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High-resolution study of the ^{113}Cd(n,γ) spectrum by statistical decay model with discrete levels and transitions

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Abstract. The gamma-ray spectrum and the decay scheme of ^{114}Cd obtained from a radiative neutron capture experiment on ^{113}Cd samples are modelled in the framework of extreme statistical model. The unfolding of the experimental spectrum with proper normalization yields a total capture cross section of 21640 b and an average gamma-ray multiplicity of 4.1. Using the extreme statistical model the development of the low energy decay scheme of ^{114}Cd is in progress. In the model the constant-temperature level density is used, where the temperature parameter was very sensitive to the shape of the modelled gamma-ray spectrum. Using this sensitivity $T = 0.62$ MeV was obtained with the constraint of good description of low energy level density and the level density at the binding energy. This is in full agreement with our earlier publication. For the description of the continuum shape of the unfolded spectrum the inclusion of low energy enhancement for the photon strength function was an important new addition.

1. Introduction

A new statistical decay code has been developed to study (n,γ) spectra in details. Our first case study is the detailed analysis of the ^{113}Cd(n,γ) spectrum which has been measured at the Budapest PGAA facility. A combined interpretation of ^{113}Cd(n,γ) and ^{114}Cd(γ, γ') reactions (latter measured at Dresden-Rossendorf) has just been published, but yet with a limited energy-resolution [1].

Here a study with ten-times improved energy-resolution for the low-energy (n,γ) spectrum will be presented. The goal is to understand whether this model can be used to improve the low-energy decay scheme and simultaneously maintain a good description of the discrete and continuum part of the spectrum of this important nucleus. Another goal of this study is to push the description to the extremes in the number of critical level energies.

The natural ^{NAT}Cd(n,γ) spectrum is very similar to the enriched ^{113}Cd(n,γ) spectrum due to the dominant thermal neutron capture cross section of ^{113}Cd isotope, which has already been confirmed by comparing measurements on natural and enriched samples under identical conditions. For this study new measurements were made with disabled Compton suppression on both the natural and enriched Cd metal samples. This was necessary because the modelling of the Compton-suppressed response function with *geant4* is not yet with proper accuracy, unlike the case of the unsuppressed spectra, where sufficient agreement could be achieved. The simulated unsuppressed spectra were then used to unfold the unsuppressed ^{114}Cd spectrum. In the comparison of the results from the simulation code and the obtained full energy spectrum is used.

With the help of this approach, the radiative neutron capture decay-scheme of ^{114}Cd is extended and improved up to 3.25-MeV critical energy, using a combination of the extreme statistical-decay model and consideration of discrete primary transitions directly fed the levels below the critical energy from the capture state. In this article the current status of this ongoing work is presented.

2. Experimental methods

Our experiment took place at the 10-MW research reactor of the Budapest Neutron Centre. We used a guided cold neutron beam with a thermal equivalent flux of $8 \times 10^7\,\mathrm{cm^{-2}s^{-1}}$ to irradiate an enriched ^{113}Cd sample placed in the evacuated target chamber of the PGAA experimental station. The gamma-ray de-excitations of the ^{114}Cd compound nuclei were detected with our lead and BGO-shielded HPGe detector [2]. The length of the irradiation was about a day in both Compton-suppressed and unsuppressed modes. In order to assign the background radiations we measured also a beam background spectrum of the same length. To keep the dead time low, all spectra were measured with a 1 mm^2 diameter pencil beam.

3. Data analysis

The Compton suppressed spectra were fit with the Hypermet PC software [3,4] to obtain best attainable

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full-energy peak areas and centroid positions. After corrections for nonlinearity, and detector efficiency [5], a linear energy calibration was applied [6] to the data. These refined peak parameters were used to establish the radiative neutron-capture decay-scheme of ^{114}Cd. Data from experimental papers and recent compilations [7–10] were used in the decay scheme construction. The unsuppressed spectrum was unfolded with the methodology described in detail in Ref. [11].

To describe the unfolded gamma-ray spectrum and the low-lying decay scheme intensities, a bin-type program called as BITS was written that relies on the extreme statistical model. This program is able to model the complete gamma-ray spectrum with 10-keV resolution in the entire energy region. For photon-strength functions (PSF) several analytical representations are implemented in the program. For E1 strength functions the Triple Lorentzian (TLO) of the Dresden group [12], Modified Lorentzian (MLO1), Enhanced General Lorentzian (EGLO), and Pygmy resonance [13], for M1 the Triple Gaussian (TG) [14], and Standard Lorentzian (SL) [13], for E2 the Global Lorentzian (GL) prescriptions are implemented. For level densities the Constant Temperature Model (CTM) and Back-shifted Fermi Gas (BSFG) [13,15] including arbitrary parity distribution are included. Besides these PSFs the low energy enhancement (LEE) referred earlier also as Soft-pole [16] is also programmed. The parallel description of the ^{114}Cd decay scheme and the gamma-ray spectrum is performed in an iterative way by improving the decay scheme, adjusting the level density and PSF parameters.

