High resolution study of the $^{113}Cd(n,\gamma)$ spectrum description by statistical decay model with discrete levels

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Introduction

Collaboration for research of RSF

- **For better understanding of the radiative strength function the HZD ELBE, EK NAL and Charles Univ. groups initiated a collaboration in the framework of EFNUDAT and ERINDA to perform (n, γ) experiments on $1/2^-$ ground state nuclei with mass A and (γ, γ') experiments on A+1 (both have to be stable)**
  - In this case the capture state has 1^- and 0^- spin
  - (γ, γ') can excite mainly 1^- states
  - Unfortunately there are only two stable nuclei pairs with this feature $^{77\text{-}78}$Se and $^{195\text{-}196}$Pt
  - **There is another not so favored case for which the ground sate spin is $1/2^+$**
  - **This is the $^{113\text{-}114}$Cd pair, which is the subject of this talk**

- **Analysis of the first set of data**
  - on $^{77\text{-}78}$Se has been finished and is published in PRC
  - on $^{195\text{-}196}$Pt has been finished and is published in PRC
  - We concluded that it is possible to simulate the (n, γ) and (γ, γ') experimental spectra with the same experimental RSF
  - The TLO based RSF description successfully joins to the EGDR tail
- G. Schramm et al. PR C **85** 014311 (2012), R. Massarczyk et al. PRC C **87**, 044306 (2013)

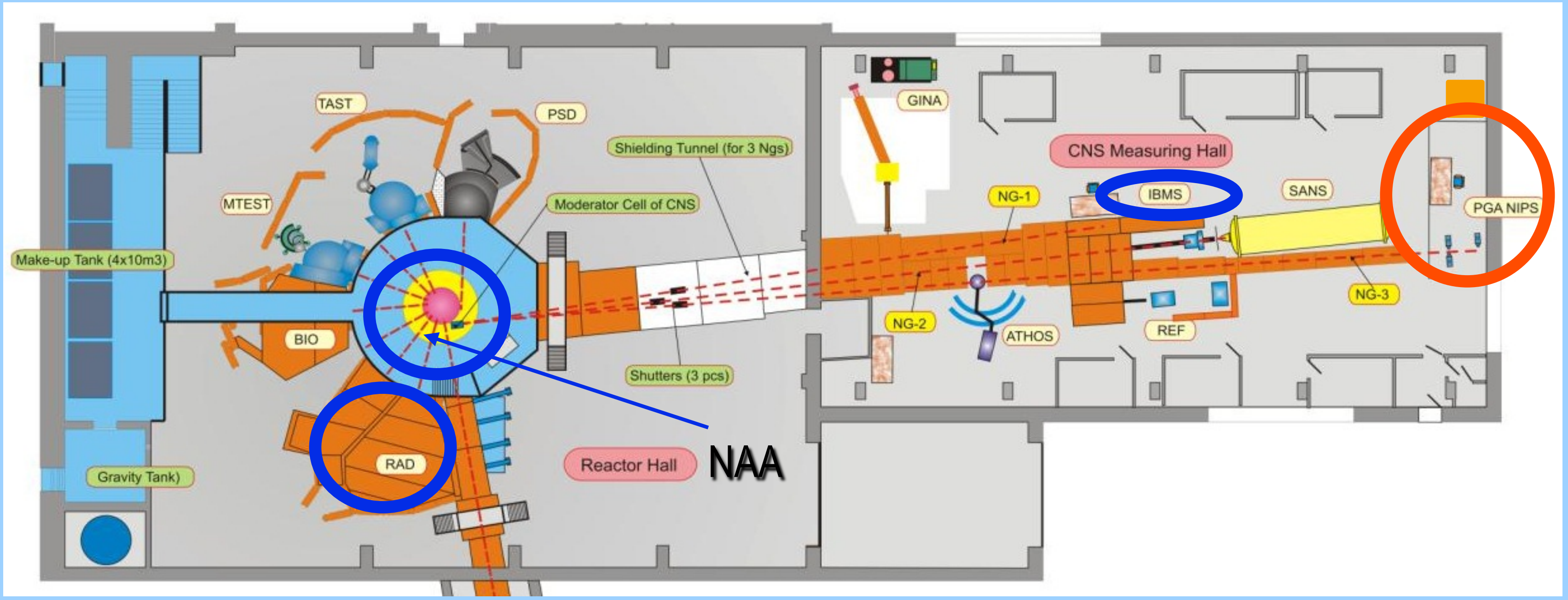
Motivation

- In our collaboration with the ELBE group, calculations were applied using 100 keV bins for the whole energy range
- In case of radiative capture we can measure a large number of discrete gamma rays.
- We have not yet considered a strict agreement for the well defined intensities below the critical number
- This should be improved since the Berkeley group uses the low energy decay-schemes in their studies successfully.
- For this reason the Budapest group started to improve the situation with so called high-energy resolution studies

R.B. Firestone et al., LBNL 60966 report (2007)

The research infrastructure of BNC

Budapest Neutron Centre (1993)



- **Nuclear analytical and imaging tools of MTA EK**
  - Prompt-gamma Activation Analysis (PGAA) (mm)
  - PGAI-NORMA elemental and structural imaging (2 mm, 200 μm)
  - Neutron-, gamma- and X-ray radiography (RAD) (100 μm)
  - Neutron Activation Analysis (NAA)
  - Mössbauer spectroscopy (chemical environment)

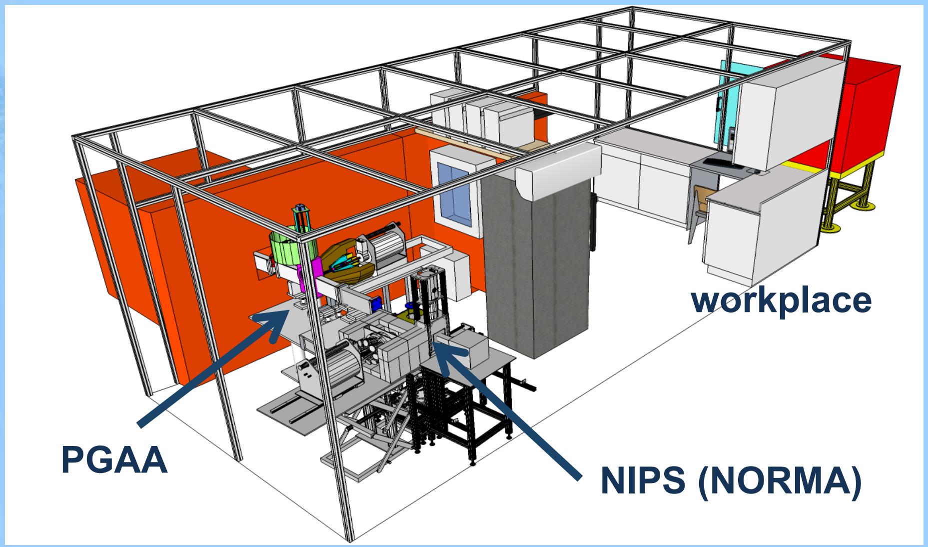
} **Macroscopic structure, composition**

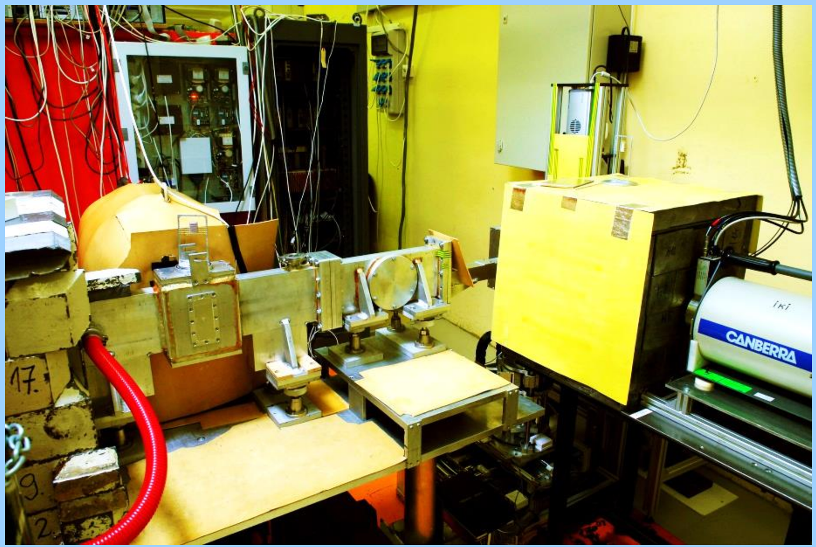
- **Material microstructure tools of Wigner FK (not all listed)**
  - Neutron powder diffractometer (PSD, MTES) (~ 0.1 nm, 1Å)
  - Small angle scattering (SANS, FSANS) (1-150 nm)
  - Reflectometer (REF and GINA) (nm surface structure)
  - TOF diffractometer (TOF) (nm lattice distance)
  - Triple Axis Spectrometer (Athos, TAST) (inelastic scattering)

} **Microscopic structure**

Experiments

at the Prompt Gamma Activation (PGA) facilities of the Budapest Neutron Centre (BNC)





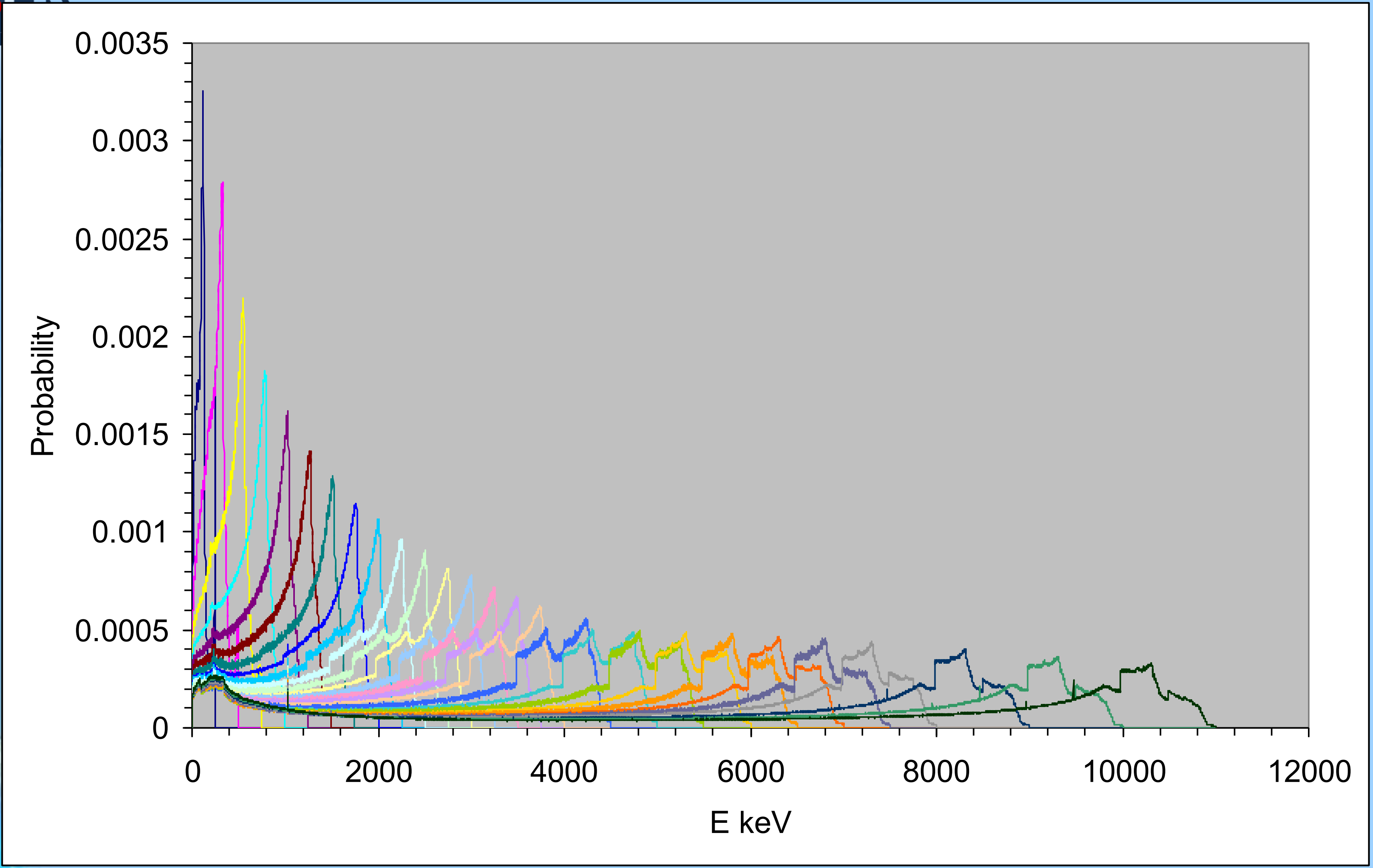
- Targets 0.1 g of enriched ^{113}Cd metal (90.2%) and 2.5 x 2.5 x 0.005 cm^3, natural and 99.99% pure Cd sheet
- Cold neutron flux of 10^8 n/cm^2/s collimated to 1-2 mm^2
- Heavy lead shielded and BGO guarded HPGe γ-detector at 90 degree relative to the beam
- Compton suppressed and normal singles acquired for about 5 days
- Detector efficiency measured with calibration standards and $^{14}N(n,\gamma)^{15}N$ reactions
- Simulated response functions with GEANT 4 code

