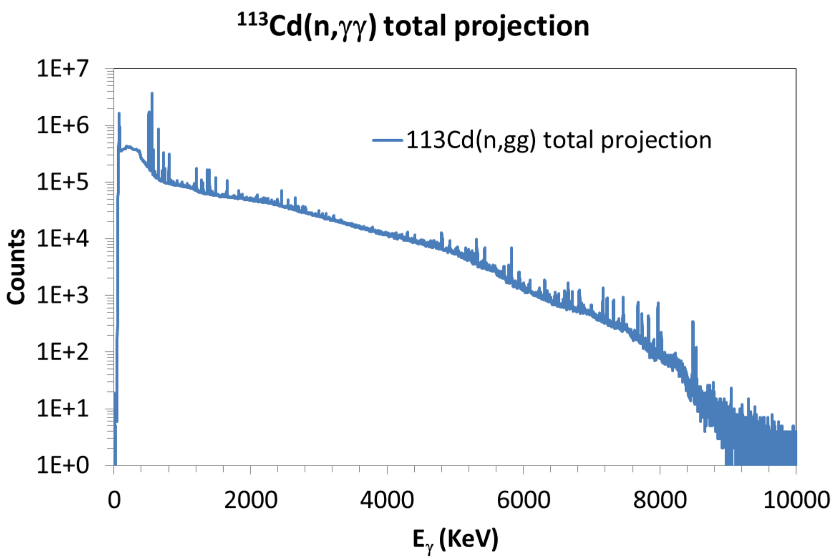
Temperature (MeV)	0.62
E0 backshift (MeV)	0.50
Emax (MeV)	9
a at binding energy 1/MeV	12.39
Capture spin	1
Capture parity	1
Critical level number	71
beta for TLO	0.2
gamma for TLO (deg)	27
Number of total levels	72
Tot capt. Cross section (b)	20600
D0 (eV)	24.8
Bn	9.042701
SF E1 type	TLO
SF M' type	M1_V1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

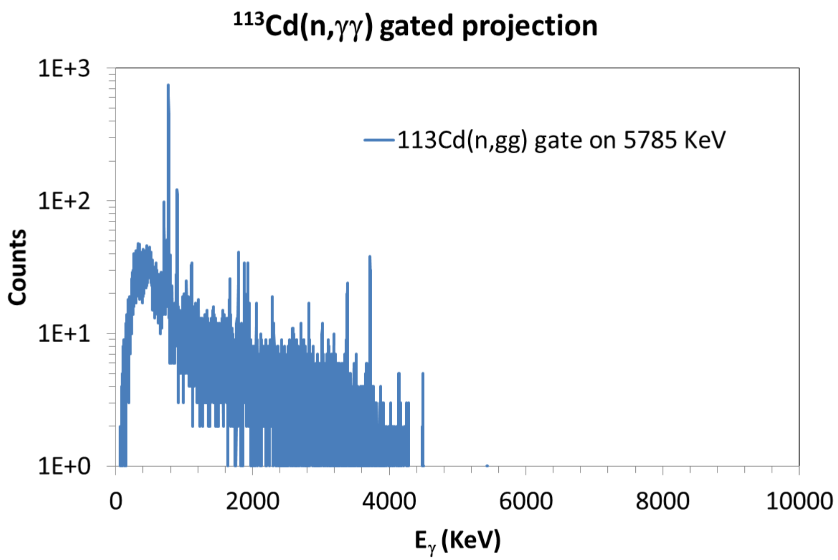
Simulation gamma-strength functions



Coincidence experiments using ^{113}Cd(n, $\gamma\gamma$) reactions in collaboration with Rez, Czech

