

## Combined study of the gamma-ray strength function of $^{114}\text{Cd}$ with $(n,\gamma)$ and $(\gamma,\gamma')$ reactions

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**Abstract.** Collaboration on strength function measurements and level density determinations is ongoing between the Budapest Prompt Gamma Neutron Activation Analysis and the ELBE Nuclear Physics groups within the framework of EU FP6 EFNUDAT project. The idea is to prove that good theoretical fits to the measured gamma-ray spectra collected in the  $(n,\gamma)$  and  $(\gamma,\gamma')$  reactions can be carried out using common photon strength and level density functions over a wide spectral energy range from 1 to 10 MeV for the same residual nucleus. Here, preliminary results on the isotope pair of  $^{113,114}\text{Cd}$  are presented for which the neutron capture state in  $^{114}\text{Cd}$  has  $1^+$  or  $0^+$  spin and parity.

### 1 Introduction

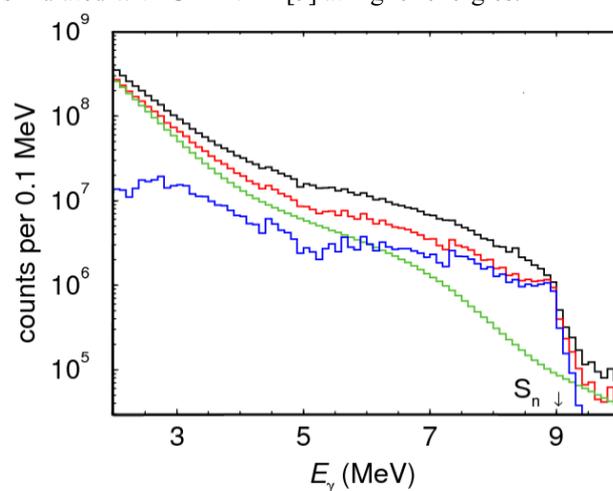
There seemed to be contradictory photon strength function (PSF) results determined from resonance capture and resonance fluorescence experiments in the past [1, 2]. To resolve this problem and to prove that theoretical descriptions of measured gamma-ray spectra collected in the  $(n,\gamma)$  and  $(\gamma,\gamma')$  reactions can be described using the same gamma-ray strength functions in a wide spectral energy range from 1 to 10 MeV for the same residual nucleus, we have selected pairs of isotopes for which the neutron capture state has  $1^-$  spin and parity, which is the favoured spin and parity that are most probably excited in the  $(\gamma,\gamma')$  reactions on even-even nuclei. We found only two stable pairs of nuclei, namely the  $^{77,78}\text{Se}$  and  $^{195,196}\text{Pt}$  for these studies and showed that indeed the same gamma strength function can be applied for each residual nucleus in describing the observed spectra independent of the exciting reactions used [2,3].

In this article the result on the pair of  $^{113,114}\text{Cd}$  isotopes is presented for which the neutron capture state has  $1^+$  or  $0^+$  spin and parity. Never the less, the combined study can underline whether the parity plays an important role or not. Preliminary results and development in the data analysis by the Budapest group will be presented.

### 2 Experiments at the ELBE and the Budapest PGAA facilities

The Electron Linear accelerator with high Brilliance and low Emittance (ELBE) facility provides an excellent high

energy gamma-beam with continuous energy distribution for exciting the nuclei of various targets [4]. In our experiment the target was 2 g of enriched  $^{114}\text{Cd}$  metal (99.37%) and 0.2 g  $^{11}\text{B}$  as a flux monitor. The electron beam energy was set to 10.5 MeV to excite states above the 9.042 MeV neutron binding energy of  $^{114}\text{Cd}$ . Two BGO guarded HPGe  $\gamma$ -detectors were placed at  $90^\circ$  and two at  $127^\circ$  degrees to the incident beam. Single gamma-ray spectra were acquired for about 4 days. The photon flux was calibrated with the  $^{11}\text{B}$  monitor. The detector efficiencies were measured with calibration standards and simulated with GEANT 4 [5] at higher energies.