4. Results

From the unfolded experimental spectrum the total capture cross section was deduced as the sum of the energy-weighted partial gamma-ray emission cross sections, giving 21640 b. The estimated uncertainty of this value is about 3%. The normalization was performed using the partial cross section of the strongest 558 keV peak which is 15220(250) b [17] and calculated from the elemental cross section using the ^{113}Cd natural abundance. From this total cross section the average multiplicity of the spectrum was found to be 4.1 and only 40% of the cross section appears to be in resolvable peaks, the rest comes from the continuum.

The description of the gamma-ray spectrum shape proved to be very sensitive to the level density parameters. In the current description the CTM is used together with the TLO E1, the SL M1, the GL E2 and low-energy enhancement for E1. This later accelerates the low-energy transitions which is important to deplete the high-energy region and increase the intensity in the low-energy portion of the spectrum, thus lowering the energy centroid of the maximum of the continuum.

After several iteration steps the following parameters were used in the program. Parameters of CTM were determined to fit the low energy decay scheme and the level density at the binding energy. The parameters of the simulation function are listed in Table 1. The corresponding strength functions can be seen in Fig. 1 compared to some not used. As it can be seen from Fig. 1, the TLO gives almost the same value as MLO-1, but it falls to low values much faster at low energies. This fall is overcompensated with the low energy enhancement. It is also observed that MLO-1 alone, i.e. without the low energy enhancement, is not sufficient to describe the shape of the continuum.

Table 1. Parameters used in the simulations.

Name	Value
CTM temperature (MeV)	0.62
CTM backshift (MeV)	0.50
Level distance D_0 at B_n (eV)	24.8
TLO E1 β (deformation parameter)	0.2
TLO E1 γ (prolate-oblate parameter)	27°
LEE a (parameter)	0.005
LEE b (parameter) (MeV)	2.6

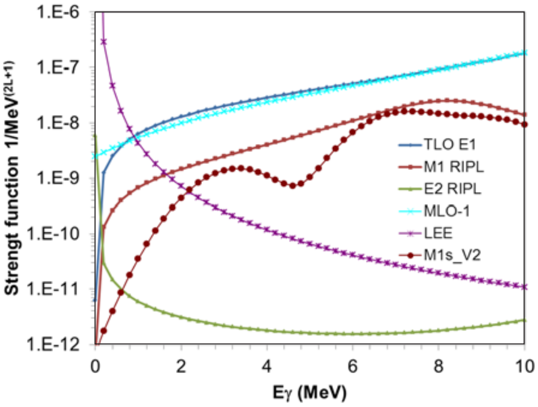

Figure 1. Strength functions for ^{114}Cd

The discrete decay-scheme part of the procedure is under development. The main goal is to improve it as much as possible and to find out whether this combined model is able to evidence new levels and spin assignments. To facilitate this we extracted the continuum level feeding probability from the extreme statistical model. It is shown in Fig. 2 for different spins and parities. The probability distribution can be very well described with 3rd order polynomial as a function of the level energy. This means that a new level can be established if the de-excitation probability is approximately equal or larger (if discrete contribution is also present) than the corresponding continuum feeding value. A scaling of the feeding probability by multiplying with the 3rd power of level energy gives much more difference between levels of different spins and parity that is not shown.

The unfolded spectrum is re-binned from 1 keV bins to 10 keV bins which still represents significantly higher resolution than the usually applied 100–200 keV binning. In the case of the modelling the continuum decays are calculated in 100 keV bins to satisfy the averaging requirement for the widely changing decay widths.

The high-resolution description (10 keV bins) in the modelling is applied for the discrete transitions separately from the continuum. In the case of the continuum transitions that change only slightly within 100 keV bins for the same type (electric, magnetic and multipole) of transitions, the probabilities are evenly distributed in 10 keV bins.

The modelled transition probabilities are then compared to the experimental unfolded spectrum to visualize the quality of the modelling. The result of this comparison

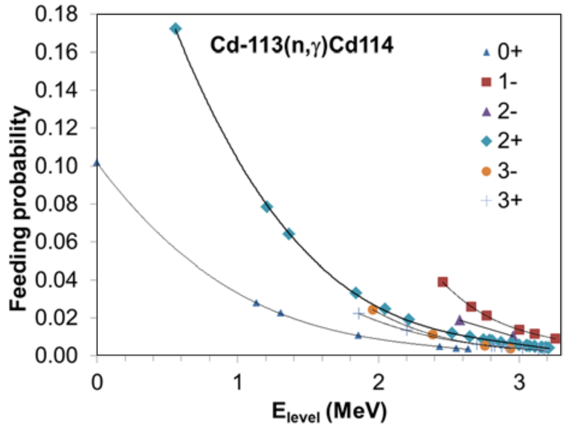

Figure 2. Continuum feeding probability of ^{114}Cd levels for different spins and parities.