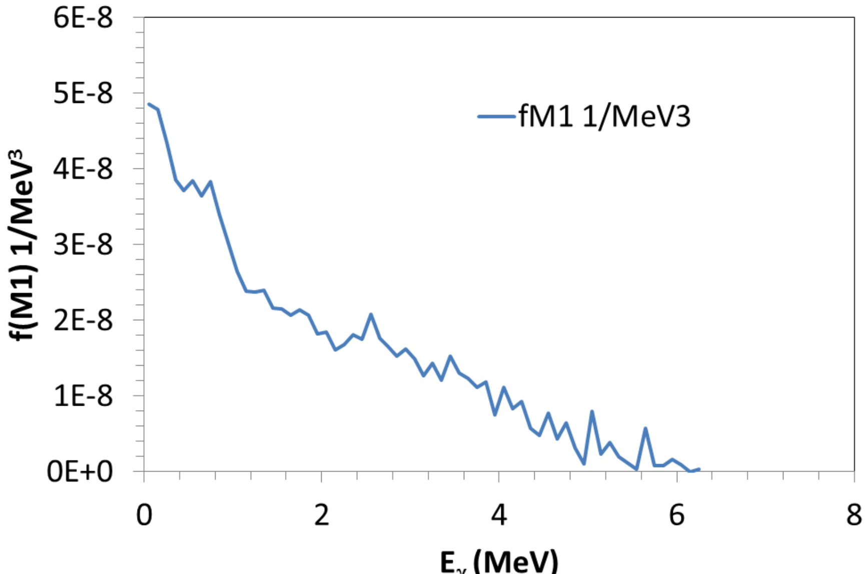
- **Purpose**:
  - To check and improve the low lying decay scheme
  - To calculate two step cascade distributions for improving spectrum modelling PSFs
- **Measurements**:
  - Ivo Tomandl at the (n,$\gamma\gamma$) facility of the Prague (Rez) Research Reactor
  - Natural Cd metal





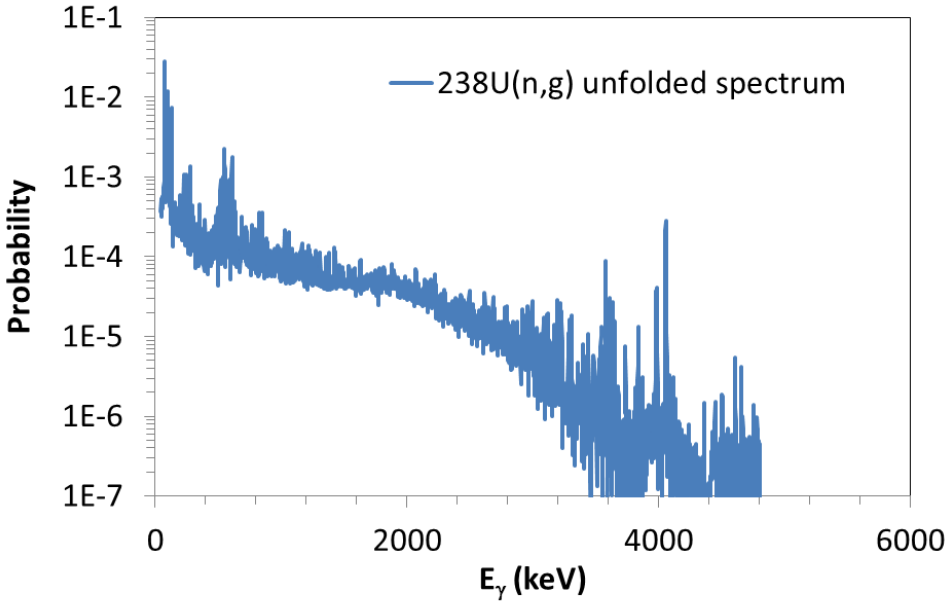
Shell model calculations of ^{114}Cd B(M1) transitions in collaboration with Ronald Schwengner

- **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 $\pi[(pf)\ g_{9/2}^{-2}]\ \nu[g_{7/2}^{6}\ d_{5/2}^{6}\ d_{3/2}^{3}\ s_{1/2}^{1}]$ (π= +) and $\pi[(pf)^{-1}\ g_{9/2}^{-1}]\ \nu[g_{7/2}^{6}\ d_{5/2}^{6}\ d_{3/2}^{3}\ s_{1/2}^{1}]$ (π = -)
  - The calculation yielded about 23000 transitions, particle space should be increased



