Combined study of the gamma-ray strength function of ^{114}Cd with (n,γ) and (γ,γ’) reactions

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- Analysis of data
- Modeling of Budapest detector response and unfolding normal spectra
- Gamma-Dex modeling of $(\gamma,\gamma')$and (n,γ) spectra
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Motivation

- Better knowledge of radiative strength functions is important for modeling competing nuclear deexcitation processes and gamma-ray spectra for calculation of gamma heating in nuclear energy systems, and for development of nuclear theory.
- In the past decades there seemed to be some difficulty to match results from radiative strength function and nuclear resonance fluorescence experiments at low energies

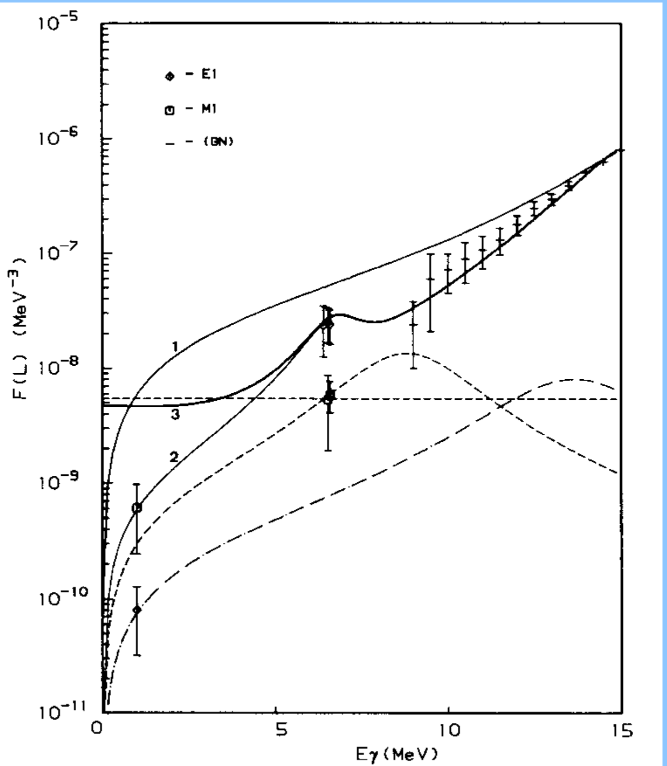


FIG. 4. The same as Fig. 1 for the ^{93}Nb(n,γ) reaction (primary strength function data, Ref. 2). Parameters used for the pigmy resonance are given in Table I.

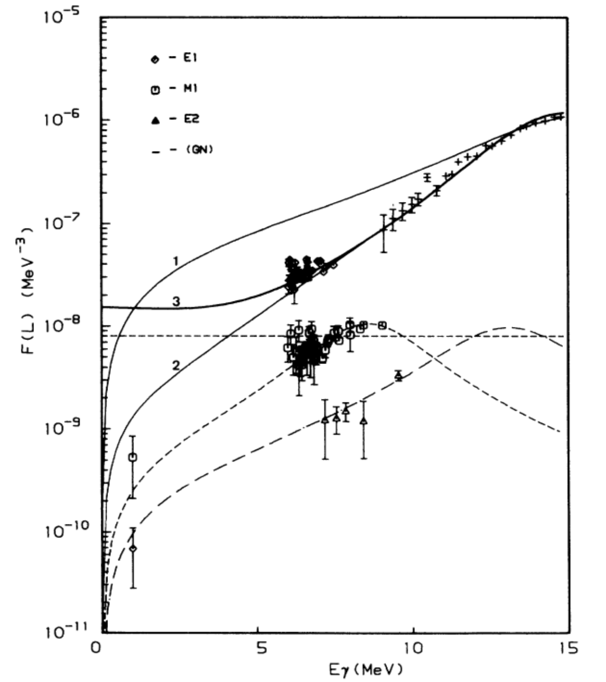


FIG. 3. The same as Fig. 1 for the ^{105}Pd(n,γ) reaction (primary strength function data, Ref. 14).

1. SLO
2. KMF
3. Lorentzian with energy dependent damping

J. Kopecky and M. Uhl, Phys. Rev. C **41**, 1941 (1990).
R. Capote *et al.*, Nuclear Data Sheets **110** 3107 (2009).

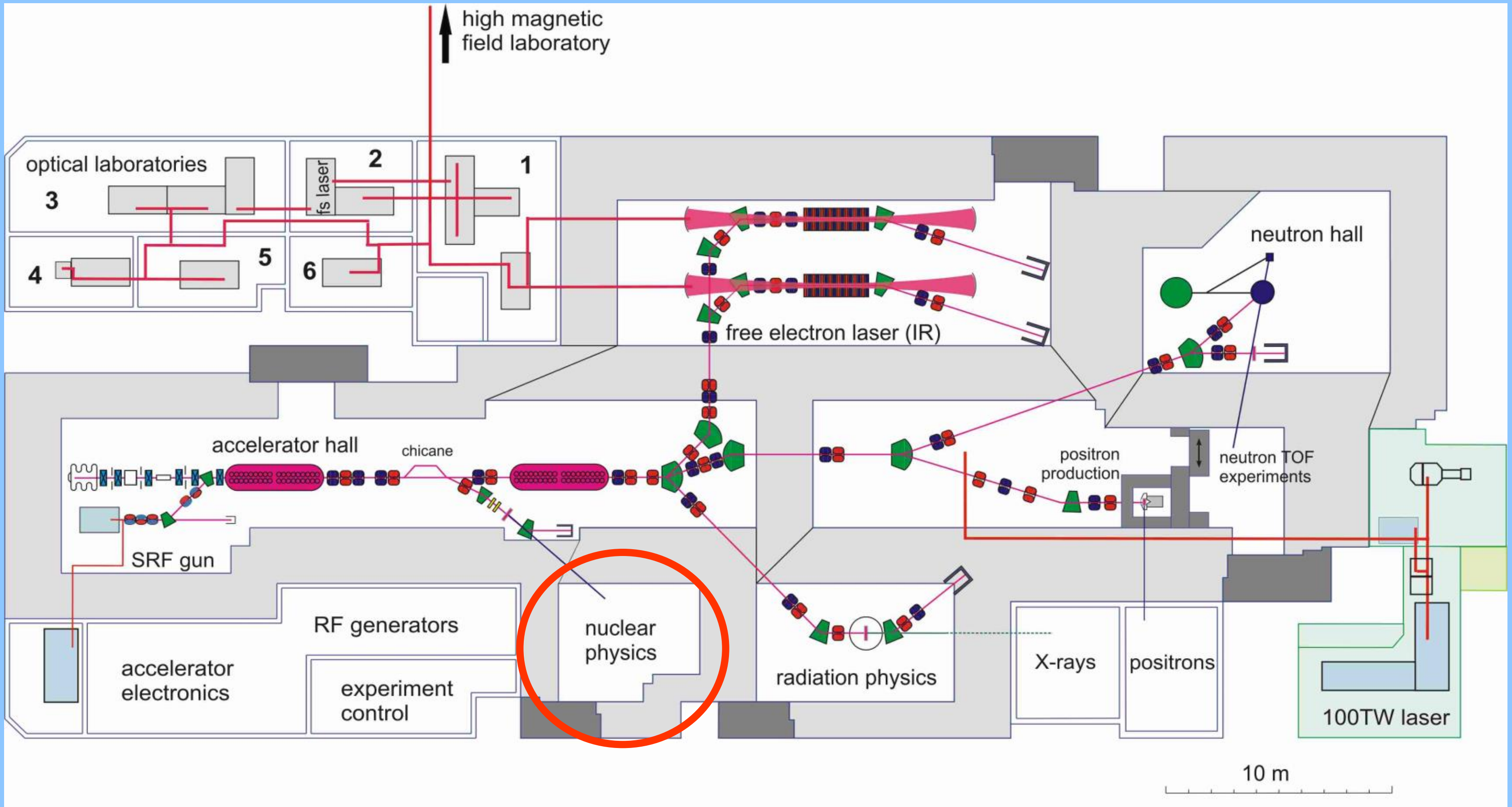
Collaboration for research of RSF

- **For better understanding of the radiative strength function the HZD INP, EK NAL and Charles Univ. groups initiated a collaboration in the framework of EU FP6 EFNUDAT and FP7 projects ERINDA projects 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/or 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 $1/2^+$, however it may clear the role of M1 strength
  - This is the ^{113,114}Cd pair, which is the subject of this talk

- **Analysis of the first two sets 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 deduced from (γ, γ')
  - The Triple Lorentzian (TLO) based RSF description successfully joins to the EGDR tail