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
- The calculation time was about 60 days of CPU time I5 proc.
- 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
  - Above Compton edge stretching and constriction were used

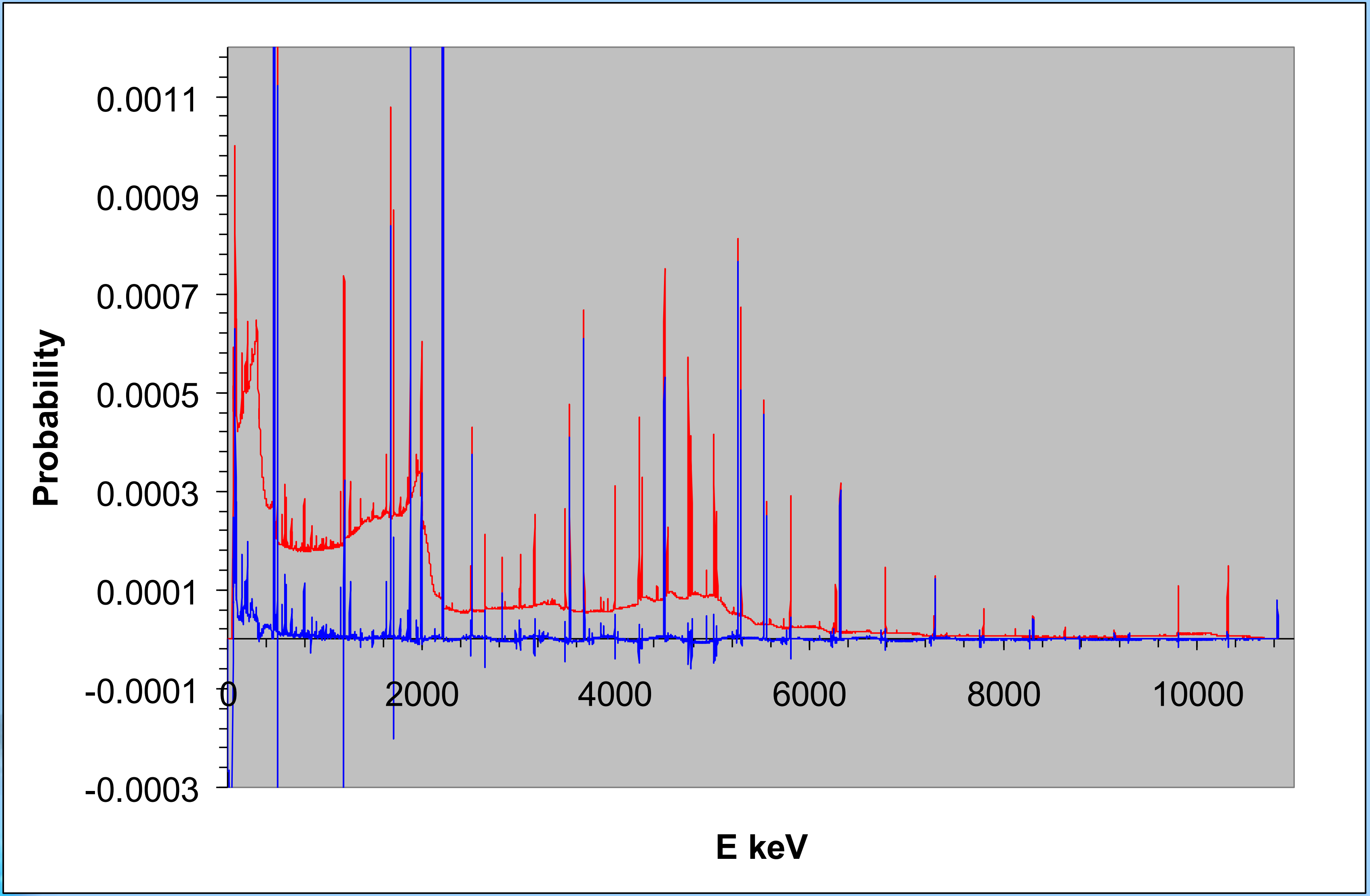
M. Guttormsen et al., Nuclear Instruments and Methods **in** Physics Research A 374 (1996) 371-376

Node spectra



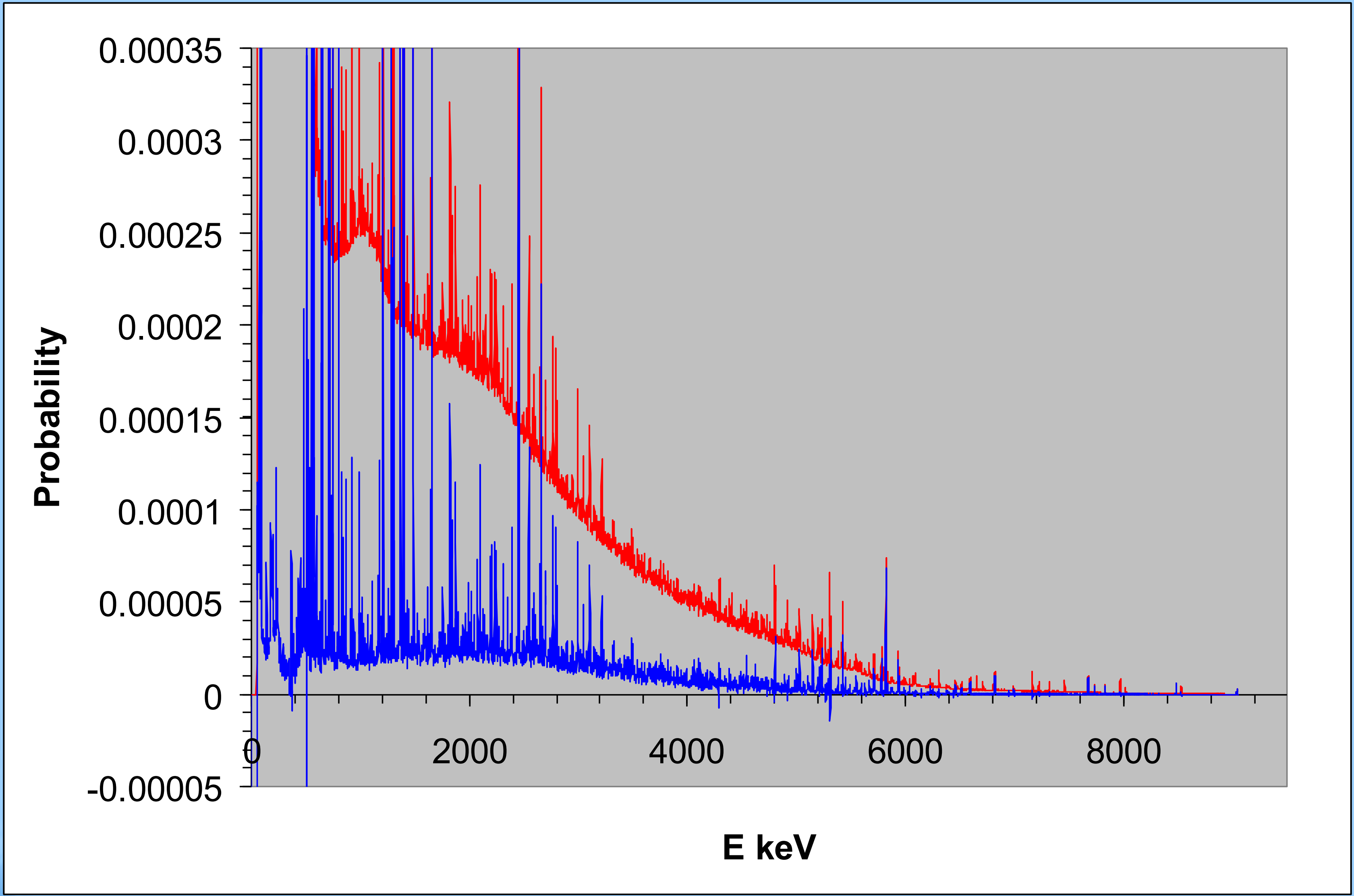
Proceedings of the European Research Infrastructures for Nuclear Data Applications (ERINDA) workshop: CERN-Proceedings-2014-002,.Genva, Switzerland 2013.10.01-2013.10.03. Geneva: CERN, 2014. pp. 119-126