$^{238}U(n,\gamma)$ unfolded spectrum

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



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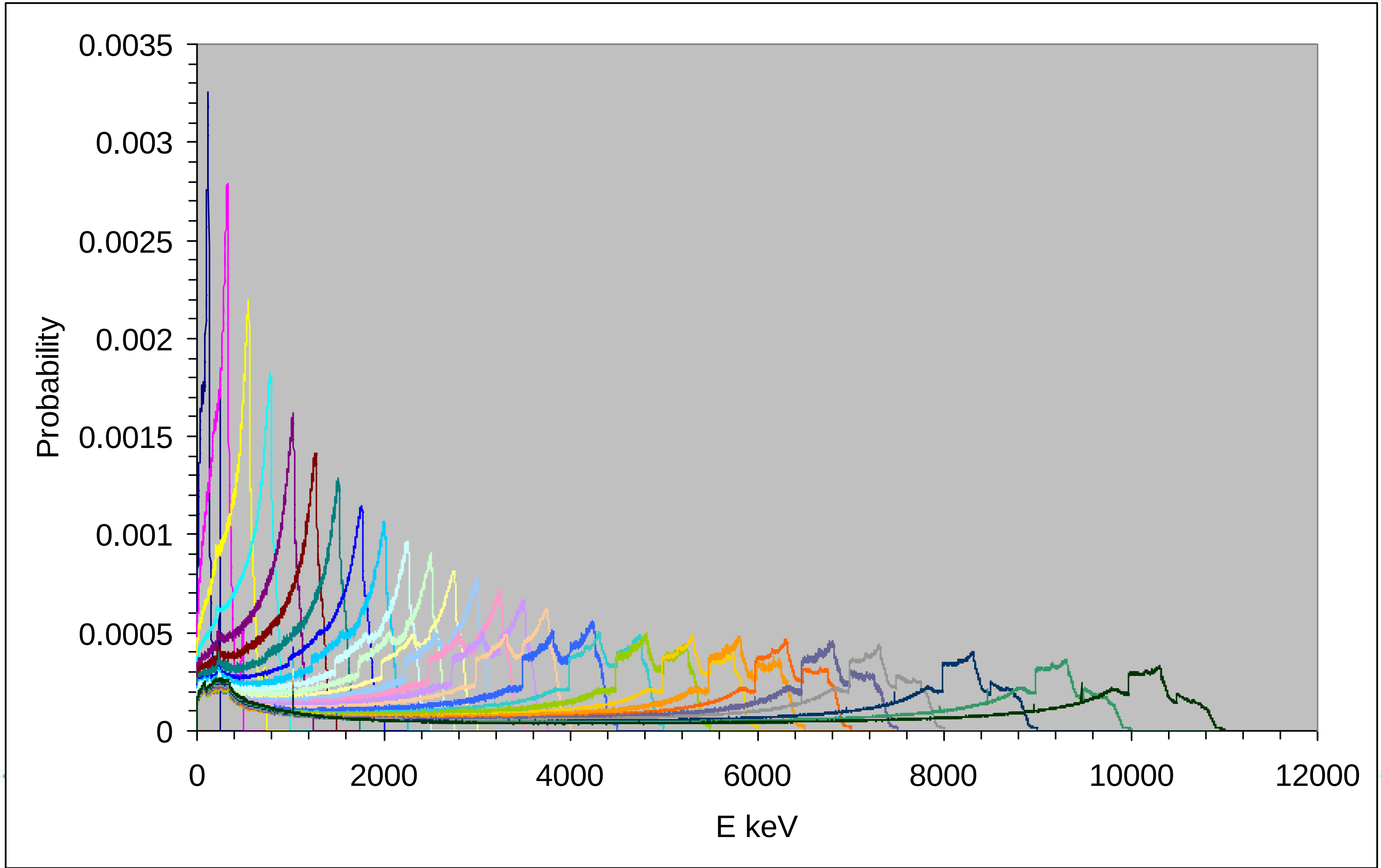
Summary