G. Schramm et al. PRC **85** 014311 (2012), R. Massarczyk et al. PRC C **87**, 044306 (2013)

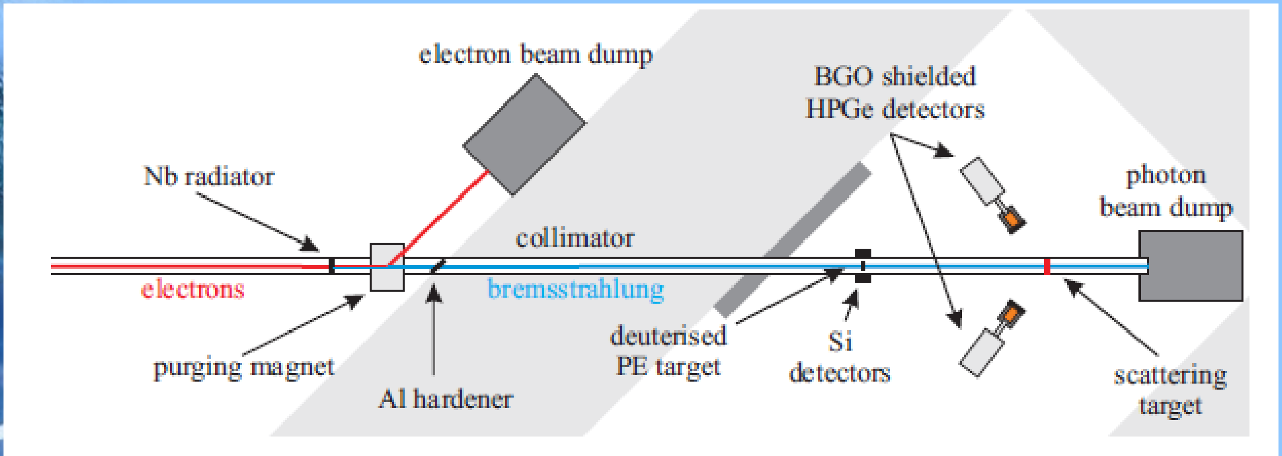
ELBE: Electron Linear accelerator with high Brilliance and low Emittance



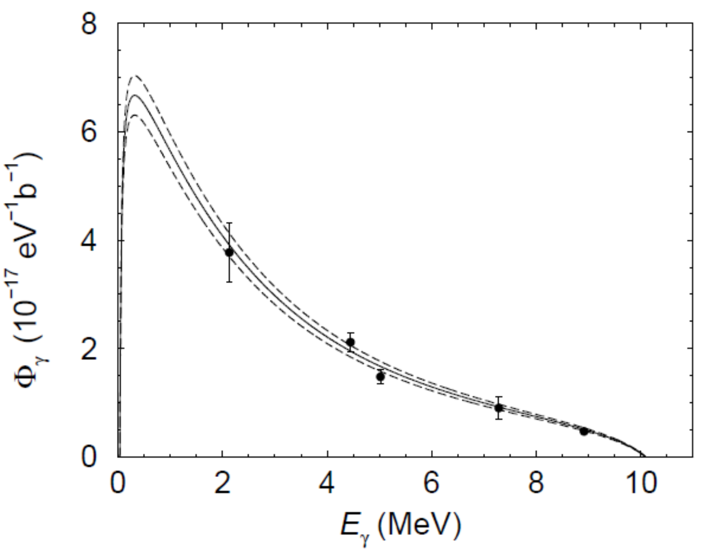
1: Diagnostic station, IR-imaging and biological IR experiment
2: Femtosecond laser, THz-spectroscopy, IR pump-probe experiment
3: Time-resolved semiconductor spectroscopy, THz-spectroscopy
4: FTIR, biological IR experiment
5: Near-field and pump-probe IR experiment
6: Radiochemistry and sum frequency generation experiment, photothermal deflection spectroscopy

Experiments

at superconducting ELectron accelerator with high Brilliance and low Emittance (ELBE)

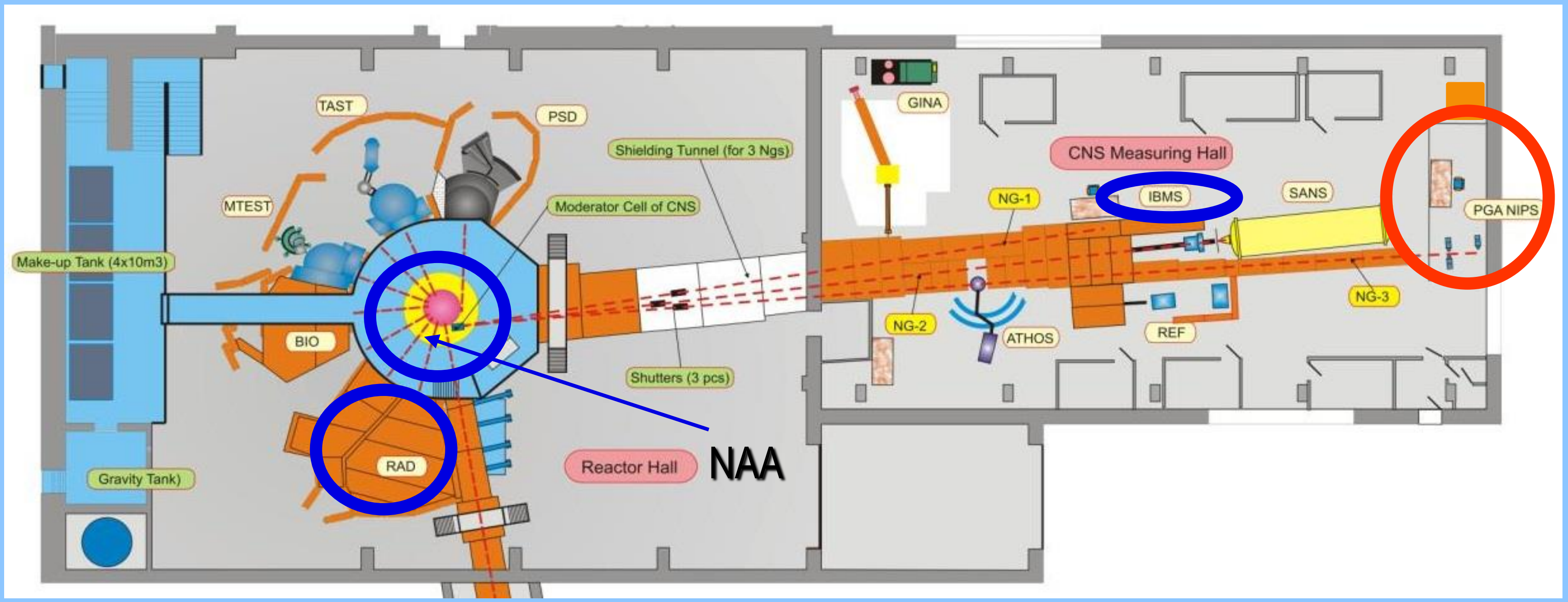


- Target 2 g of enriched ^{114}Cd metal (99.37%) and 0.2 g ^{11}B monitor
- Electron beam energy was set to 10.5 MeV to excite states above the 9.042 MeV binding energy
- 2 BGO guarded HPGe γ-detectors at 90 and 2 at 125 degrees
- Singles acquired for about 4 days
- Photon flux calibrated with the ^{11}B monitor
- Detector efficiencies measured with calibration standards and simulated with GEANT 4 at higher energies



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)

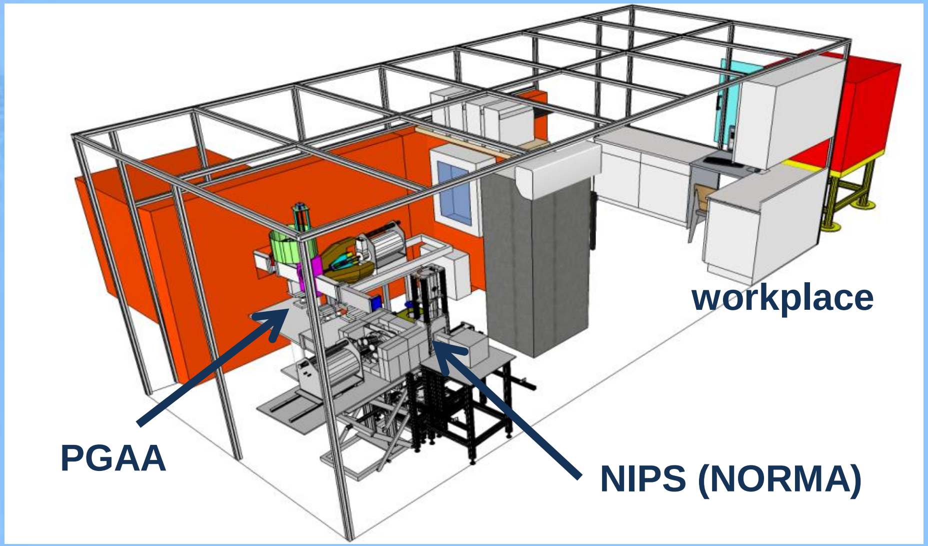
  } **Macroscopic structure, composition**