Unfolding of Urea-D capture spectrum



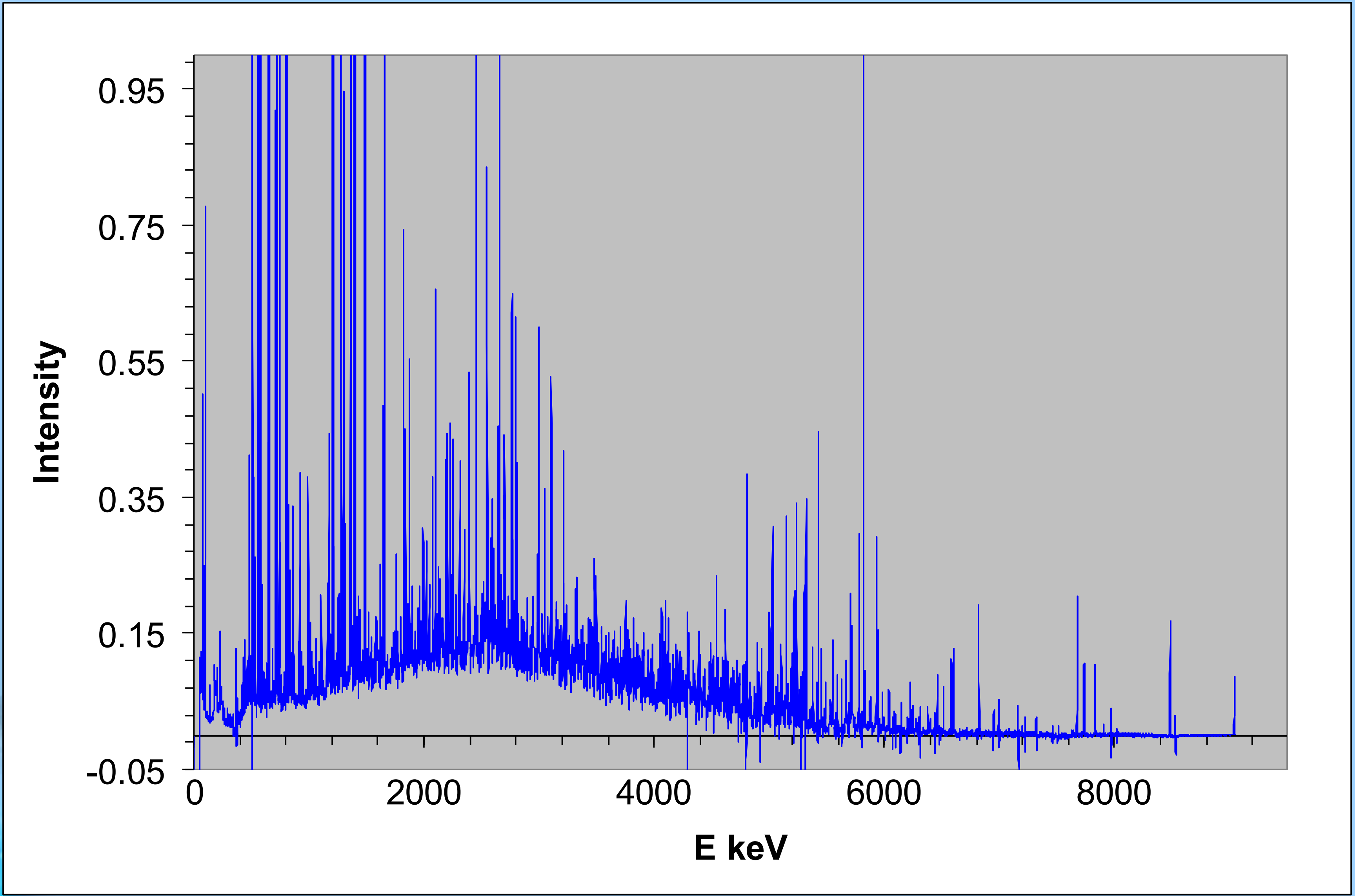
Inv-Q value 90 mb, literature 81.5(15) mb, H contribution subtracted, C, Cl, B not yet

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



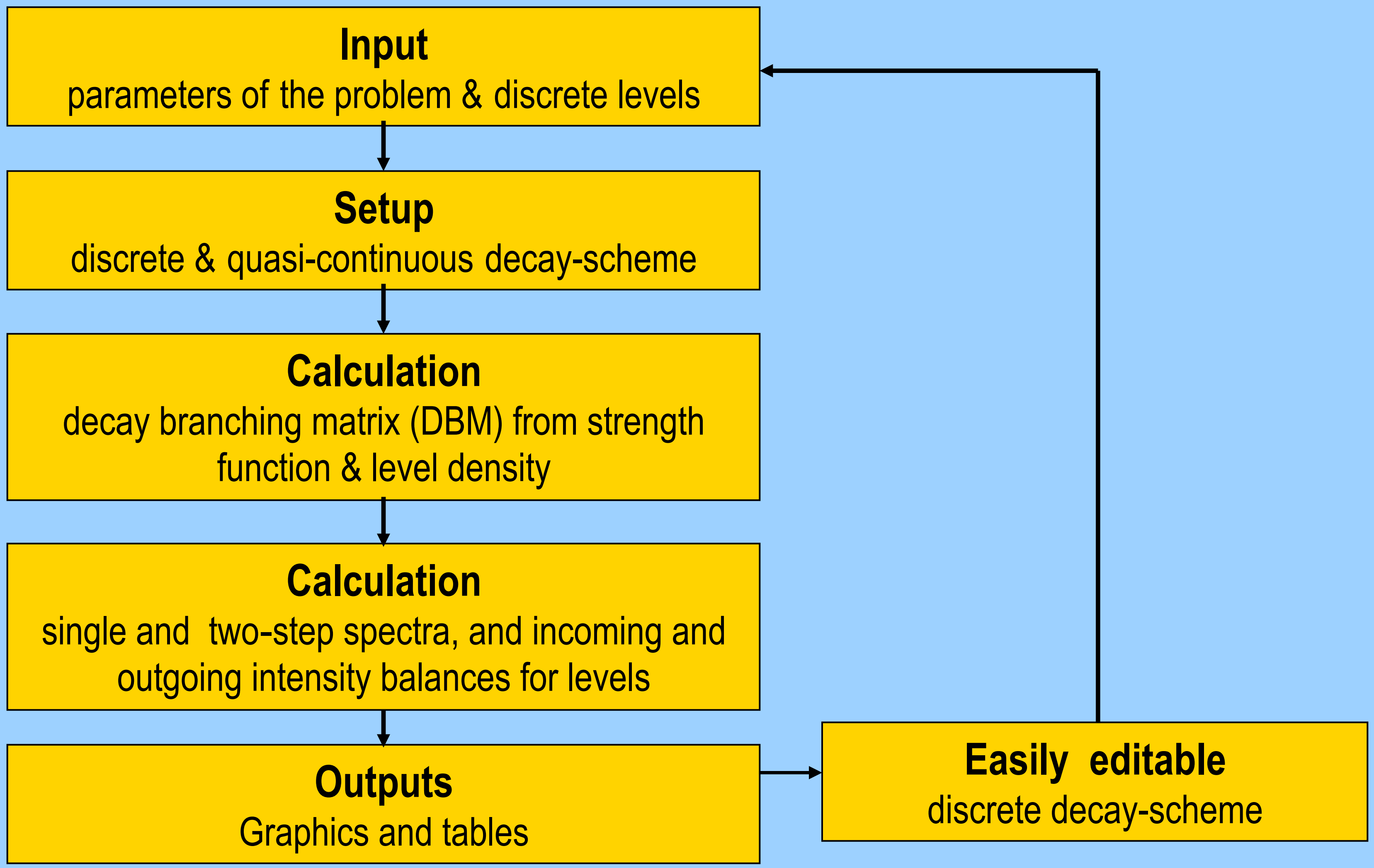
Measured (red), unfolded (blue)

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



Inv-Q value 21640 b, literature 20600(400) b, multiplicity 4.1

BIn Type Statisticall code for Gamma-decay (GBITS) software in VBA



Features of GBITS software

& parameterization for the simulation of $^{113}Cd(n,\gamma)$ decay

- RIPL-3 decay scheme input
- Level densities : CTM & BSFG
- E1 strength function: Triple Lorentzian (TLO), MLO1, EGLO, soft-pole, pigmy resonance
- M1 strength function: SLO, TLO
- E2: SLO Global parameterization from RIPL1
- Conversion electron contribution

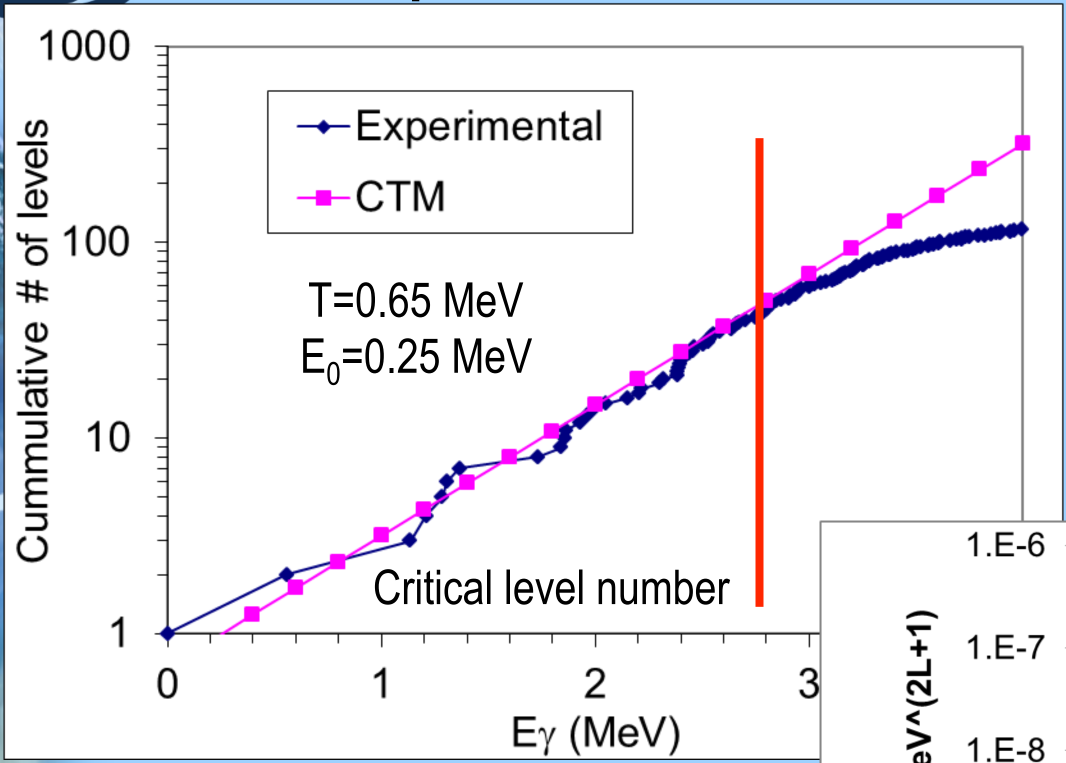
Red is: strength functions used in $^{113}Cd(n,g)^{114}Cd$ simulations

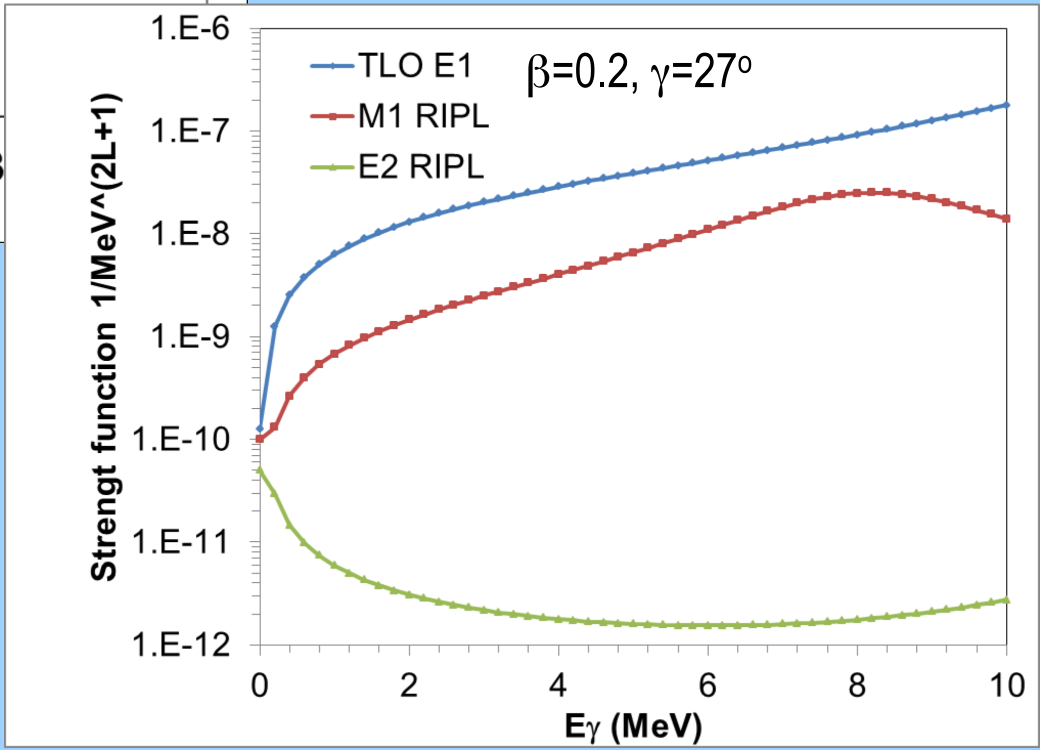
CTM parameters are: T=0.65 MeV, E_0=0.25 MeV in agreement with Massarczyk et al. in preparation