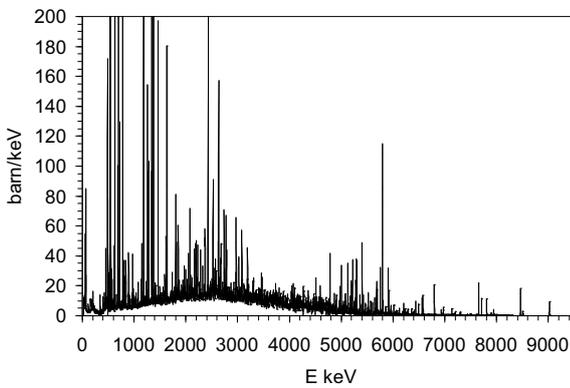
**Figure 1.** Measured spectrum (black) for the detector pair under  $127^\circ$  at ELBE. The unfolded spectrum (red), the simulated atomic background (green), and the resulting spectrum (blue).

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The detector response functions were calculated also with GEANT 4 in order to unfold the experimental spectra. The unfolding procedure described in [3]. After the unfolding the simulated atomic contribution was subtracted. The steps and result is shown in Figure 1, where the spectra were binned in 0.1 MeV bins.

The Prompt Gamma Activation Analysis (PGAA) facilities at the Budapest Neutron Centre (BNC) have been described in details in a number of papers [6,7]. The targets of 0.1 g of  $^{113}\text{Cd}$  metal (enriched to 90.2%) and one natural (99.99% pure Cd) sheet with a size of  $2.5 \times 2.5 \times 0.005 \text{ cm}^3$  were irradiated using a cold neutron flux of  $10^8 \text{ n/cm}^2/\text{s}$  collimated to 1-2  $\text{mm}^2$ .

A lead shielded and BGO guarded HPGe  $\gamma$ -detector placed at 90 degree relative to the beam was used in Compton suppressed and normal modes. Single spectra were acquired for about 5 days. The detector efficiency was measured with calibration standards and the  $^{14}\text{N}(n,\gamma)^{15}\text{N}$  reactions. Simulated response functions were calculated with the GEANT 4 code [5]. Details of the response function calculations and unfolding procedure have been presented in [8]. The resulting of efficiency corrected unfolded  $\gamma$ -spectrum is shown in Figure 2.



**Figure 2.** The result of efficiency corrected unfolded  $\gamma$ -spectrum measured in the  $^{113}\text{Cd}(n,\gamma)^{114}\text{Cd}$  experiment at the Budapest PGAA facility. It is normalised to the 558 keV gamma-ray cross section (see below).

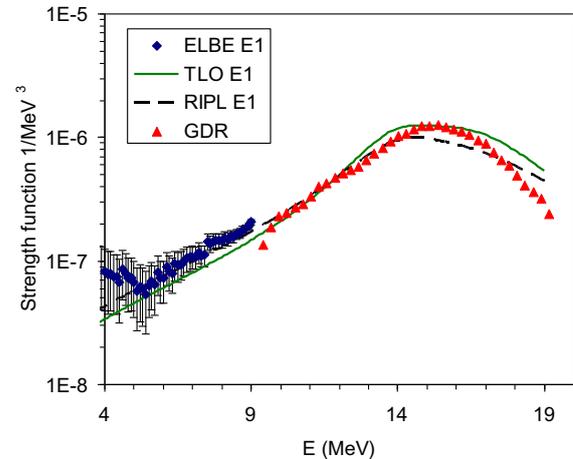
By normalising the spectrum using the strongest 558 keV transition's partial gamma-ray cross section of 15211(245) b and peak area we could calculate the total capture cross section from the energy weighted sum rule (the inverse of the Q-value test) [9]. It gave 21640(500) b which agrees reasonably with the literature value of 20600(400) b [10]. The  $\gamma$ -multiplicity can be calculating by summing up the cross sections in the normalised spectrum and dividing by the total capture cross section, which yields 4.11. This is in good agreement with the value of 4.1 reported by Muehlhause [11]. It confirms that the unfolding is reliable.

### 3 Preliminary results of the combined $(\gamma,\gamma')$ and $(n,\gamma)$ analysis of $\gamma$ -strength function

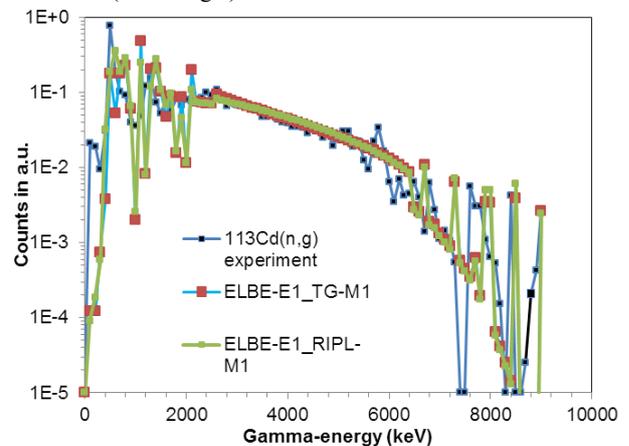
An upgraded version of simulation program called  $\gamma$ DEX [2] was used to determine the  $\gamma$ -absorption and the elastic

scattering by fitting the resonance fluorescence spectrum. As a starting point for the iterative simulation: the Triple Lorentzian (TLO PSF) for E1, Triple Gaussian (TG M1 PSF), and the ones recommended in RIPL3 [12] for M1 and for E2 were used for the photon strength function (PSF).