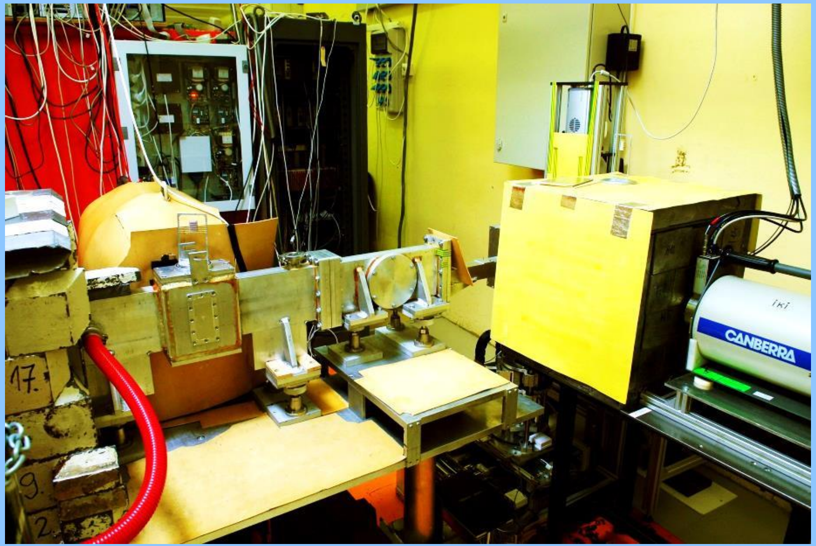
- **Material microstructure tools of Wigner FK (not all listed)**
  - Neutron powder diffractometer (PSD, MTES) (~ 0.1 nm, 1Å)
  - Small angle scattering (SANS, FSANS) (1-150 nm)
  - Reflectometer (REF and GINA) (nm surface structure)
  - TOF diffractometer (TOF) (nm lattice distance)
  - Triple Axis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

  } **Microscopic structure**

Experiments

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

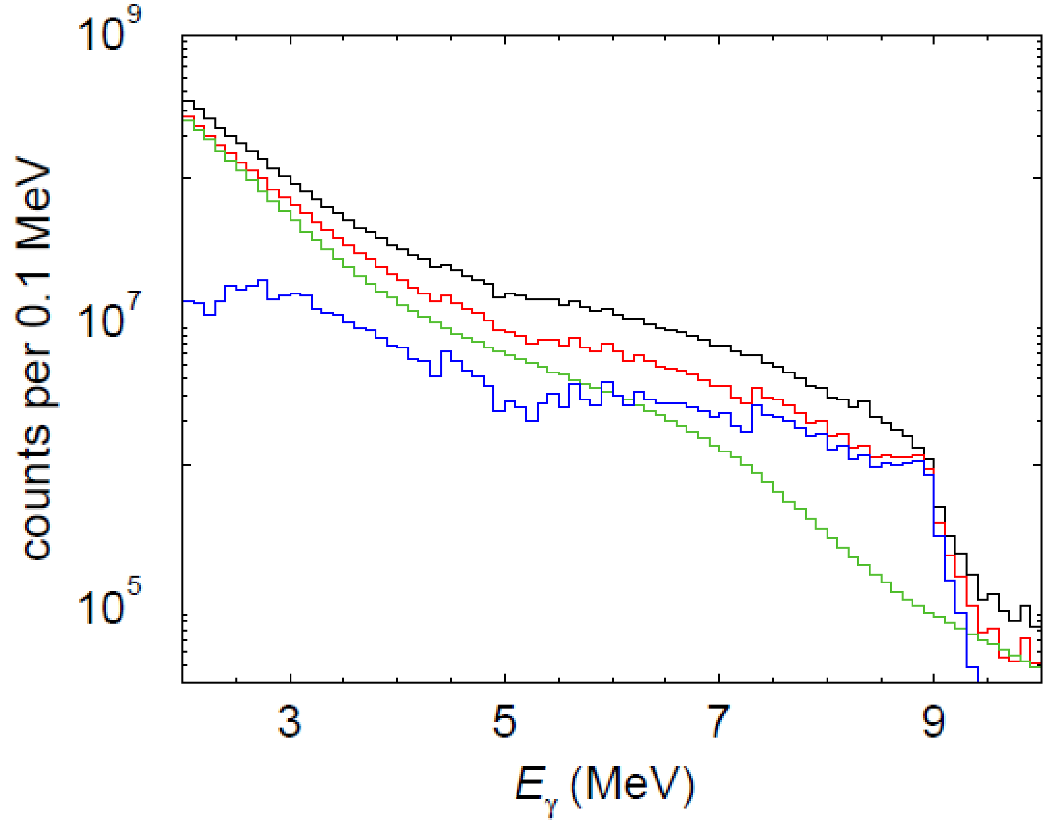




- Targets 0.1 g of enriched ^{113}Cd metal (90.2%) and 2.5 x 2.5 x 0.005 cm^3, natural and 99.99% pure Cd sheet
- Cold neutron flux of 10^8 n/cm^2/s collimated to 1-2 mm^2
- Heavy lead shielded and BGO guarded HPGe γ-detector at 90 degree relative to the beam
- Compton suppressed and normal singles acquired 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

Data analysis

HZDR ELBE data



- Black: measured gamma-spectrum at 127 deg
- Red: Unfolded spectrum
- Green: simulated atomic contribution
- Blue: Nuclear fluorescence spectrum, (unfolded-atomic); it contains a large number of unresolved gamma signal
- Fluorescence threshold stars at the expected 9.04 MeV binding energy

- The fluorescence spectrum contains both **elastically and inelastically** scattered photon signals from the impinging beam
- We are interested in the **elastic spectrum** (corrected for the ground state branching) which provides direct information on the **average decay widths** that determine the **strength function**

Data analysis

HZDR ELBE data

- The total photon absorption:

$$\langle \sigma_{\gamma,\mathrm{abs},XL} \rangle = 3\left(\frac{\pi\hbar c}{E_\gamma}\right)^2 \langle \Gamma_{i,0,XL} \rangle \rho(E_i)$$

- The elastic photon scattering:

$$\langle \sigma_{\gamma,\gamma,XL} \rangle = 3\left(\frac{\pi\hbar c}{E_\gamma}\right)^2 \left\langle \Gamma_{i,0,XL} \frac{\Gamma_{i,0,XL}}{\Gamma_{i,tot}} \right\rangle \rho(E_i)$$

- The elastic part can be expressed with the absorption using the enhancement factor S_{XL}:

$$\langle \sigma_{\gamma,\mathrm{abs},XL} \rangle = \langle \sigma_{\gamma,\mathrm{abs},XL} \rangle \frac{\langle \Gamma_{i,0,XL} \rangle}{\langle \Gamma_{i,\mathrm{tot}} \rangle} S_{XL}$$

- Gamma strength function:

$$\mathrm{f}_{\mathrm{XL}}(\mathrm{E}_\gamma) = \mathrm{E}_\gamma^{-(2\mathrm{L}+1)} \langle \Gamma_{\mathrm{i,0,XL}} \rangle \rho(\mathrm{E_i})$$

- An upgraded version of simulation program called γDEX was used to determine the γ-absorption by fitting the fluorescence spectrum
- As starting point for an iterative simulation:
  - The Triple Lorentzian photon strength function (TLO PSF) for E1, Triple Gaussian (TG PSF), and the one defined in RIPL3 for M1 and for E2 recommendation were used.
  - For description of the nuclear level density the Constant Temperature Model (CTM) was used with parameters published by von Egidy.

G. Schramm et al. PRC **85**, 014311 (2012); A. R. Junghans et al. Phys. Lett. B 670, 200 (2008); R. Capote et al., Nucl. Data Sheets 110, 3107 (2009); T. von Egidy and D. Bucurescu, Phys. Rev. C **80**, 054310 (2009)

Data analysis

BNC PGA data (under development)

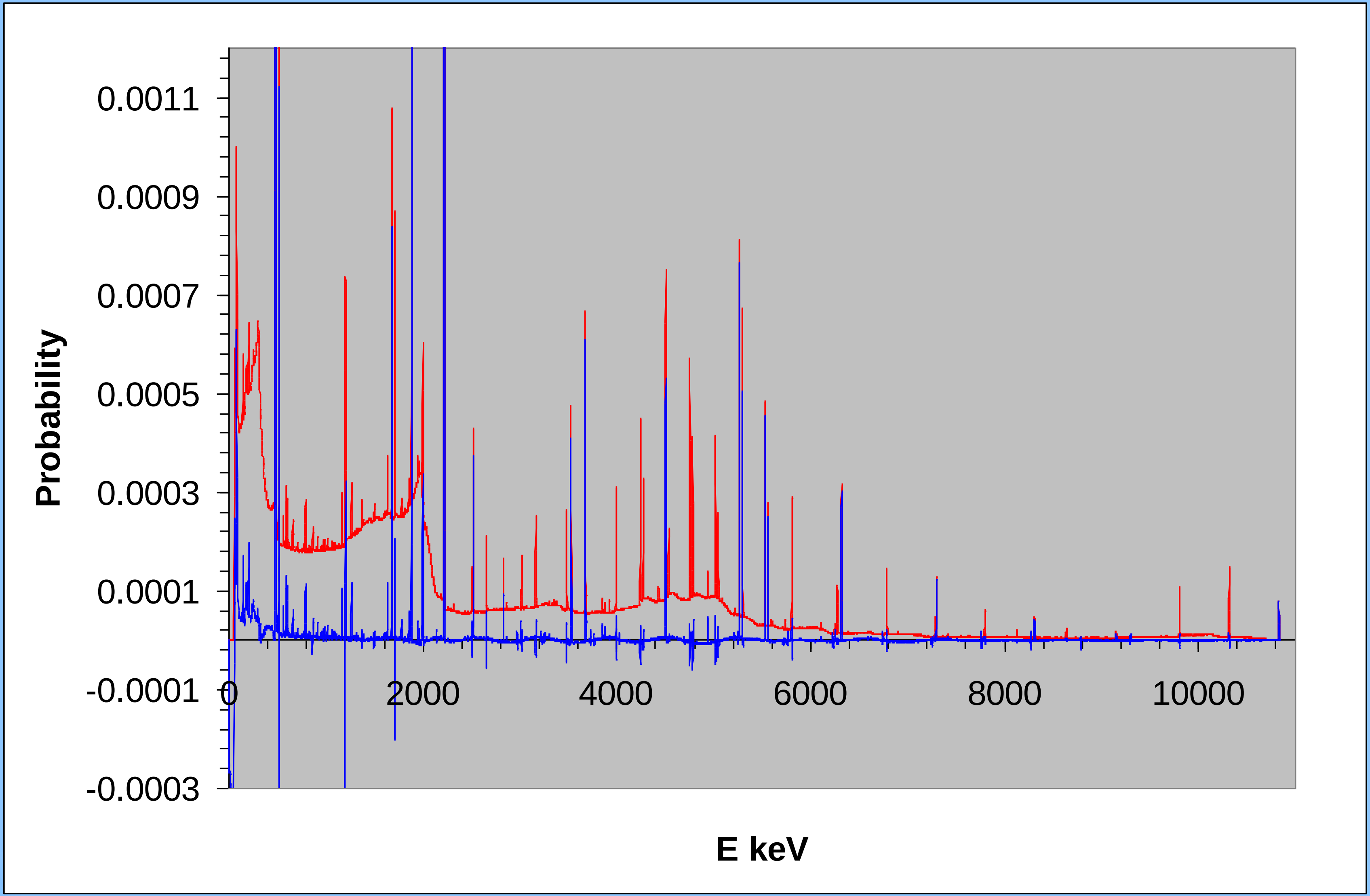
- GEANT 4 simulations of the Budapest HPGe-detector's response
  - In the unfolding procedure of ^{113}Cd(n,γ) spectrum the OSLO method was used
  - Provide input for Monte Carlo simulation of (n,γ) decay spectra
  - Makes it possible to determine radiative capture cross sections from prompt-gamma spectra using the inverse Q-value formula