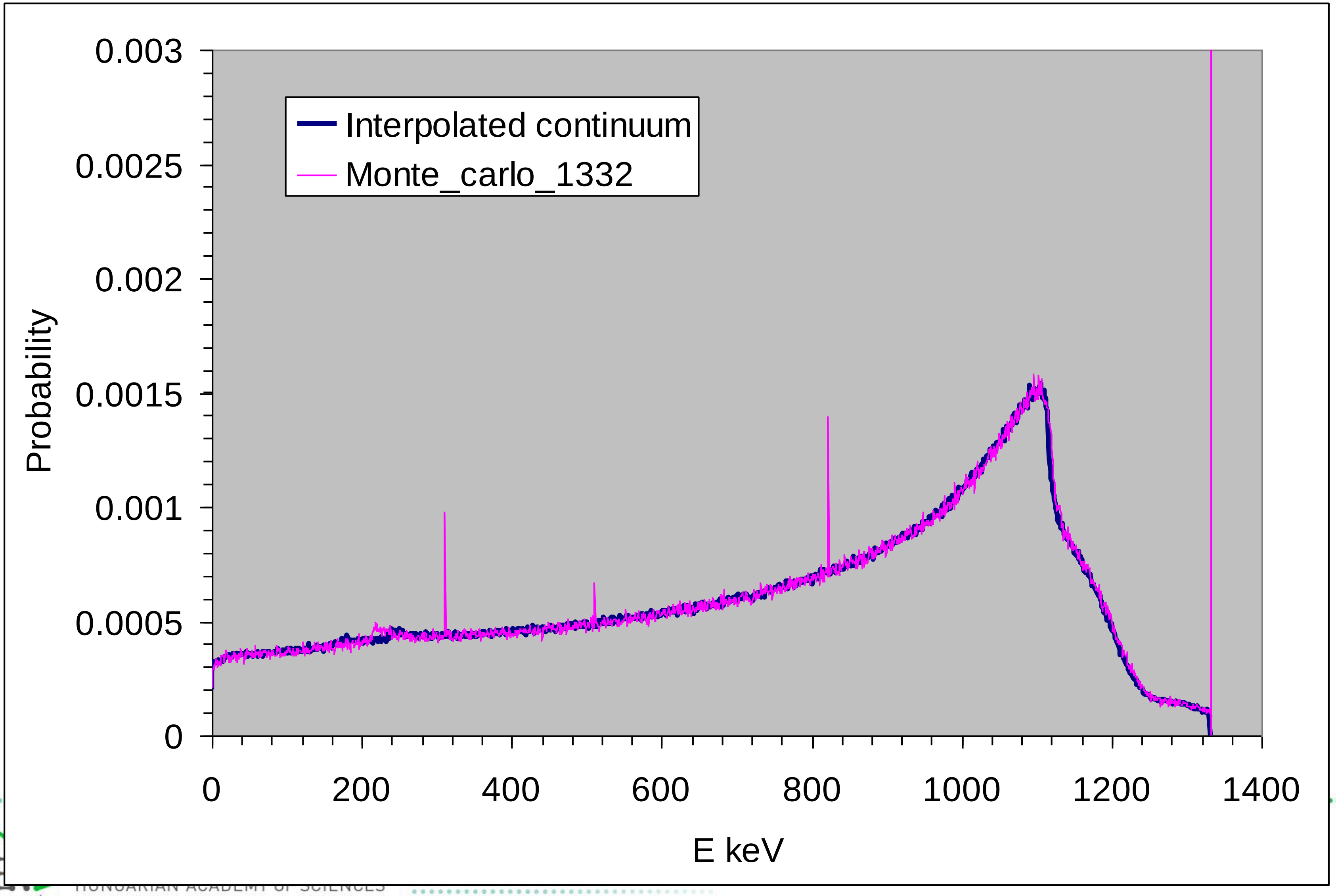
- Radiative capture spectrum modelling continuously improving with better decay-scheme
- Comparison with model about 15 levels had to be removed
- Continuum feeding is very sensitive for certain spins and is decreasing smoothly with increasing level energy
- Low Energy Enhancement was needed to get better 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!