For description of the nuclear level density the Constant Temperature Model (CTM) was used with parameters published by von Egidy [13,14]. In the first step of  $\gamma$ DEX simulation the TLO strength function was used to deduce the  $\gamma$ -absorption cross section in the 4 MeV to binding energy region. From the obtained cross section a new radiative strength function (RSF) was calculated and using this updated version, new iterations were repeated until the update did not change significantly. This was labelled as ELBE RSF for E1. Below the 4 MeV region, TLO or RIPL E1 RSF from the literature was used. The final result is shown in Figure 3. The ELBE RSF joins rather smoothly to the giant dipole resonance data (GDR) for natural Cd that was calculated from cross section data taken from the EXFOR library.



**Figure 3.** The result of the RSF iterative fitting procedure. The ELBE E1 RSF (blue diamonds) is compared to the TLO E1 (green line) and RIPL E1 RSF (black dashed line) and to the GDR data (red triangle) for natural Cd.



**Figure 4.** The result of the statistical model calculations, where the CTM level density was fitted to the radiative neutron capture spectrum. The experimental spectrum (blue squares) is compared to the  $\gamma$ DEX calculation with ELBE E1 RSF (green line) and TG M1 (green small squares) or RIPE M1 (red large squares) RSFs.

The measured efficiency-corrected unfolded  $(n,\gamma)$  spectrum was also simulated with the  $\gamma$ DEX statistical code using the ELBE and TLO RSFs combined with TG or RIPL-M1 RSFs.

The calculation results were compared to the re-binned experimental spectrum with 0.1 MeV bins by a fitting procedure, where the CTM temperature was changed, while the back-shift parameter was used to set the level density at the binding energy to the experimental value. A temperature of 640(15) keV gave the best fit to the capture spectrum. The result with ELBE E1 and TG M1 RSFs gave a somewhat better description of the experimental spectrum, which is shown in Figure 4. It can be seen that the fitting averages out the structure appearing at 2.5 MeV and around 5.5 MeV.

## 4 Discussion of the results

It is interesting to note that neither the strength function nor the associated derived resonance fluorescence photon absorption cross section show a bump or pygmy resonance such as was observed in the other two pairs of nuclei in our previous comparative studies [2,3]. The reason is not yet understood.

Unfortunately there is no isotopic data on the GDR for the  $^{114}\text{Cd}$ , which is only 29% of the natural cadmium. Thus the direct comparison is not so straightforward at the joining point. Nevertheless the agreement at the joining point seems to be satisfactory, though perhaps fortuitous. Here it may be necessary to determine the TLO as a natural Cd composition weighted sum and use the TLO which belongs to the  $^{114}\text{Cd}$  renormalized to the enriched composition.

Due to the  $1/2^+$  ground state spin of the  $^{113}\text{Cd}$  nucleus, the capture state can have spins of  $1^+$  or  $0^+$ . Because of the well-known low energy strong neutron resonance at 0.17 eV has a spin and parity of  $1^+$  in the  $^{114}\text{Cd}$  compound nucleus, we can expect that the capture will happen mostly with  $1^+$  character. This contribution is supported by the presence of the ground state M1 transition, which can not happen in the case of  $0^+$  capture state. Further study is needed to determine the  $0^+$  contribution to the decay yields.

Before the investigation we expected more role of the M1 RSF due to the positive parity of the capture state, but we did not find any big influence, even when we changed the TG M1 to the RIPL M1 RSF. This means that the 7-8 times stronger E1 RSF has the more dominant role in the decay process except from the lowest lying levels.

The ELBE E1 RSF gives the best fit to the experimental spectrum, but the fit does not differ much from that with the TLO or from the RIPL E1 RSF.

Further study of the feedings of the low lying states is needed to get better agreement between the statistical model calculations and the experiment, especially for the radiative neutron capture case where the decays between the low lying states can be clearly observed due to the much better background conditions compared to the resonance fluorescence experiments.

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