$$\sigma_{cap} = \sum_i E_{i,\gamma} \sigma_{i,\gamma} (1 + \alpha_i) / B_n$$

- Development of a BIn Type Statisticall code for Gamma-decay (GBITS)
  - Purpose: simulation of (n,γ) spectra taken at the Budapest PGAA facilities to learn about the statistical decay process and nuclear structure
  - The program is using the RIPL discrete level library for input
  - CTM and BSFG level densities
  - TLO, MLO1, pygmy, soft pole, TG, RIPL M1 and E2 RSF are implemented

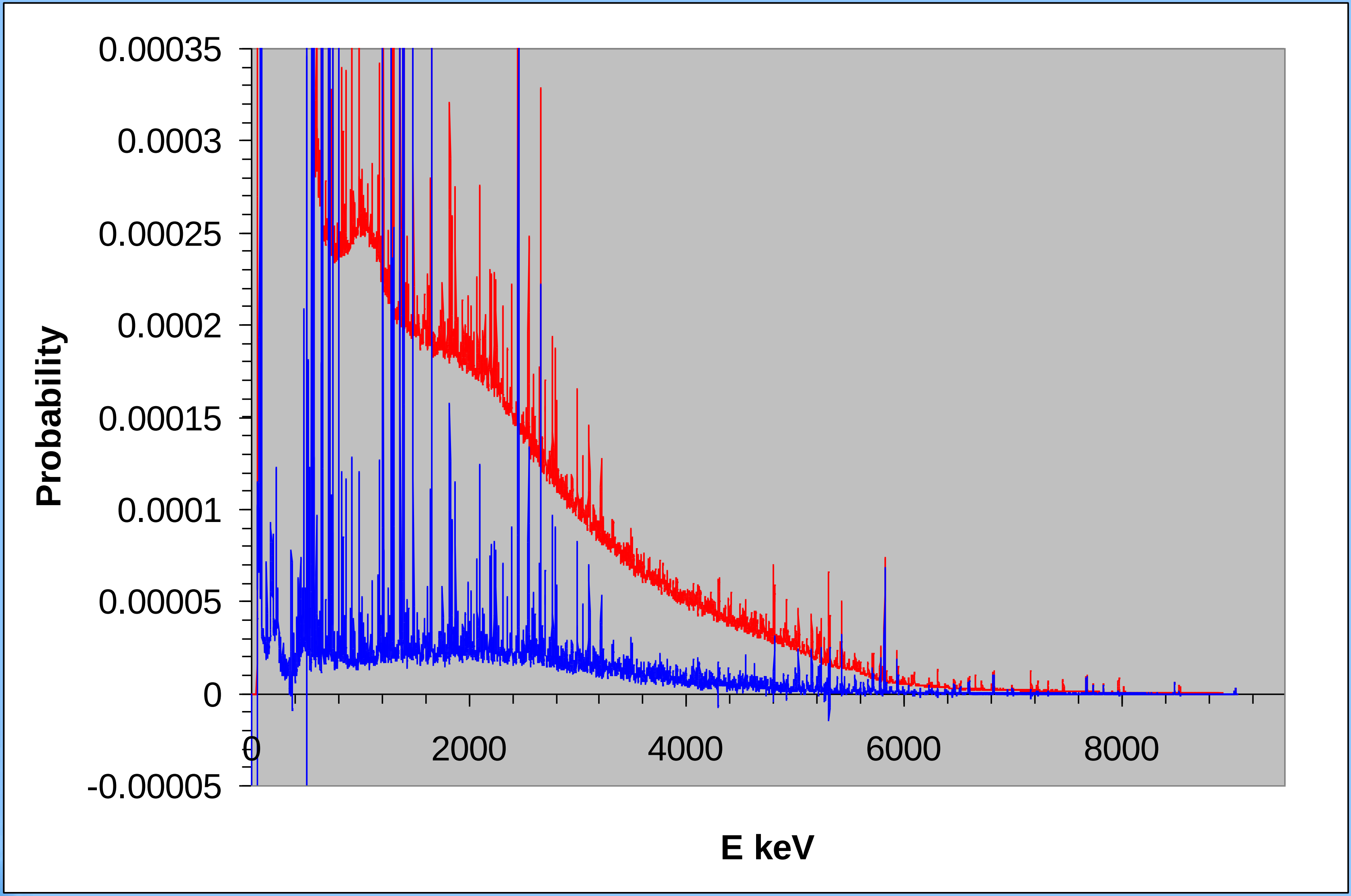
T. Belgya et al. CERN-Proceedings-2014-002 (CERN, Geneva 2014) pp. 119-126

Unfolding of Urea-D capture spectrum



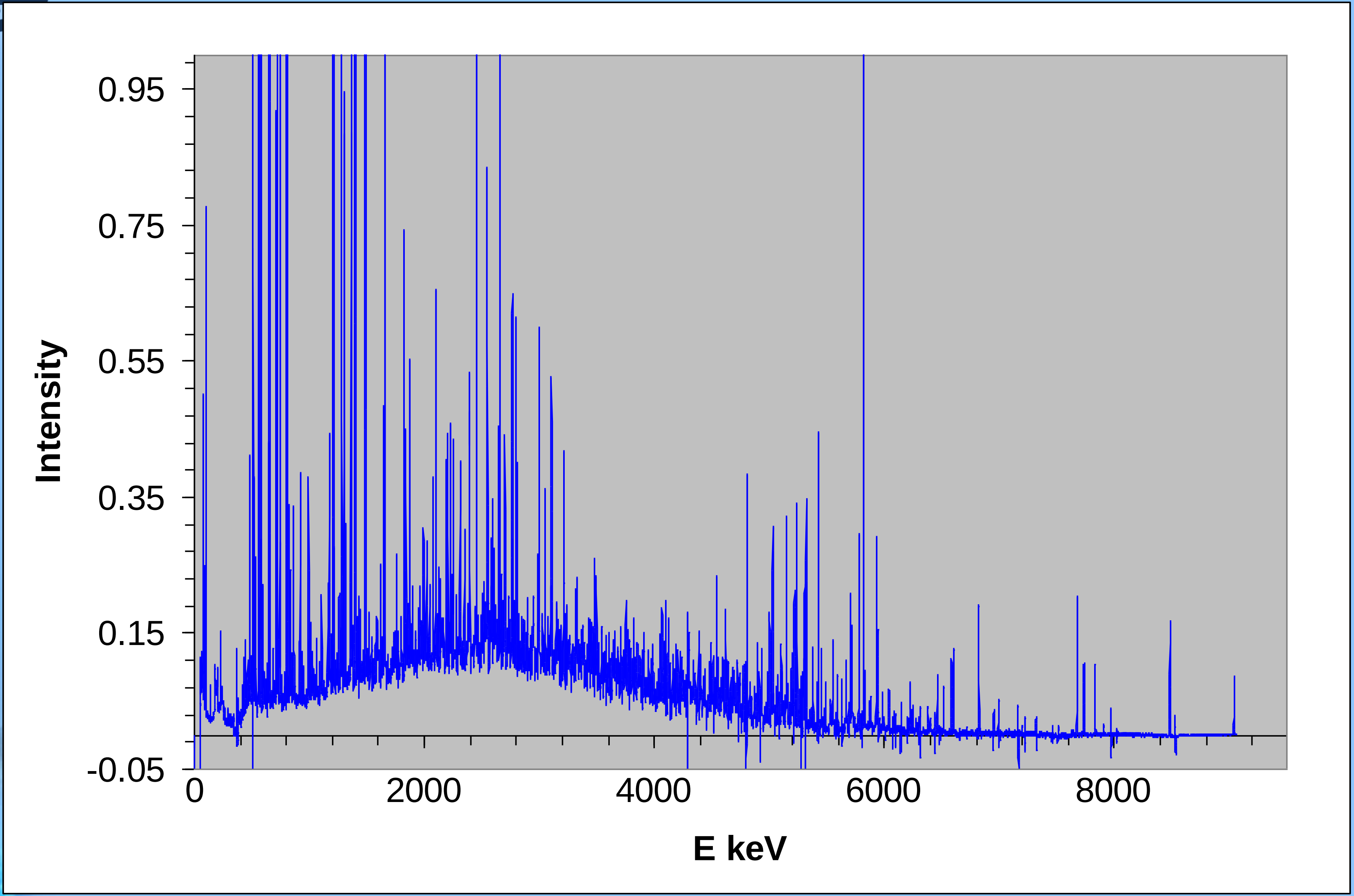
Inv-Q value 90 mb, literature 81.5(15) mb, H contribution subtracted, C, Cl, B not yet