For the level density the odd-even staggering as described by von Egidy is used at the Bn

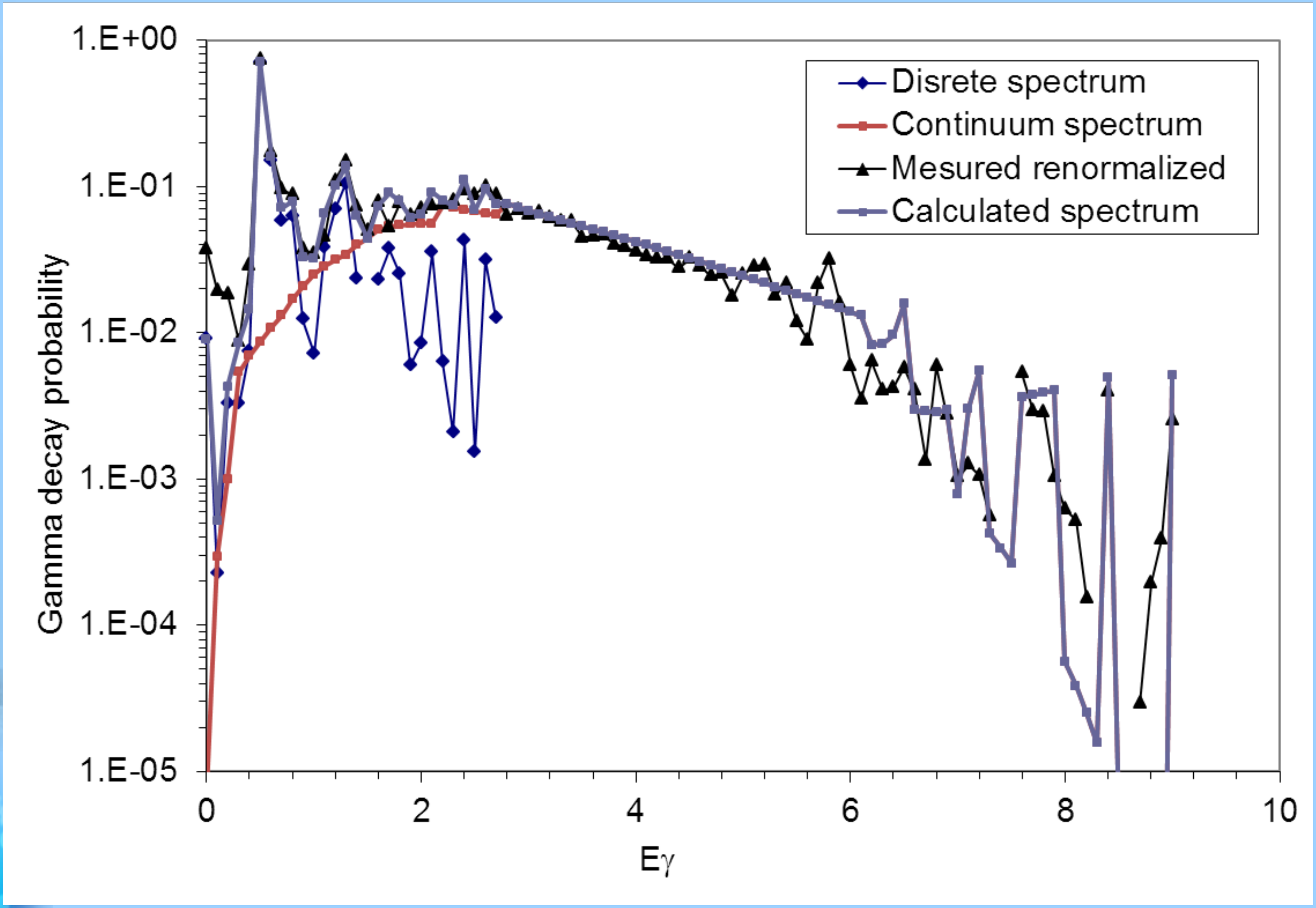
TLO is parameterized as prescribed by Massarczyk at al. in preparation

Level density & strength functions
parameterization for the simulation of $^{113}Cd(n,\gamma)$ decay

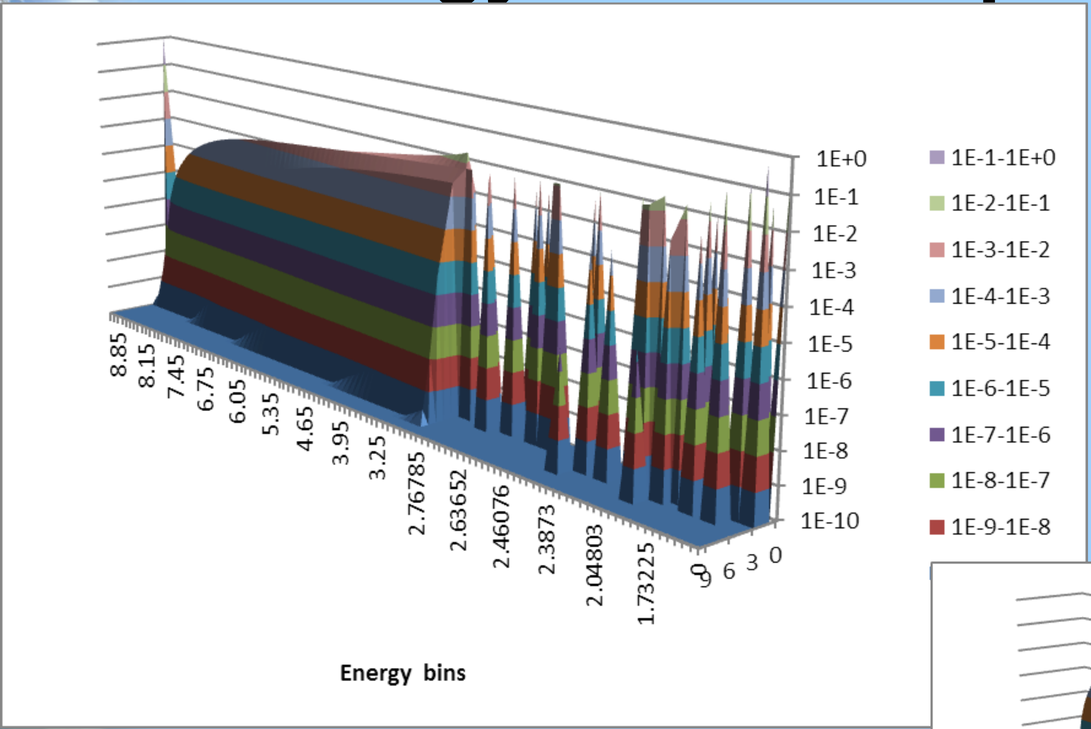


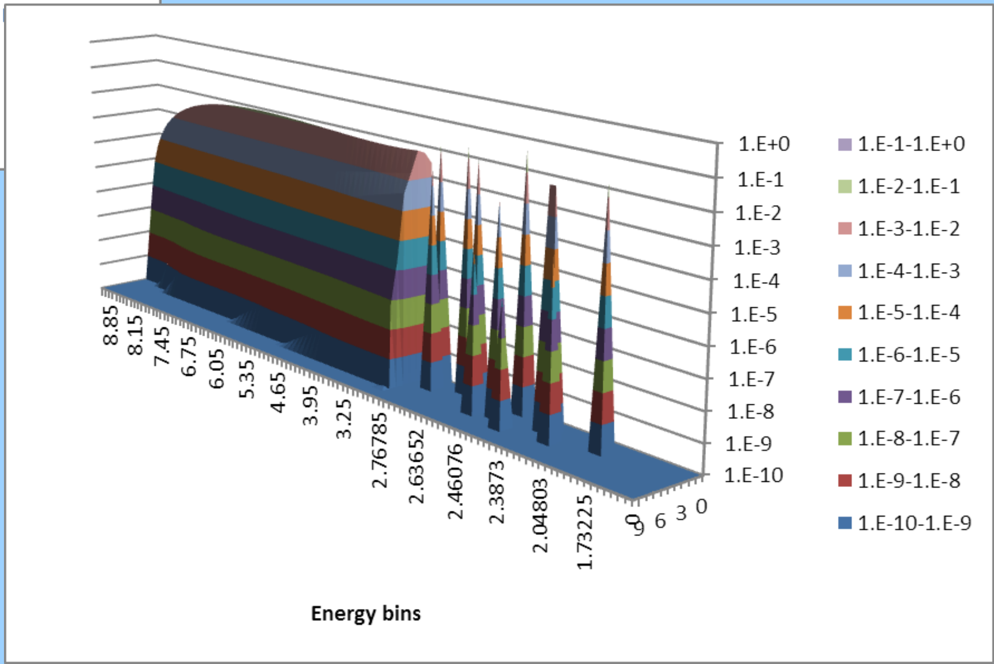


Low resolution model for the $^{113}Cd(n,\gamma)$ spectrum

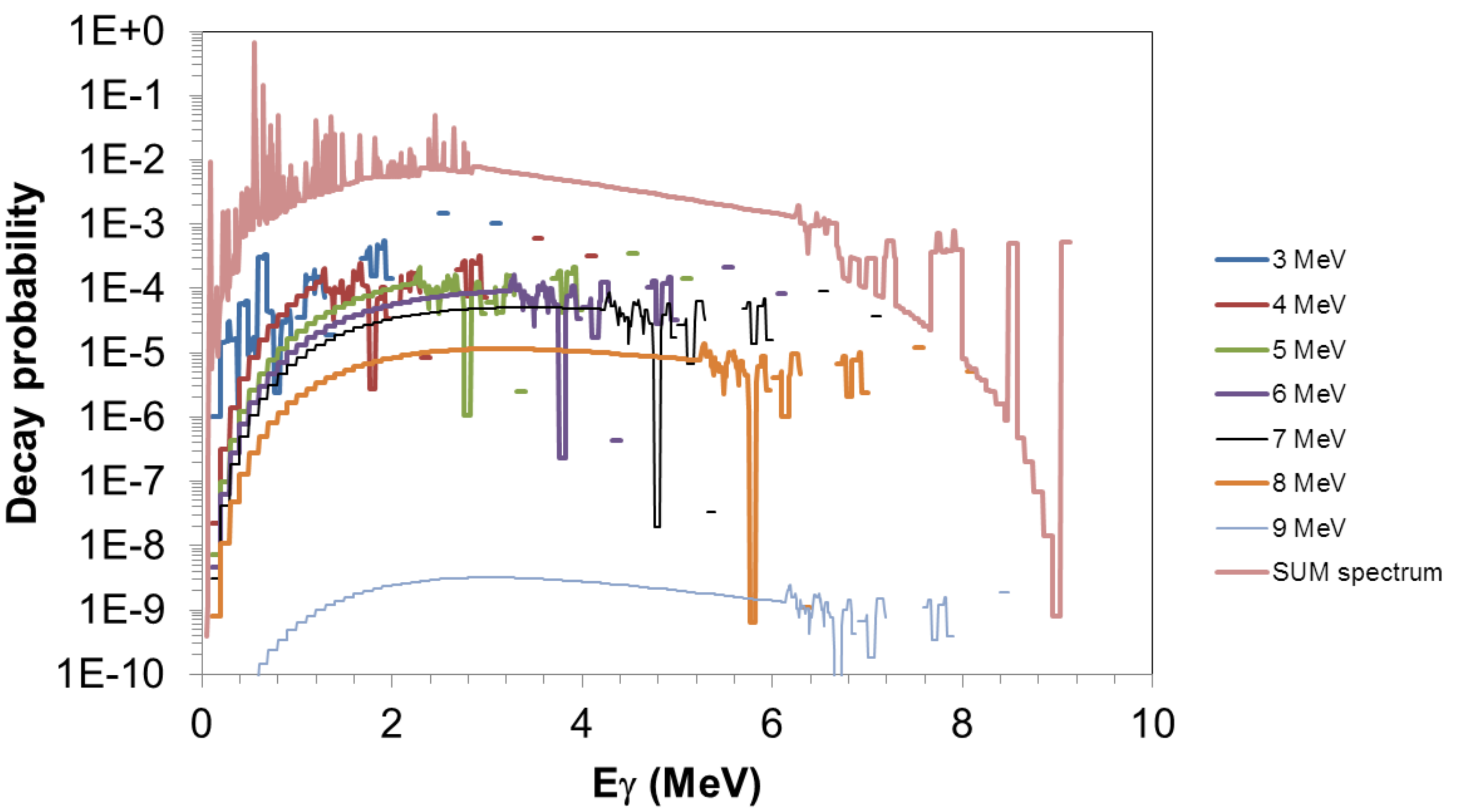


Outgoing intensity matrix as a function of energy bins and spin for $^{113}Cd(n,\gamma)$