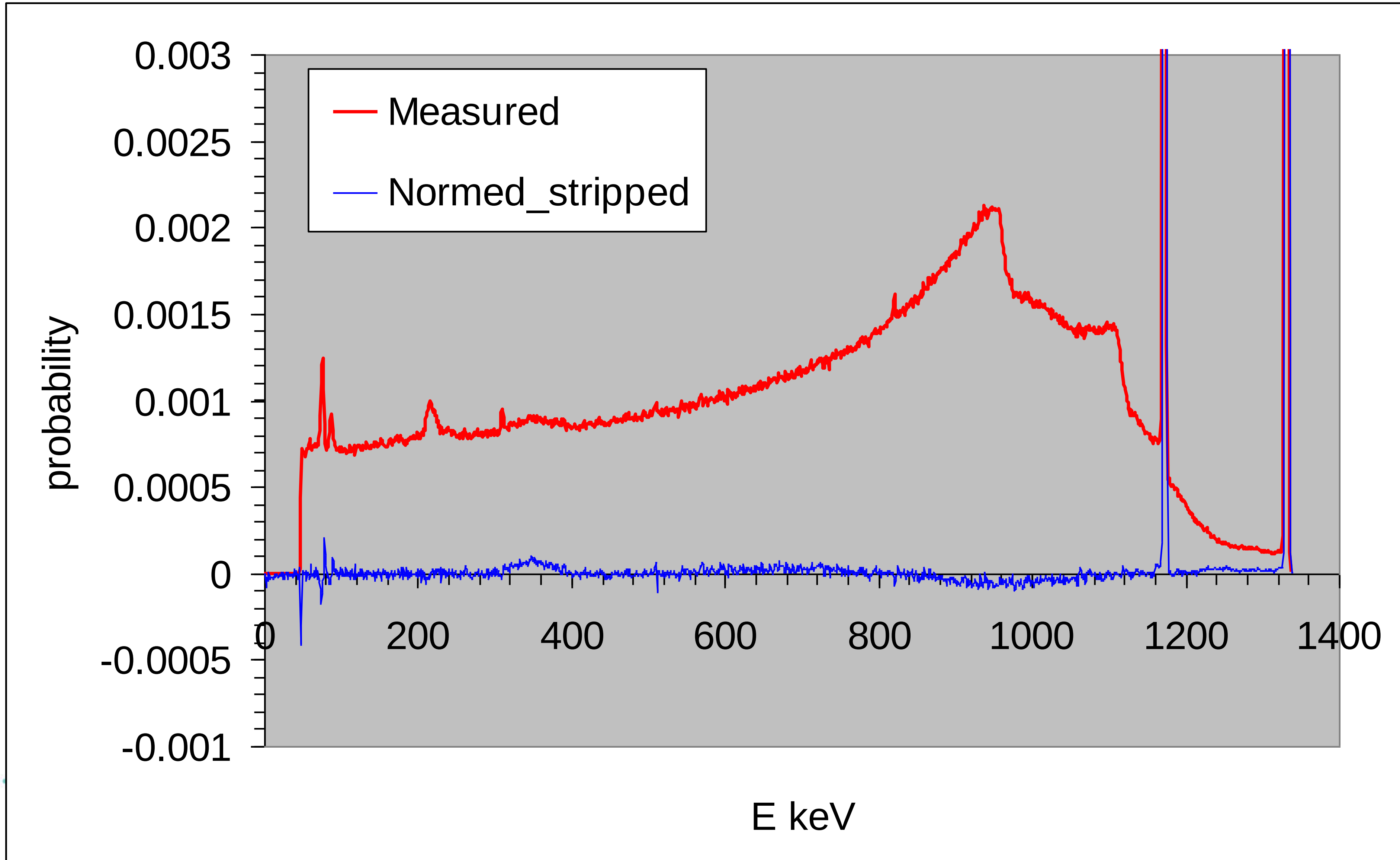
Node spectra



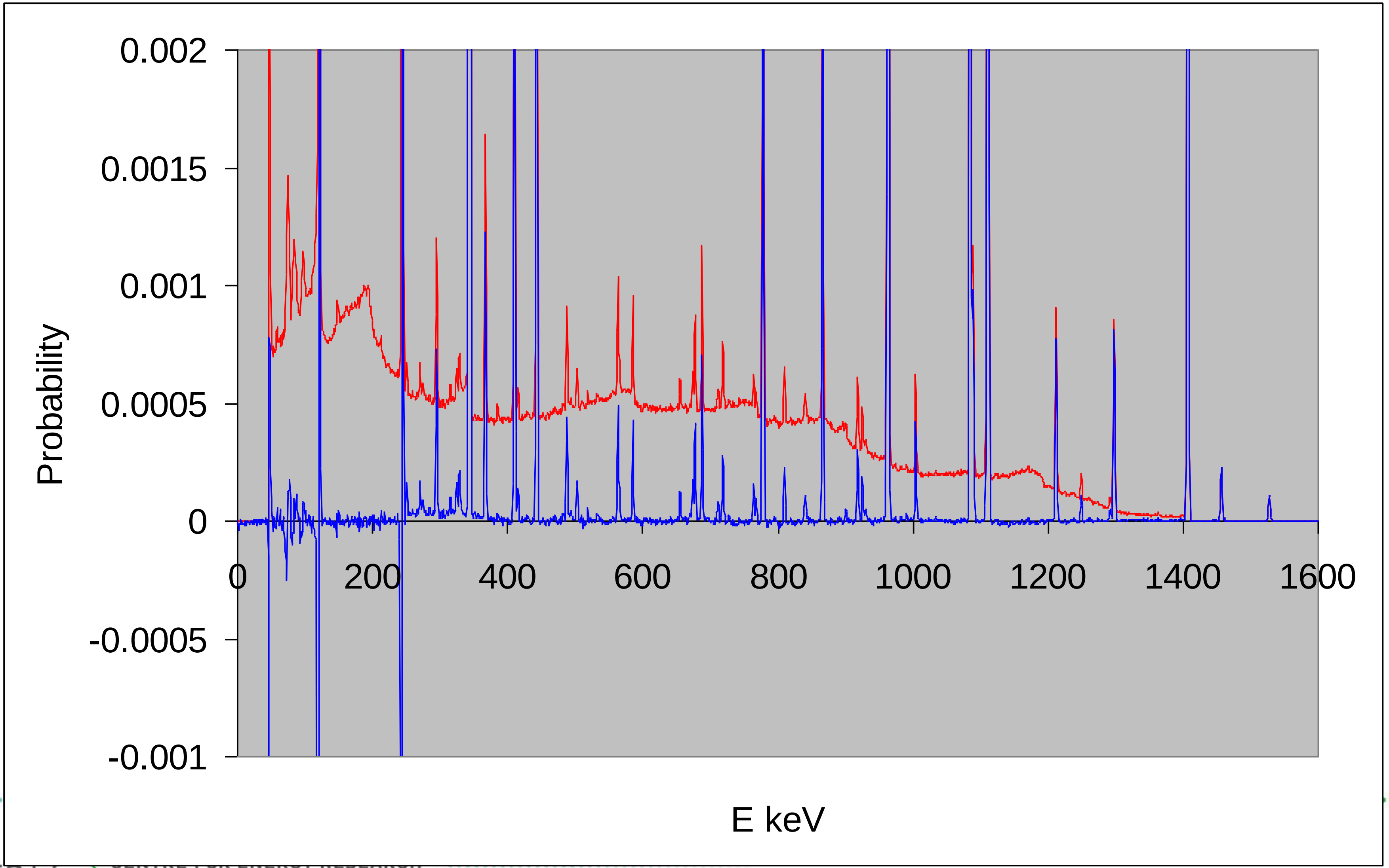
Interpolation and calculated GEANT4 spectra



Unfolding of Co-60 spectrum



Unfolding of Eu-152 spectrum



Unfolding of enriched $^{113}Cd(n,\gamma)$ spectrum