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



Measured (red), unfolded (blue)

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

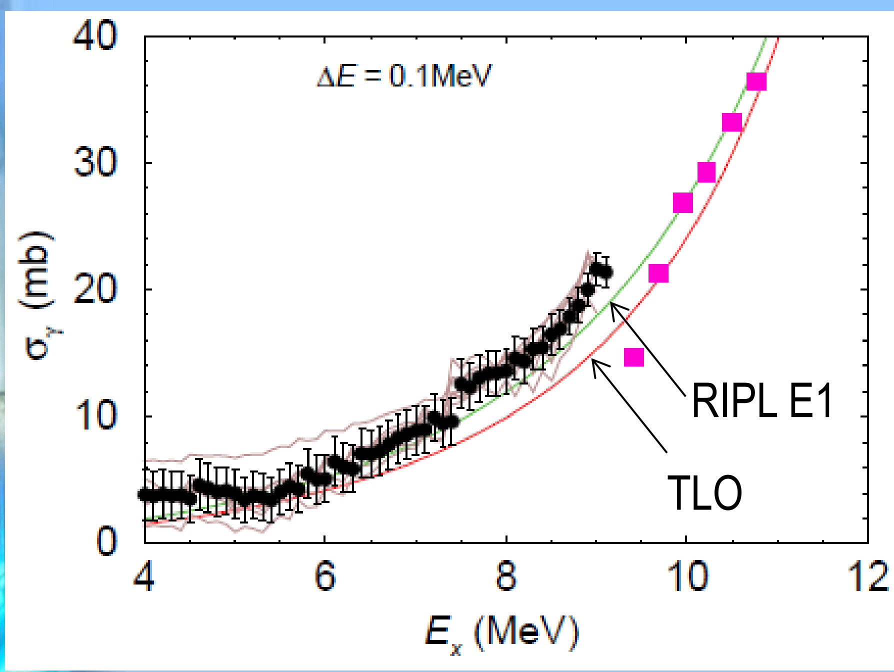


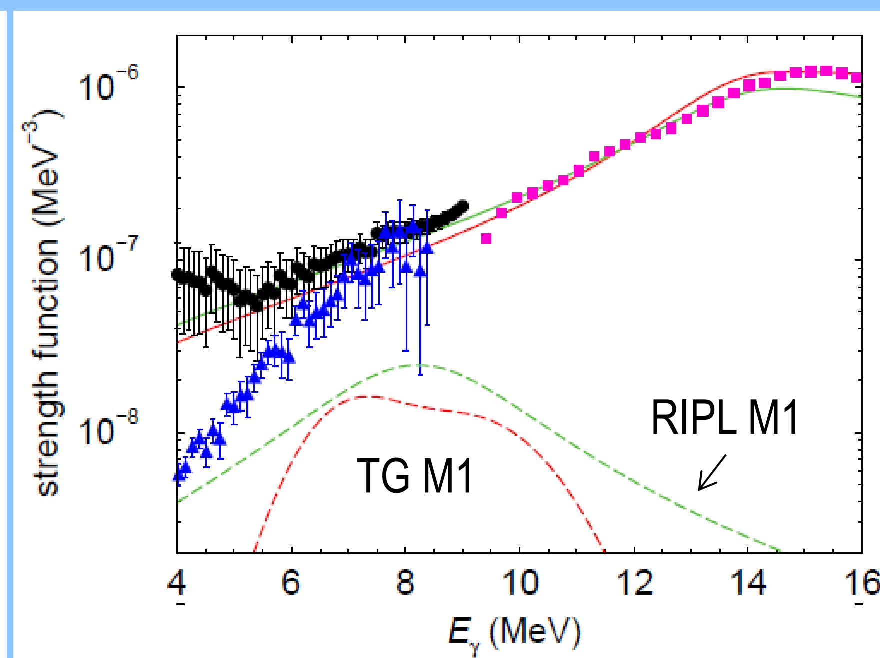
Total radiative capture Xsection=Inv-Q value 21640 b, literature 20600(400) b, Multiplicity= 4.11, agrees with Muehlhause, Phys. Rev. 79, 272 (1950)

Results

γ-absorption cross section

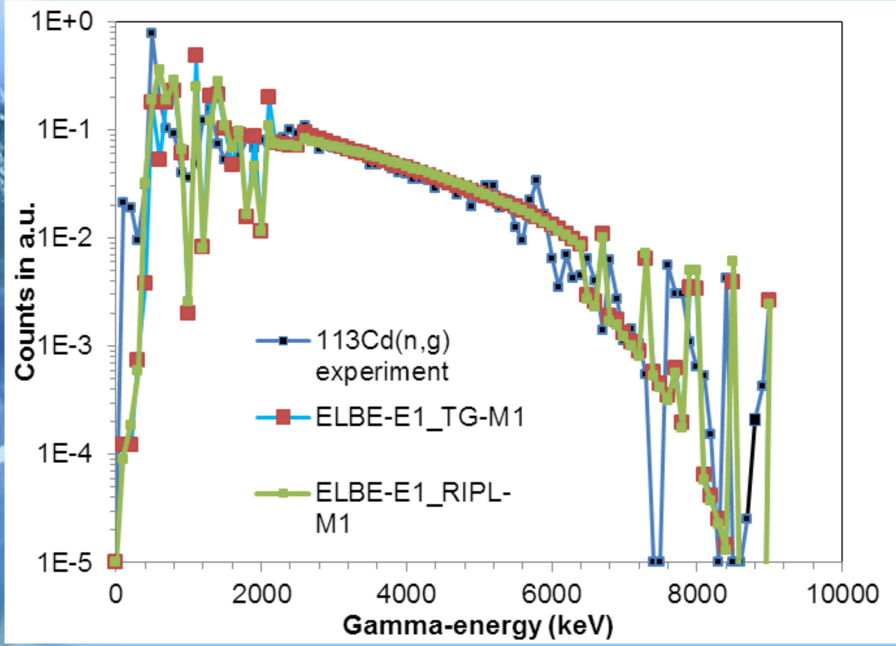
- In the first step of γDEX simulation the TLO strength function was used to deduce the γ-absorption cross section in the 4 MeV to binding energy region
- From the obtained cross section a new strength function was calculated and using this new iterations were repeated until the results did not change considerably (ELBE RSF for E1)
- The final result is shown below. ELBE RSF joins rather smoothly to the giant resonant data for natural Cd