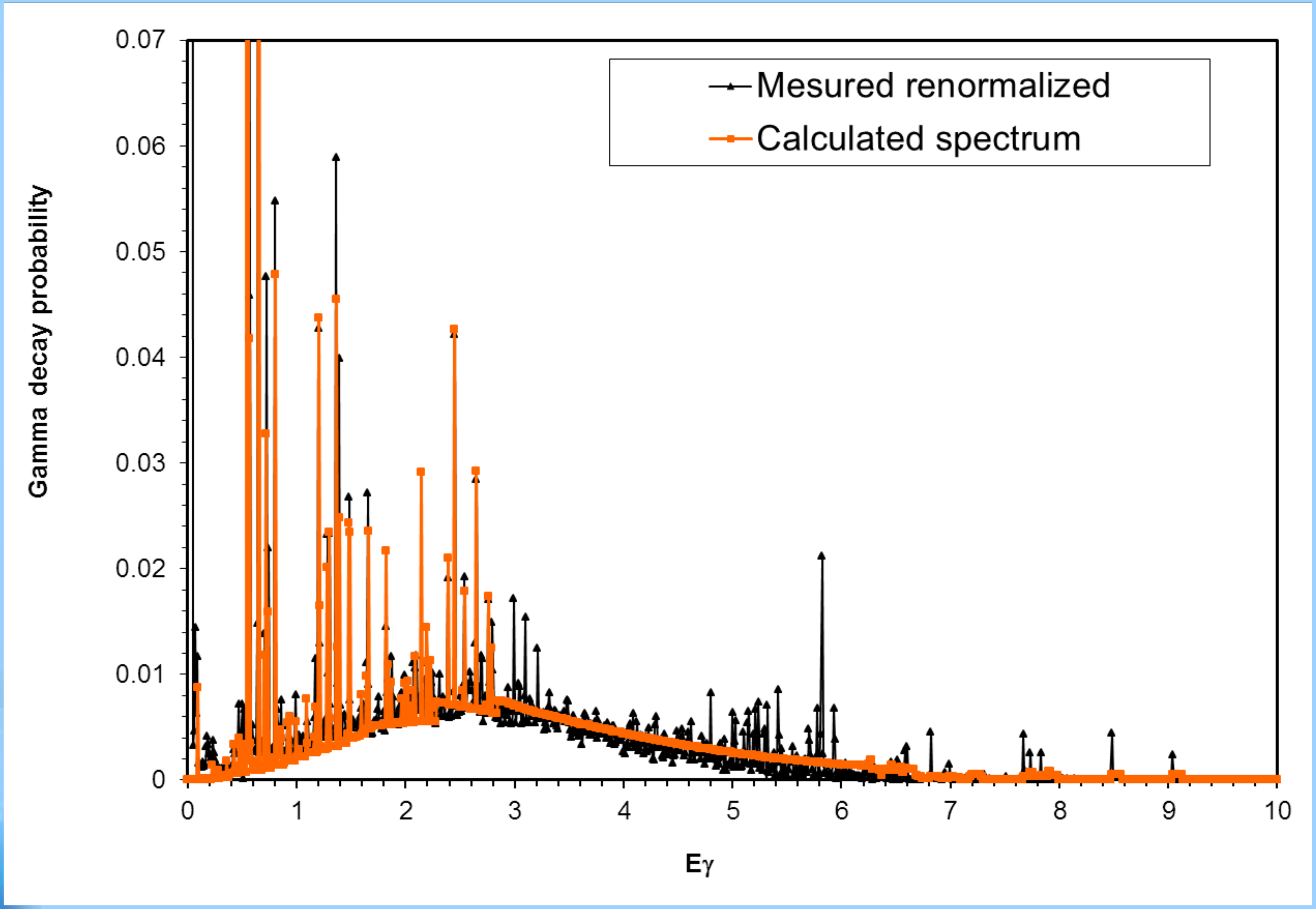




Energy spectra arrising from each shown bins and the sums of all bins



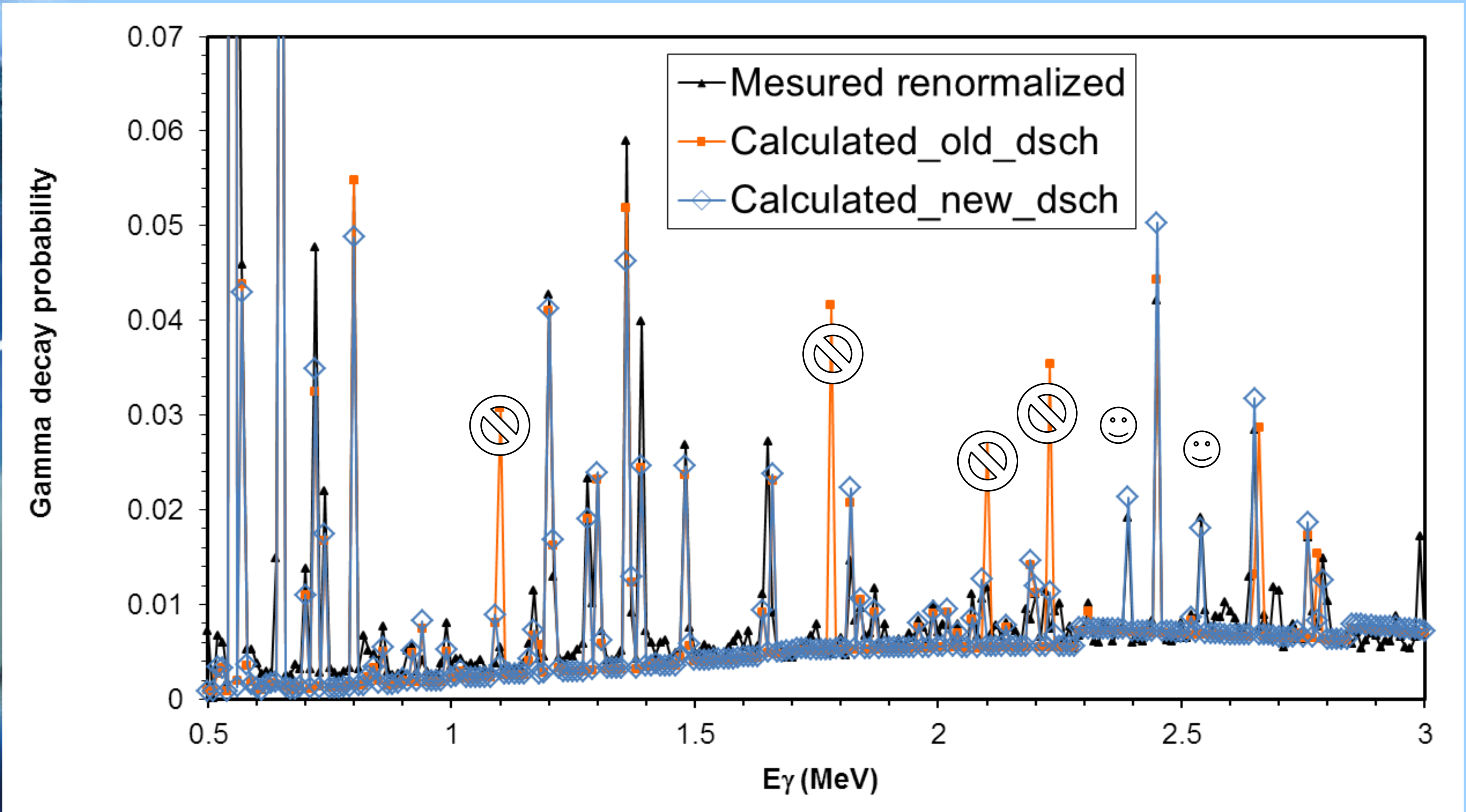
High resolution model for the (n,γ) spectrum



The decay-scheme has been changed to improve the agreement for the low energy spectrum