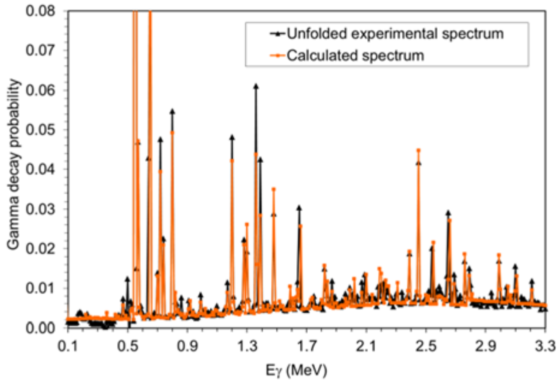

Figure 3. Low energy simulation of ^{113}Cd(n,γ)^{114}Cd spectrum.

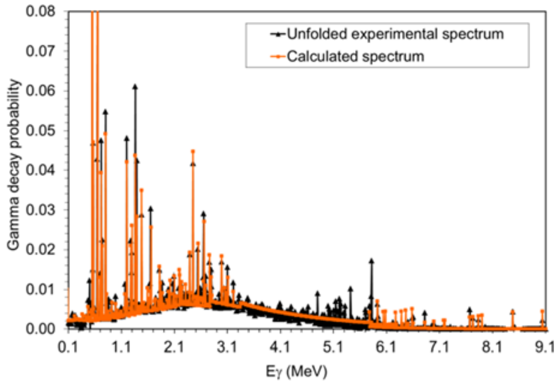

Figure 4. Simulation of ^{113}Cd(n,γ)^{114}Cd full range γ-spectrum.

for the low energy part can be seen in Fig. 3. For the whole gamma-ray spectrum the simulation result is in Fig. 4.

As it can be seen from Figs. 3 and 4, the continuum description well represents the experimental data. Since the critical energy was set to 3.25 MeV we can only expect to describe peaks up to this energy including primary transitions from 5.8 MeV to the 9.042 MeV binding energy. In both the low energy and the high energy regions the peak-to-peak agreement is rather good, but there is still place for some improvement by adjusting the decay scheme. It has to be noted that the overall description of the gamma-spectrum of ^{114}Cd in the radiative neutron capture process by extreme statistical model seems to be possible; however there is no good explanation for the peak grouping at 5.2 MeV. It can not be attributed to pygmy resonance since this is expected at about 8 MeV. This group of transitions can not be a result of two-step transitions since there in no higher area group of peaks at about 3.8 MeV.

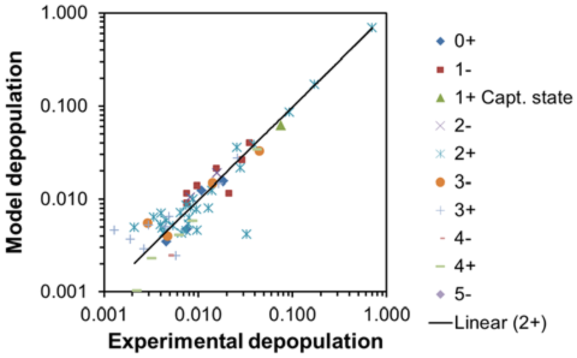

Figure 5. Comparison of modelled and experimental depopulation of levels.

Currently 71 levels are included and 381 γ-rays are placed in the decay scheme up to the critical energy. The gamma-ray energies and intensities up to 2 MeV were taken from the crystal spectrometer measurements at ILL [18], since it had much better resolution than our HPGe detector, above that from the present experiment. The level energies are least-square fit to the placed gamma-ray energies which gave a reduced chi square of 2.5. This means that further development is needed. Nevertheless it is also important to compare the modelled level-depopulation to the experimental one. This is shown in Fig. 5.

As it can be seen from Fig. 5 that there are still scattered discrepancies, which can be up to factor of two too high or too low, but many of the data points are in satisfactory agreement. The work to complete the uncertainty analysis of the data is still in progress.

5. Summaries

Our preliminary results show that the radiative neutron capture gamma-ray spectrum and the decay scheme of ^{113}Cd(n,γ)^{114}Cd reaction can be well described with the extreme statistical model. To obtain good description of the continuum a low-energy enhancement of the E1 transitions is needed. Feeding properties of levels provided by the statistical model with different spins and parities can be well described with 3rd order polynomials, which help to build up decay schemes. A group of peaks at about 5.2 MeV could not be well described within this model, it requires theoretical explanations.

In the long-term prospective more prompt-gamma spectra of nuclei excited with (n,γ) reactions will be studied.

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