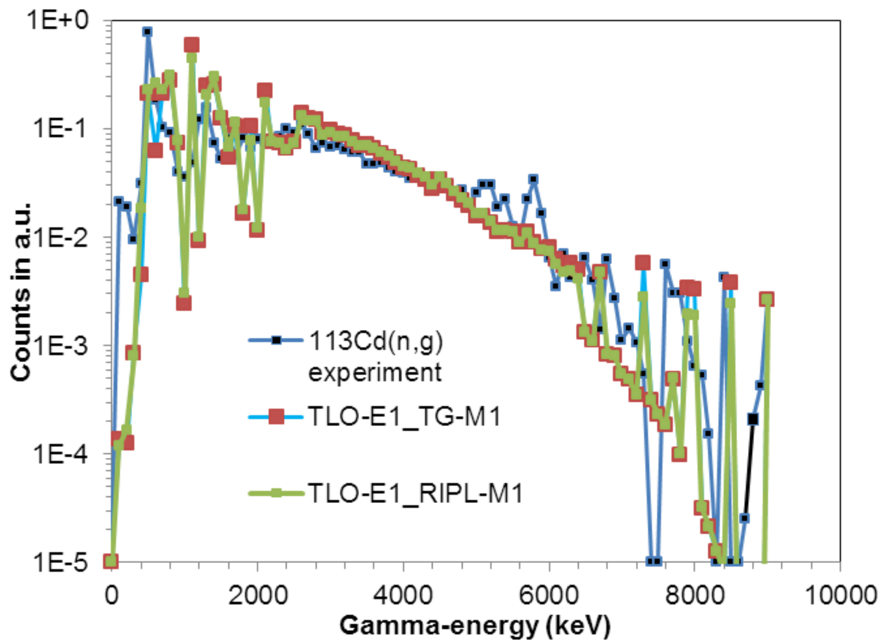




Results

Comparison of performance of RSFs at 670 keV temperature

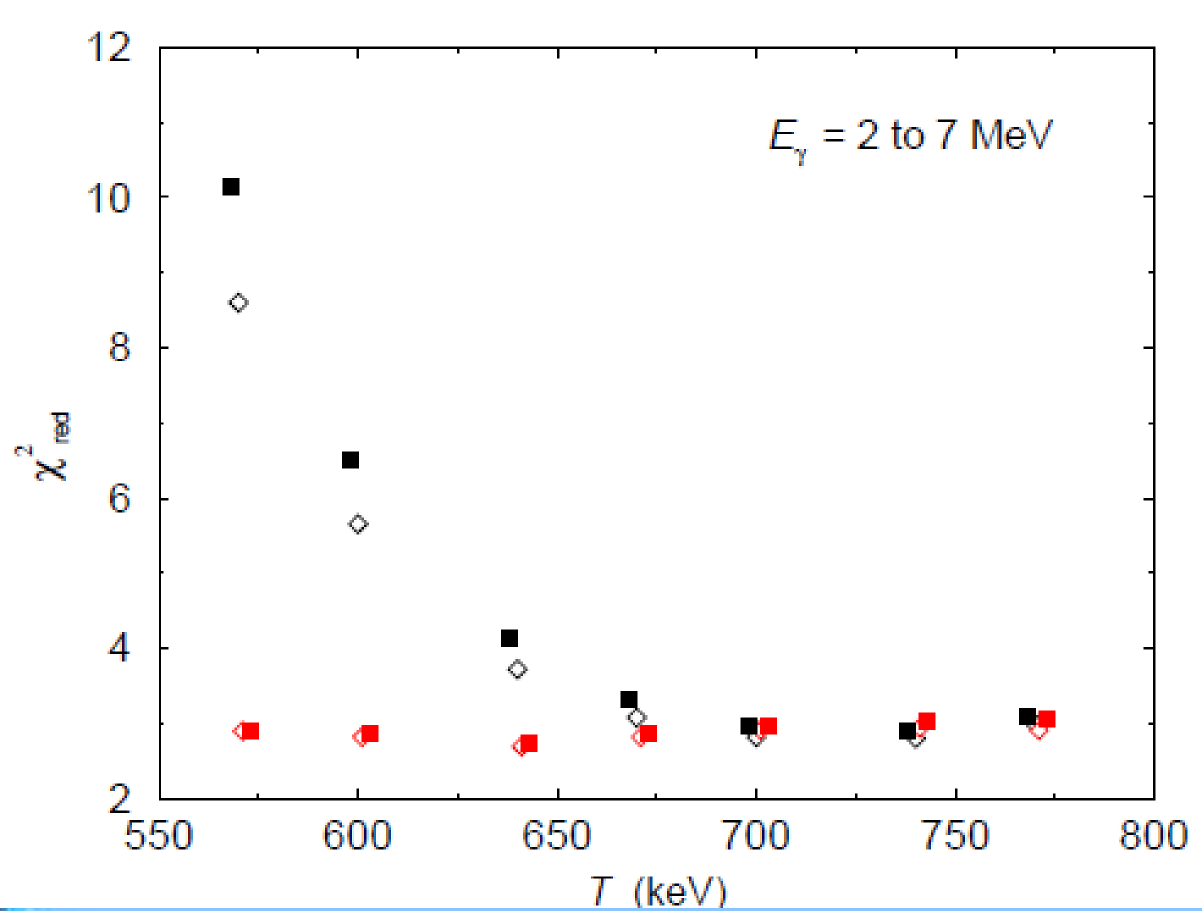




- ELBE and TLO RSF combined with TG and RIPL-M1 RSF and the measured (n,γ) was simulated
- ELBE and RIPL-M1 gives better description of the spectrum
- There are structures around 5.5 and 2.5 MeV
  - The natures of these structures are not known (pygmy would be around 8.4 MeV)
- Influence of M1 functions are low on the calculated spectra

Results

Comparison of performance of RSFs at different temperatures
For which Khi-square was calculated



- Red square is ELBE experimental strength function
- The full is TG
- Empty is RIPL.M1

- Black square is TLO E1
- The full is TG
- Empty is RIPL-M1

- The best agreement could be achieved with T=640 keV CTM temperature
  - In these calculations the whole iteration procedure was repeated

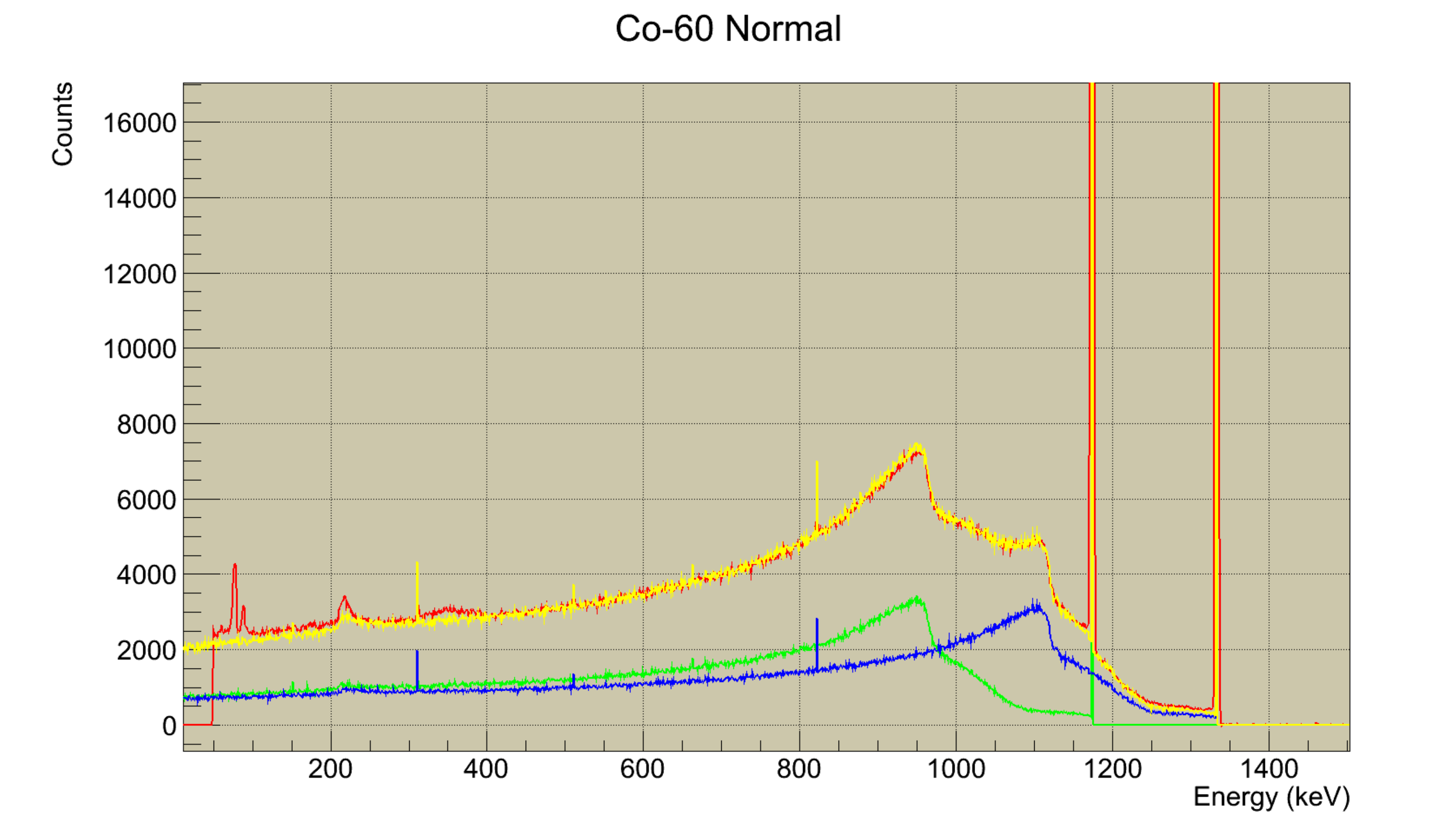
Summary

- Preliminary results of combined analysis of the data from the (n,γ) and the (γ,γ') experiments allowed us to study the effect of the electric and magnetic dipole strength function for the decay of excited states.
- The description of the ^{113}Cd(n,γ) decay spectrum using the strength function deduced from the RF experiment was better than using the TLO RSF
- The positive parity of the capture state does not have big influence on the spectrum
- We need to study the nature of the structures around 2.5 and 5.5 MeV
- We need to improve the agreement of the intensities of low energy transitions between the low lying discrete level with the experimental observations