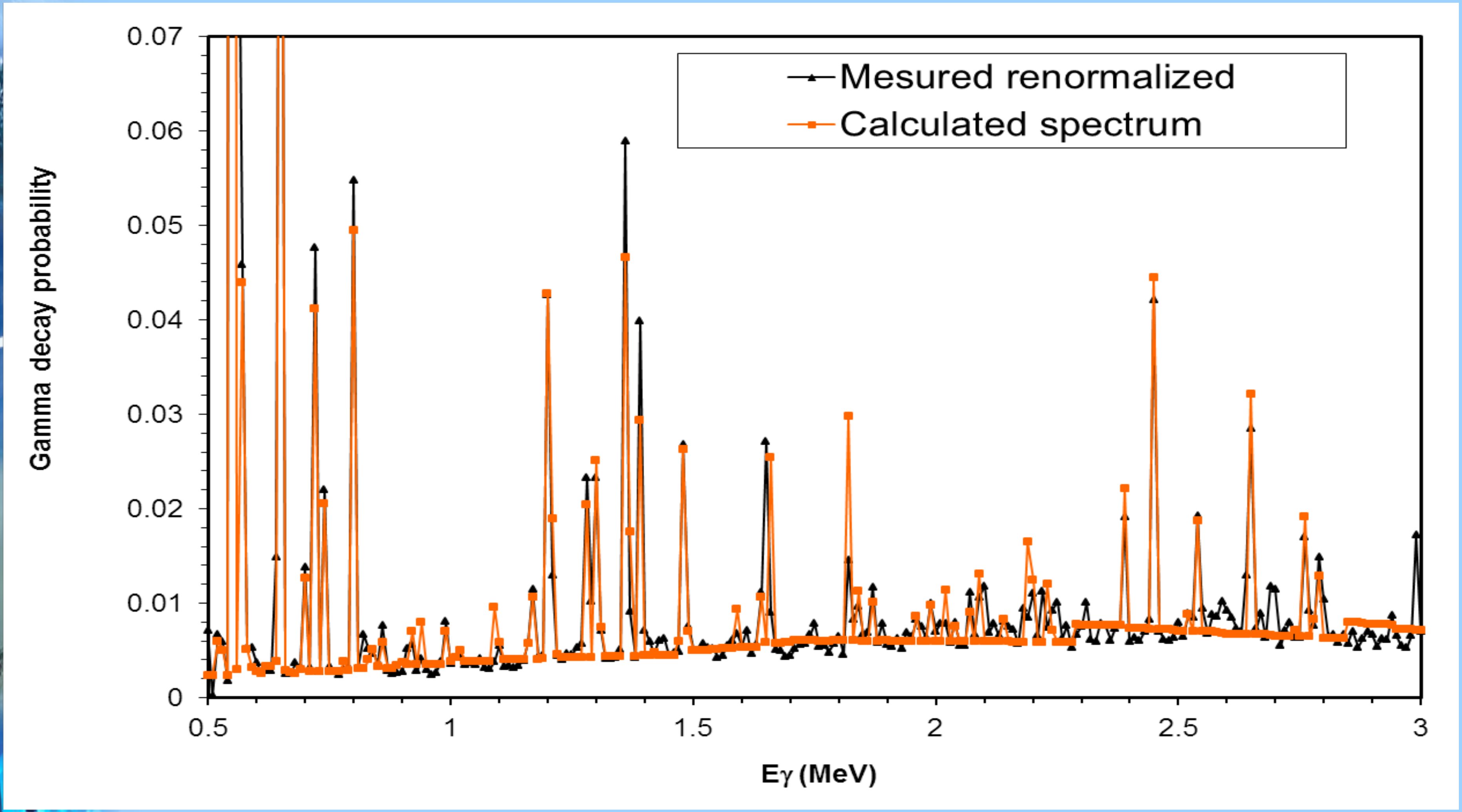
New decay-scheme					Old decay-scheme ENSDF 2007			
I	Ei	Ji	Pi		I	Ei	Ji	Pi
1	0	0	1		1	0	0	1
2	0.558456	2	1		2	0.558456	2	1
3	1.13453	0	1		3	1.13453	0	1
4	1.20971	2	1		4	1.20971	2	1
5	1.28374	4	1		5	1.28374	4	1
6	1.30561	0	1		6	1.30561	0	1
7	1.36434	2	1		7	1.36434	2	1
8	1.73225	4	1		8	1.73225	4	1
					9	1.784	2	1
9	1.84195	2	1		10	1.84195	2	1
10	1.8597	0	1		11	1.8597	0	1
11	1.86426	3	1		12	1.86426	3	1
12	1.93208	4	1		13	1.93208	4	1
13	1.95809	3	-1		14	1.95809	3	-1
14	1.9903	6	1		15	1.9903	6	1
15	2.04803	2	1		16	2.04803	2	1
16	2.15227	3	1		17	2.15227	3	1
17	2.20456	3	1		18	2.20456	3	1
18	2.21886	2	1		19	2.21886	2	1
19	2.29893	5	-1		20	2.29893	5	-1
20	2.3171	4	1		21	2.3171	2	1
21	2.38476	3	-1		22	2.38476	3	-1
22	2.3873	3	-1		23	2.3873	3	-1
23	2.3915	4	1		24	2.3915	4	1
24	2.398	2	1					
25	2.4002	6	1		25	2.4002	6	1
26	2.4125	6	-1		26	2.4125	6	-1
27	2.43764	0	1		27	2.43764	0	1
28	2.456	1	-1		28	2.456	1	-1
29	2.46076	4	-1		29	2.46076	4	-1
					30	2.4652	2	-1
30	2.5026	2	1		31	2.5026	2	1
31	2.52542	2	1		32	2.52542	2	1
32	2.53581	5	-1		33	2.53581	5	-1
33	2.542	2	1					
34	2.55387	0	1		34	2.55387	0	1
35	2.58036	2	-1		35	2.58036	2	-1
36	2.63652	0	1		36	2.63652	0	1
37	2.65012	2	1		37	2.65012	2	1
38	2.658	1	-1		38	2.6609	2	1
39	2.6693	8	1		39	2.6693	8	1
40	2.70107	3	1		40	2.70107	3	1
					41	2.7352	7	-1
41	2.74926	2	1		42	2.74926	2	1
42	2.75692	3	-1		43	2.75692	3	-1
43	2.76785	1	-1		44	2.76785	1	-1
44	2.7885	2	1		45	2.7885	1	1
45	2.79999	2	1		46	2.79999	2	1

Effect of new and old decay-schemes

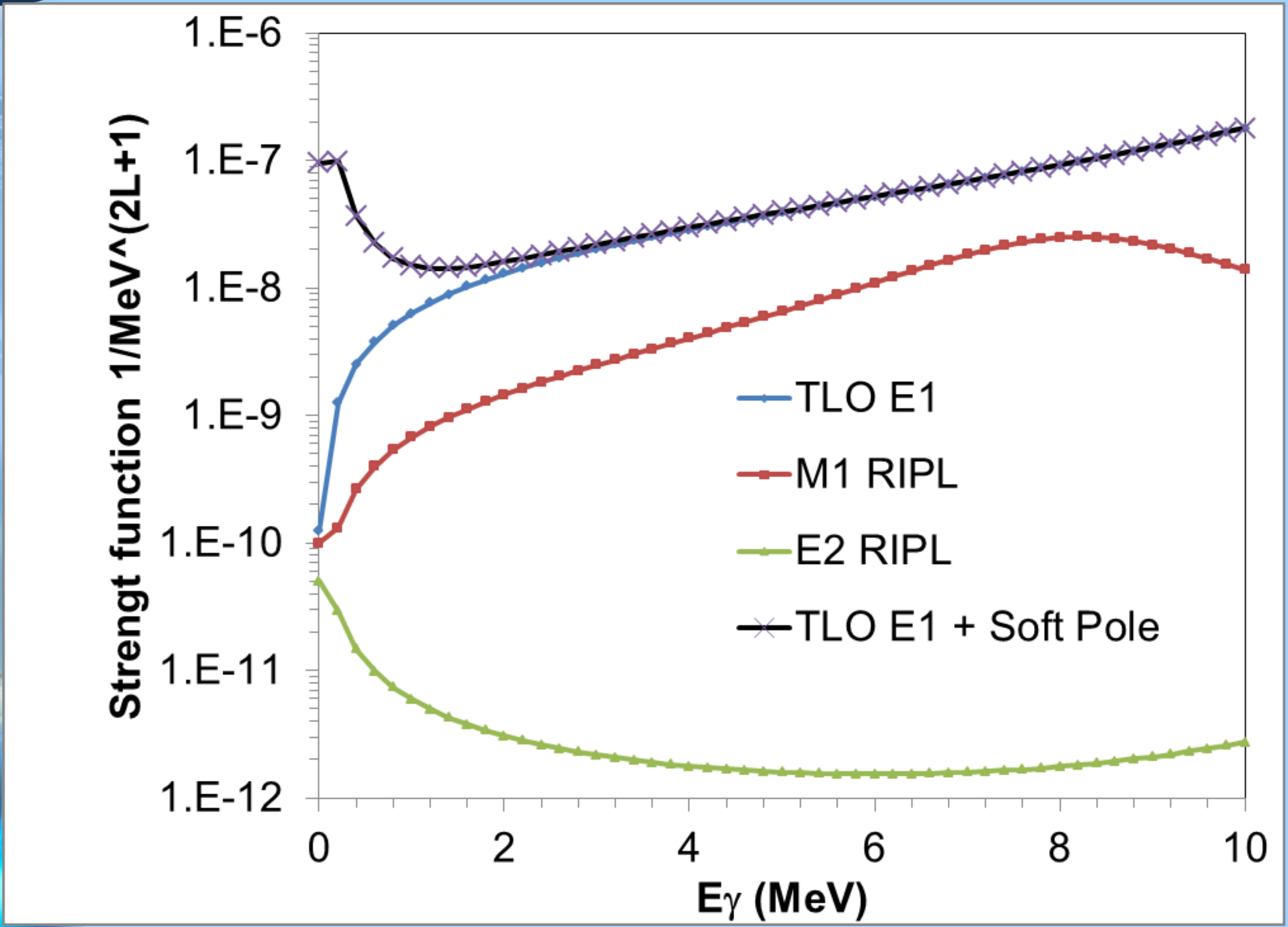


Updating the decay-scheme is important and yields are very sensitive for the spin and parity

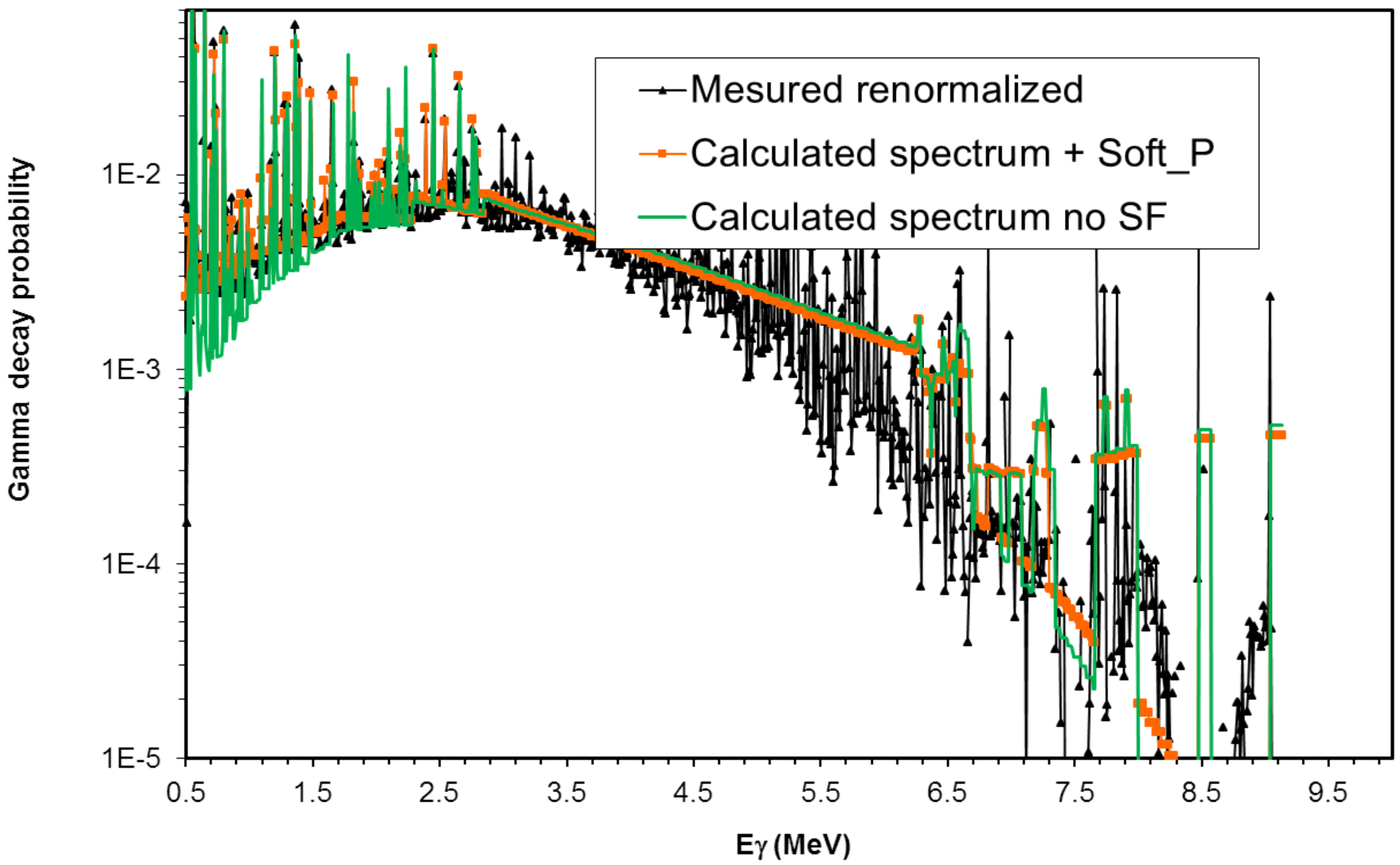
Effect of soft-pole on decay-schemes



Effect of soft-pole on decay-schemes



Effect of soft-pole on decay-schemes



Summary

- Modeling of Budapest detector response reached an acceptable accuracy
- Unfolding normal spectra follows the Oslo method
- A new software has been developed to study the statistical modelling in high resolution
- Preliminary results were shown
- The decay-scheme of ^{114}Cd were changed to improve agreement with the observed data
- A lot more work is needed to obtain better agreement