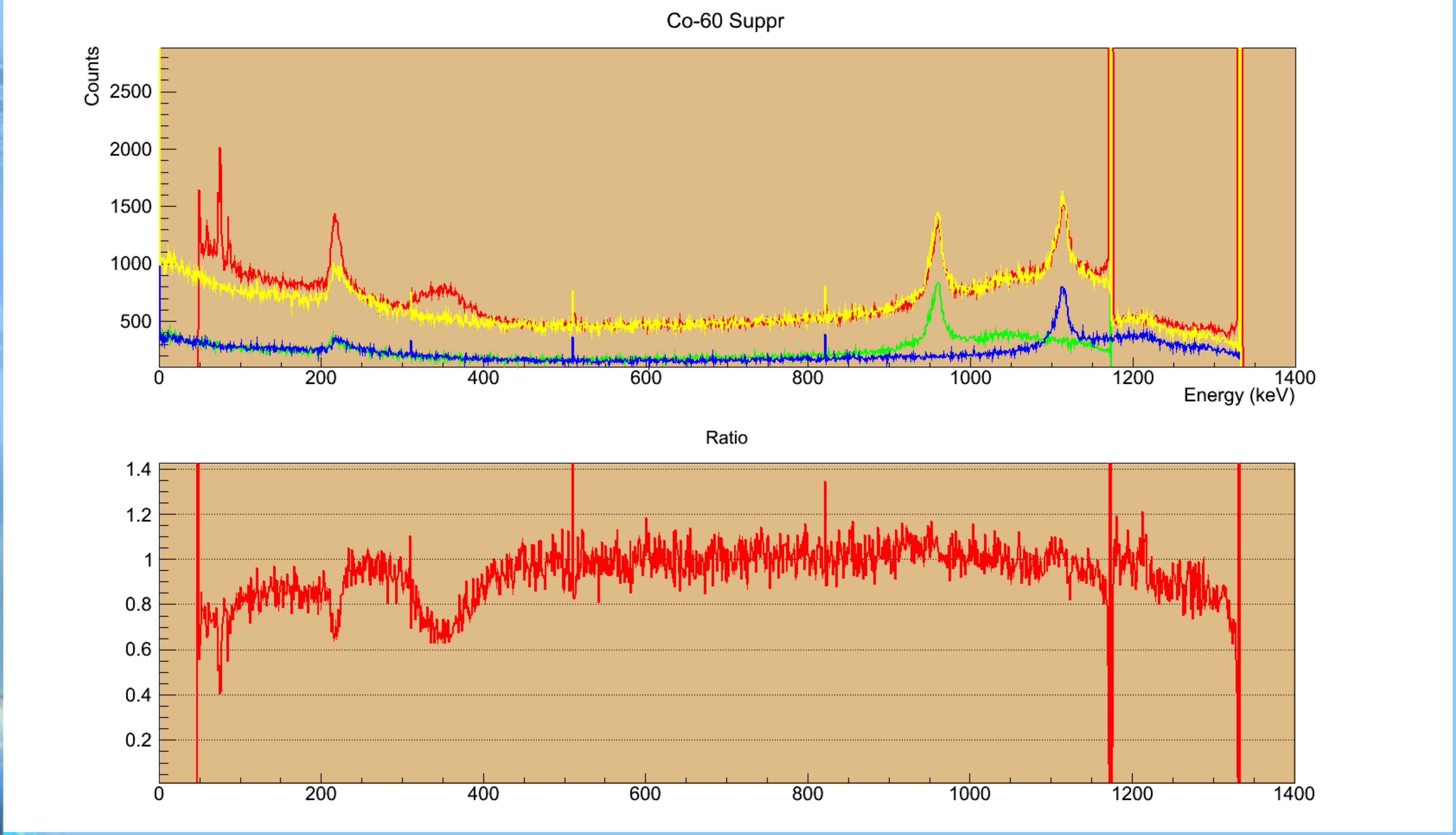
Thanks for your attention!

Modeling of Budapest detector response

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

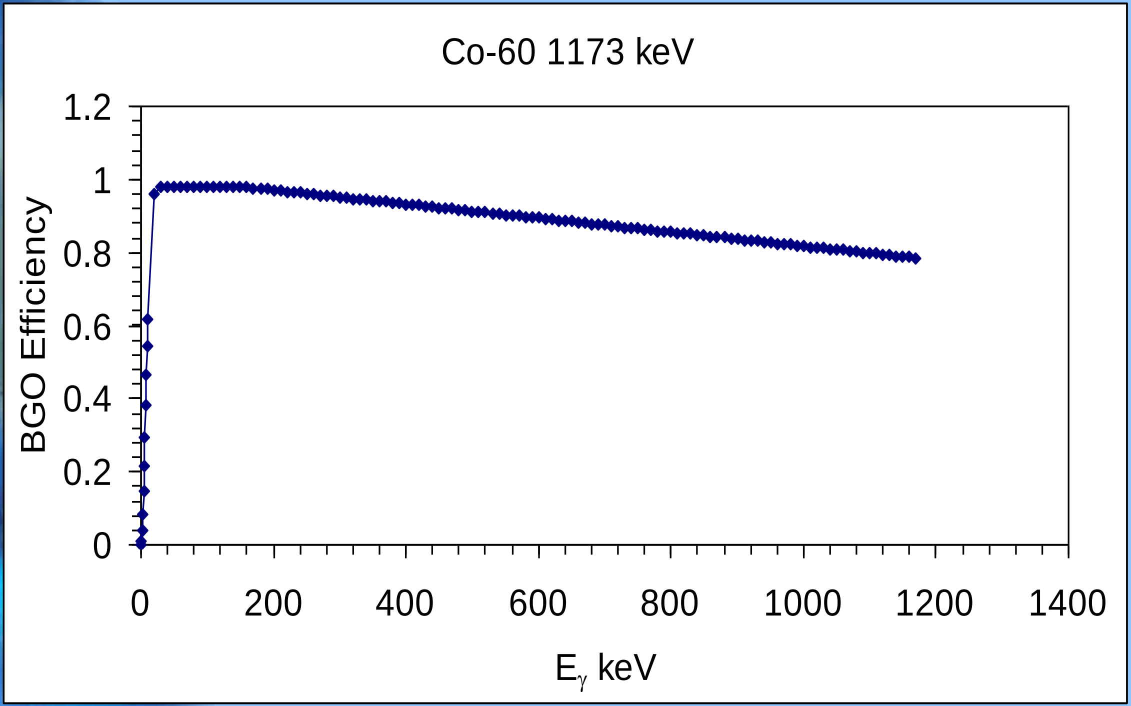


Modeling of Budapest detector response



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



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

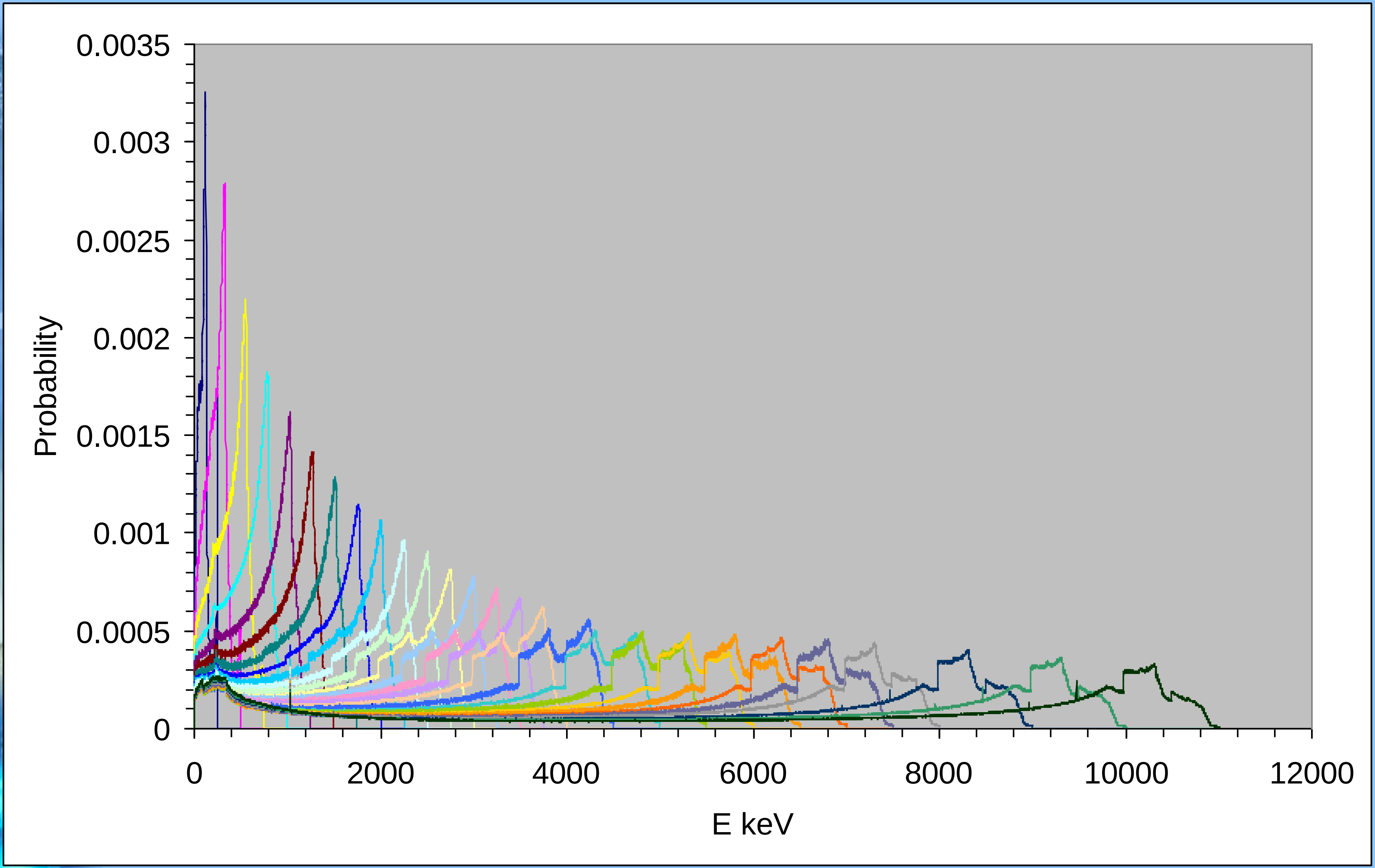
$$a = 150\,\mathrm{keV} \quad b = 1173\,\mathrm{keV} \quad c = 0.2$$

Unfolding normal spectra

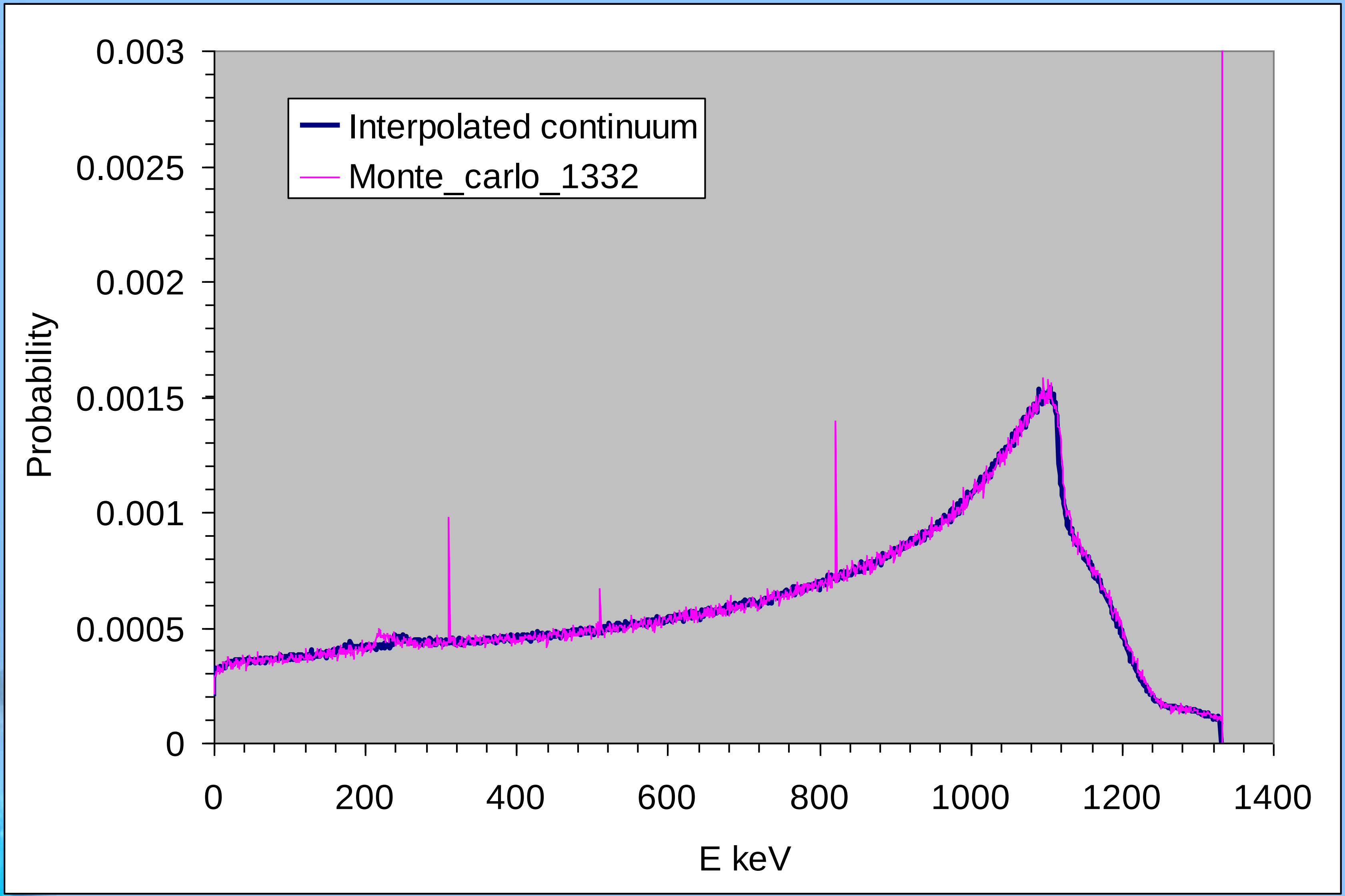
- Node spectra and list mode were calculated using GEANT4 from 250 keV to 11 MeV with steps of 250 keV and with 1 keV binning
- The calculation time was about 60 days of CPU time I5 proc.
- Further treatment is according to Oslo description
  - Full spectra were normalized to 1
  - Full energy, SE, DE 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

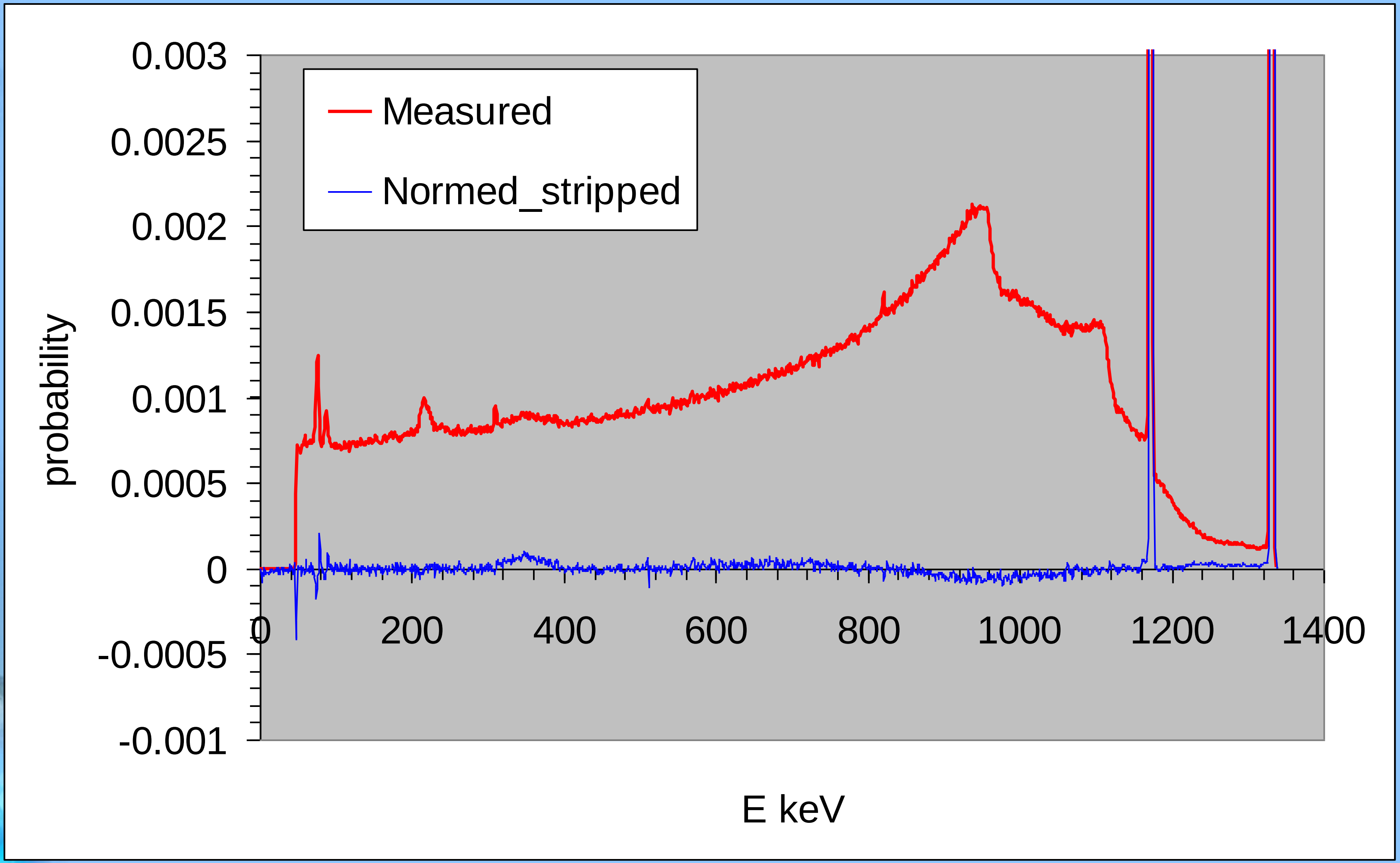
Node spectra



Interpolation and calculated GEANT4 spectra



Unfolding of Co-60 spectrum



Unfolding of Eu-152 spectrum