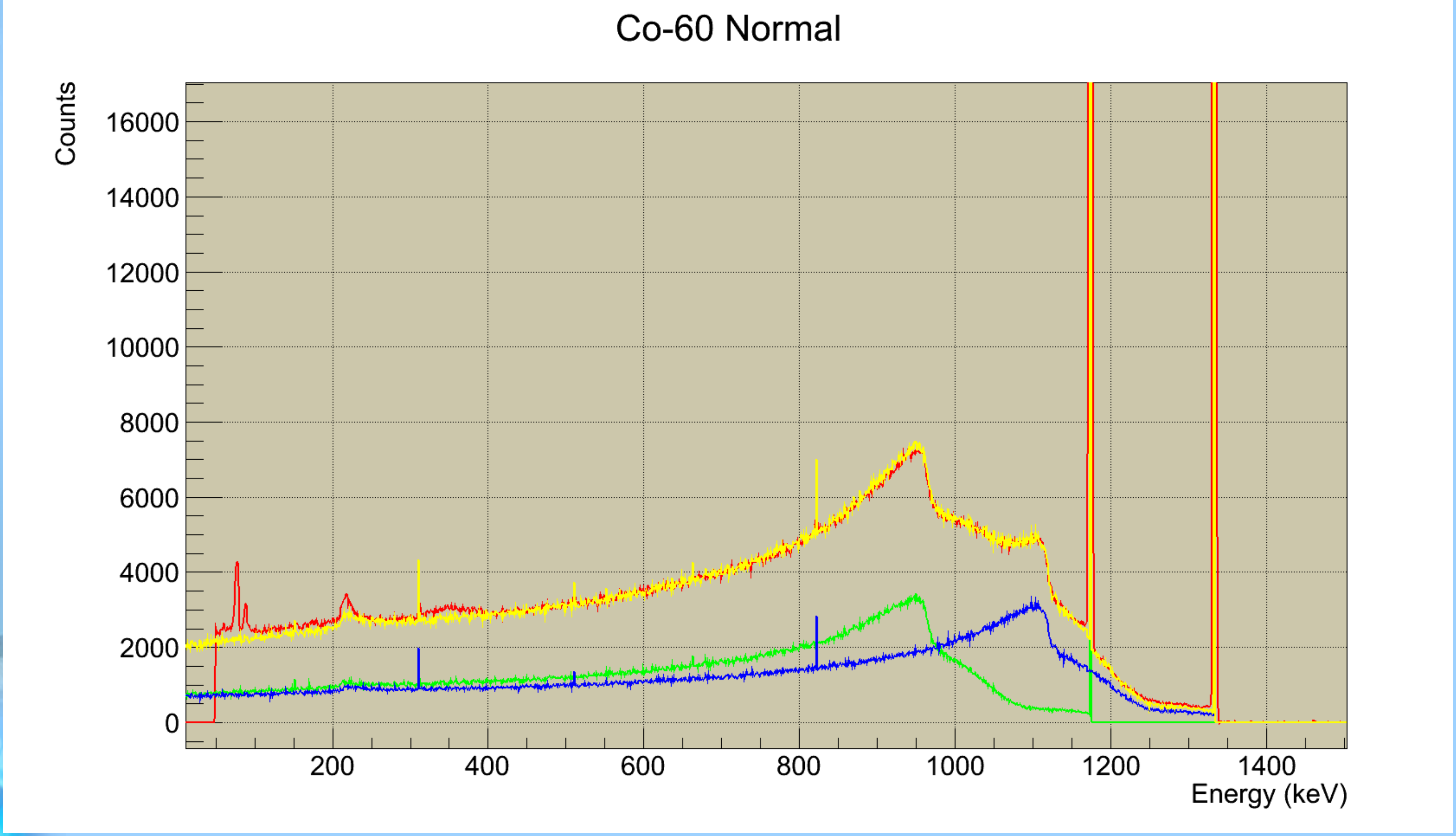
Thanks for your attention!

Works remained
(Jyväskylä)

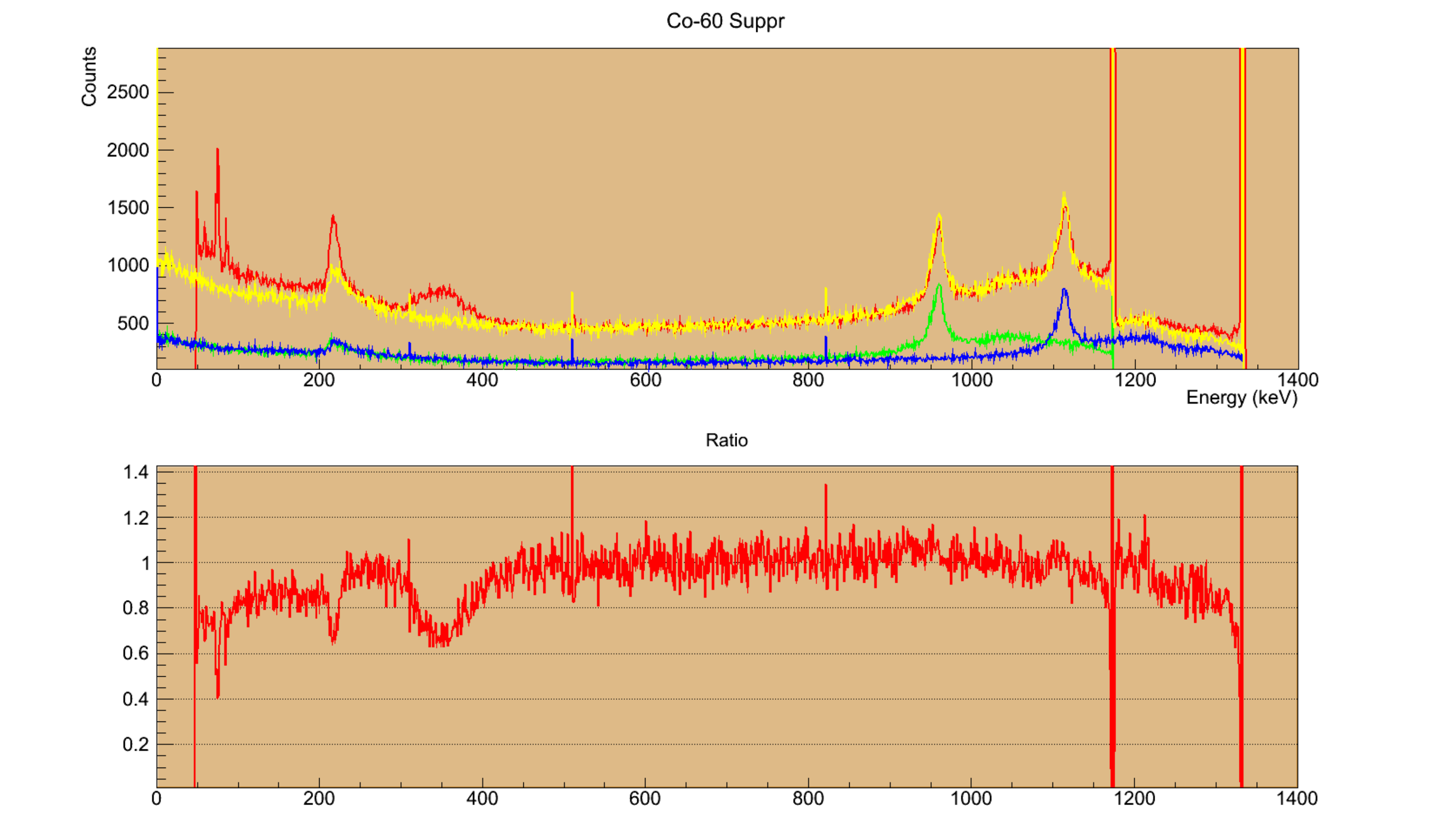
- Modeling of Budapest detector response needs more work
- Unfolding of Budapest spectra is to be done
- Total capture Xsection at thermal energy
- Combined evaluation and modeling of have to be done
- Expected outcome is better understanding of the role of M1 and E1 transitions and their strength function

Modeling of Budapest detector response

More works were done on the quality of modeling
Below 400 keV we still have discrepancies

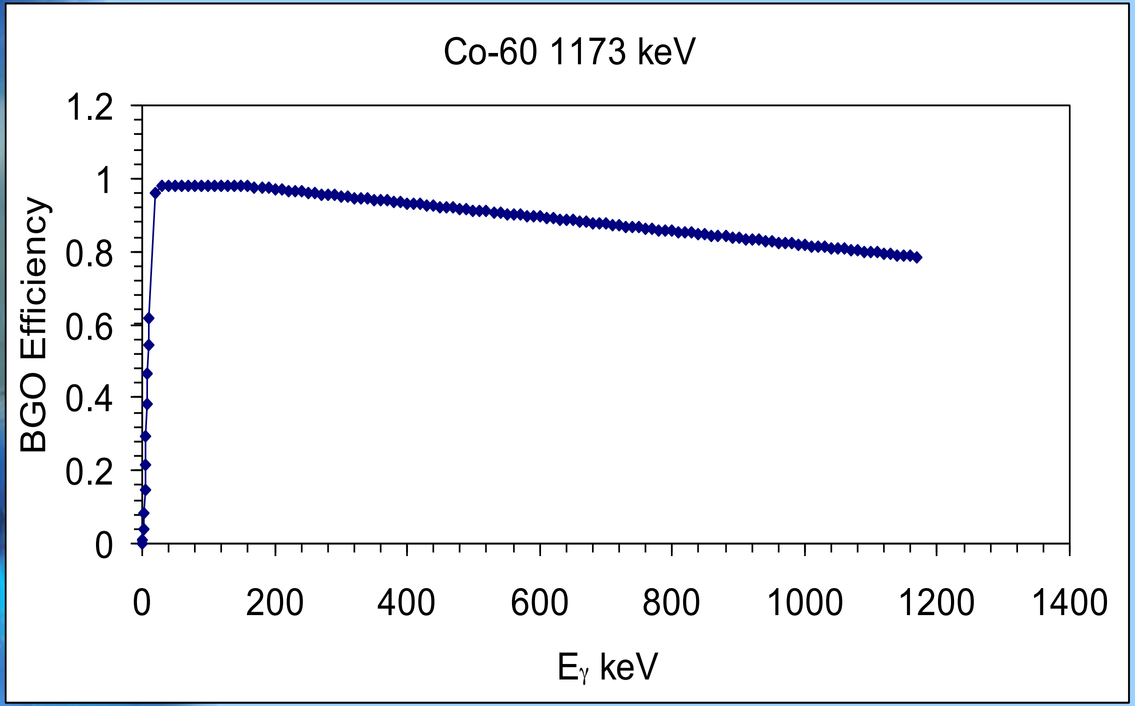


Modeling of Budapest detector response



Modeling of Budapest detector response

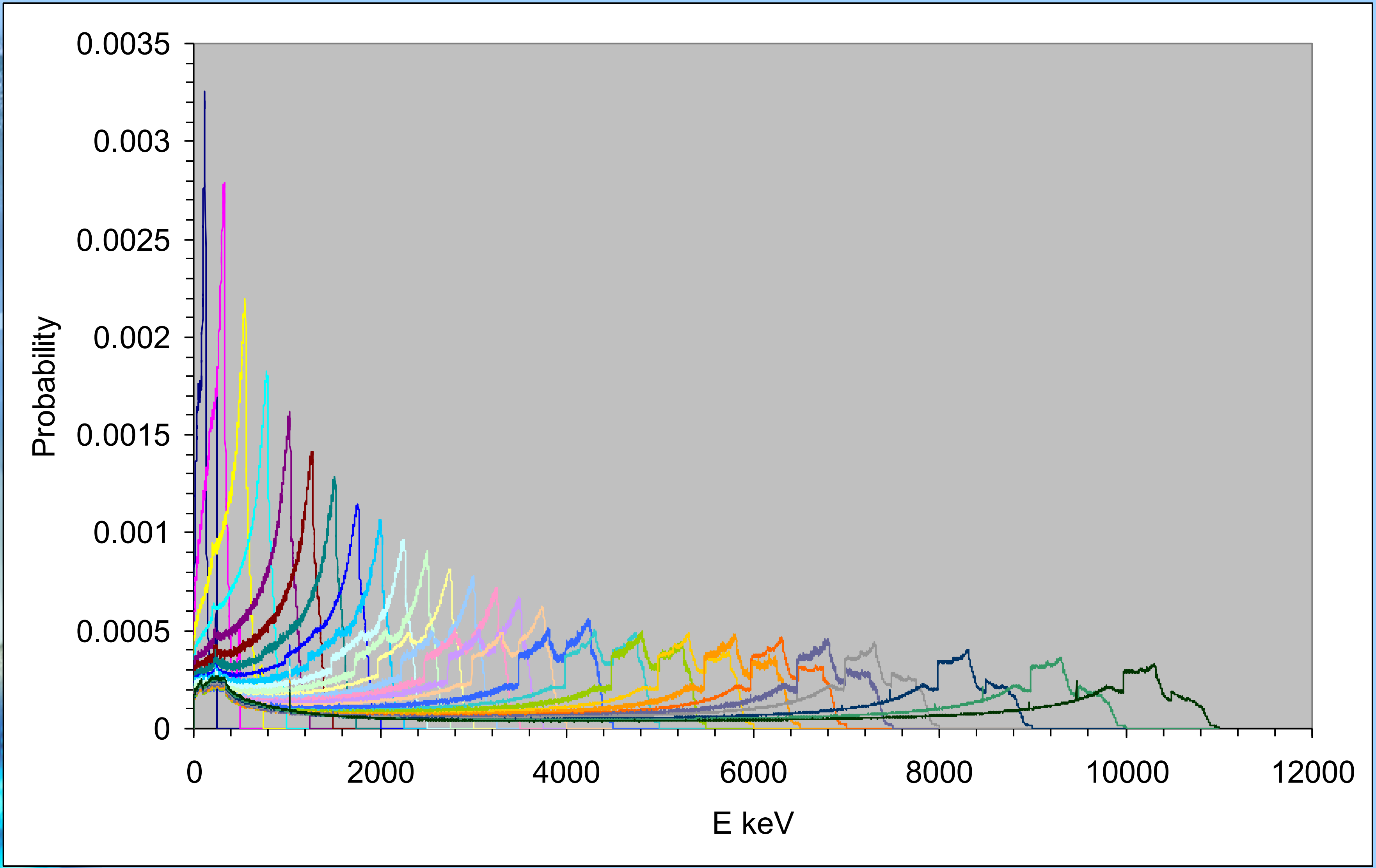
- HPGe geometry was further adjusted slightly to describe the normal mode
- List mode acquisition of Monte Carlo total energy in the sensitive volumes (HPGe, BGO-main, catcher)
- From the calculation we realized that the catcher is not really working
- Special energy dependent BGO efficiency was introduced to describe the main BGO coincidence efficiency of Compton-suppression
- There are still discrepancies at lower energies which do not depend on the Compton-suppression
- Compton-suppression is less tested than normal mode thus more uncertain



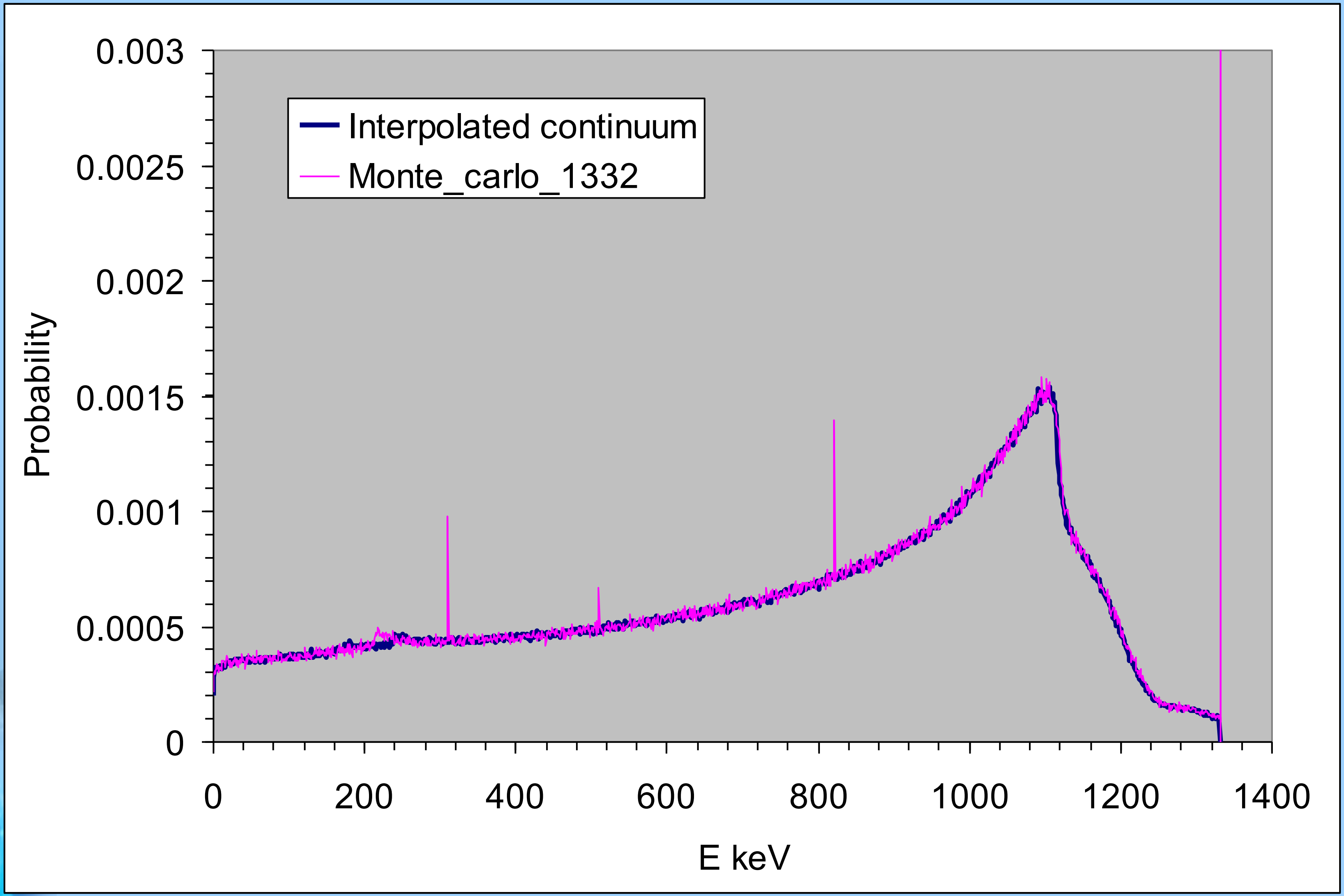
$$\mathrm{BGO}_{\mathrm{effi}} = 0.98 \times \begin{cases} 1-\exp\left(-\dfrac{E_\gamma^2}{2/3a}\right); & \text{if } E_\gamma < a \\ 1-\dfrac{c(E_\gamma - a)^2}{(b-a)(1+(E_\gamma - a))}; & \text{else} \end{cases}$$

$$a = 150\,\mathrm{keV} \quad b = 1173\,\mathrm{keV} \quad c = 0.2$$

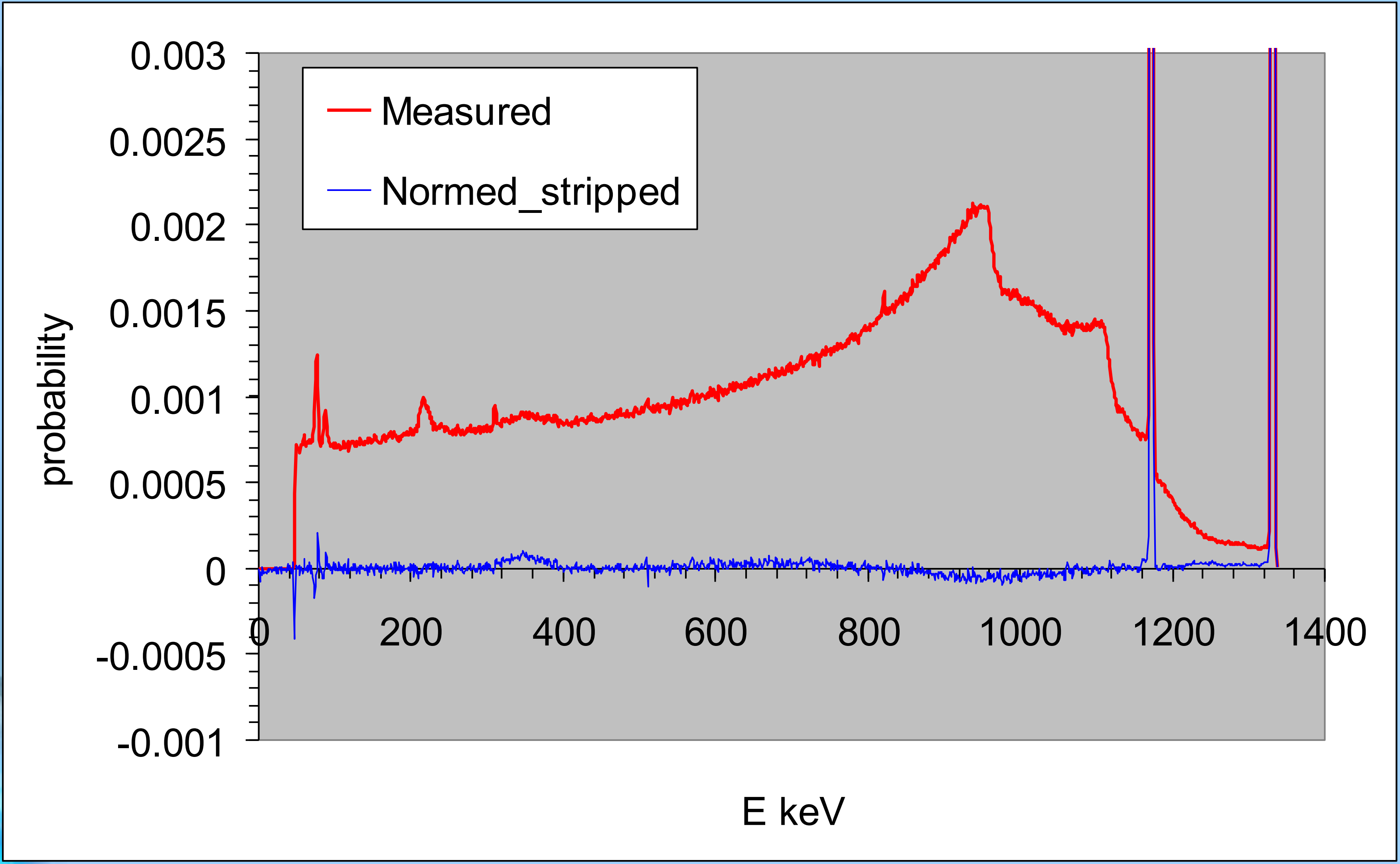
Node spectra



Interpolation and calculated GEANT4 spectra



Unfolding of Co-60 spectrum



Unfolding of Eu-152 spectrum