Cascade γ rays following capture of thermal neutrons on ^{113}Cd

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Intensity distributions of cascade γ-ray transitions following the capture of thermal neutrons by ^{113}Cd have been measured at the Los Alamos Neutron Science Center for various γ-ray multiplicities. The experiment was carried out at the highly segmented 4π γ-ray calorimeter—Detector for Advanced Neutron Capture Experiments (DANCE). A measured two-dimensional spectrum of counts versus γ-ray energy versus γ-ray multiplicity, from the strongest resonance in the ^{113}Cd(n,γ) reaction at 0.178 eV has been compared to predictions from the statistical model. The best representation of the γ-ray cascades following the capture of thermal neutrons on ^{113}Cd is presented. The intensity distribution of these cascades is of great importance for estimates of response to thermal neutrons of devices that use natural or enriched cadmium.

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Natural cadmium is often used as shielding against thermal neutrons because of the large cross section of ^{113}Cd for the capture of neutrons with energies below 1 eV. The ^{113}Cd$(n,\gamma)^{114}$Cd reaction leads to the emission of γ-ray cascades from ^{114}Cd with the sum energy of 9.043 MeV. Intensity distributions of the γ-ray cascades have to be known with good accuracy to model well the secondary radiation produced in the shielding. Additionally, the product of the neutron-capture reaction, ^{114}Cd, is a stable nucleus which does not transmute further emitting subsequent radiation, therefore the cascade transitions from ^{113}Cd$(n,\gamma)^{114}$Cd are the only source of γ rays.

Based on its large neutron-capture cross section, cadmium is also used in detectors sensitive to thermal neutrons, such as cadmium-doped plastic scintillation detectors, crystal scintillation detectors such as $CdWO_4$ [1] and semiconductor detectors such as CdZnTe [2]. The response to neutrons of these detectors depends on the energy and multiplicity distributions of the capture γ rays. Additionally, multidetector systems, which detect neutrons by registering multiple neutron-capture γ rays [3], strongly depend on the output of the ^{113}Cd(n,γ) reaction.

The distribution of the capture γ rays from the 0.178-eV resonance in the ^{113}Cd(n,γ) reaction is the only one relevant to the mentioned applications in presence of thermal neutrons because this is the first resonance for the reaction covering also the whole thermal-neutrons range. As we demonstrated in our earlier work on the cascade transitions following capture of epithermal neutrons ($E_n > 8$ eV) by ^{111}Cd and ^{113}Cd [4], the intensity of the two-step cascade transitions may differ by more than 50% at a given γ-ray energy for two s-wave resonances with the same angular momentum (cf. Figs. 3–6 in Ref. [4]). Therefore, the unique set of partial transition widths deexciting the resonance at 0.178 eV cannot be predicted accurately by Hauser-Feshbach [5] calculations because they would provide a spectrum averaged over many sets of transition widths which may differ substantially from the specific spectrum from the 0.178-eV resonance. Hence, a dedicated measurement of the thermal-neutron-capture γ rays is of a great importance for estimating the response of cadmium-contained detectors or shielding.

In general, neutron-capture resonances are weakly coupled to the ground state leading to the emission of multiple γ rays in a cascade and a much less probable single transition to the ground state. Therefore, a measurement of the neutron-capture γ rays requires the usage of a multidetector array to ensure the detection of individual γ rays and obtain the multiplicity of the γ-ray cascades, i.e. obtaining a two-dimensional spectrum $A(E_\gamma,M_\gamma)$ of counts (A) versus detected γ-ray energy (E_γ) versus the γ-ray multiplicity (M_γ) of the cascade. However, the detector response may modify E_γ or M_γ perturbing the measured spectrum $A(E_\gamma,M_\gamma)$ from the real γ-ray intensity distribution $I_\gamma(E_\gamma,M_\gamma)$ emitted from the target. The direct way of obtaining $I_\gamma(E_\gamma,M_\gamma)$ is the deconvolution of the detector response from the measured spectrum $A(E_\gamma,M_\gamma)$. Due to the complex nature of the detector-response matrix, we chose the alternative approach of comparing the measured spectrum with predicted ones based on statistical-model simulations.

In this Brief Report, we report a coincidence measurement of the neutron-capture γ rays from the ^{113}Cd(n,γ) resonance at 0.178 eV carried out for 20 hours at the Manuel J. Lujan, Jr. Neutron Scattering Center at the Los Alamos Neutron Science Center (LANSCE). The neutrons were produced by the irradiation of a tungsten spallation target with 800-MeV protons and moderated by a 2.54-cm-thick water block. The $A(E_\gamma,M_\gamma)$ spectrum was collected with the Detector for Advanced Neutron Capture Experiments (DANCE). DANCE is a high granularity and high efficiency γ-ray detector array consisting of 160 BaF_2 crystals. The crystals have four different pentagonal and hexagonal shapes designed such that they form a ball with minimal gaps [6]. Taking into account the two openings of the ball for the neutron-beam line and the plastic insulation of the crystals, DANCE covers a solid angle of 90% of 4π [7]. Each of the crystals have length of 15 cm and equal volume of 734 cm^2 providing very similar

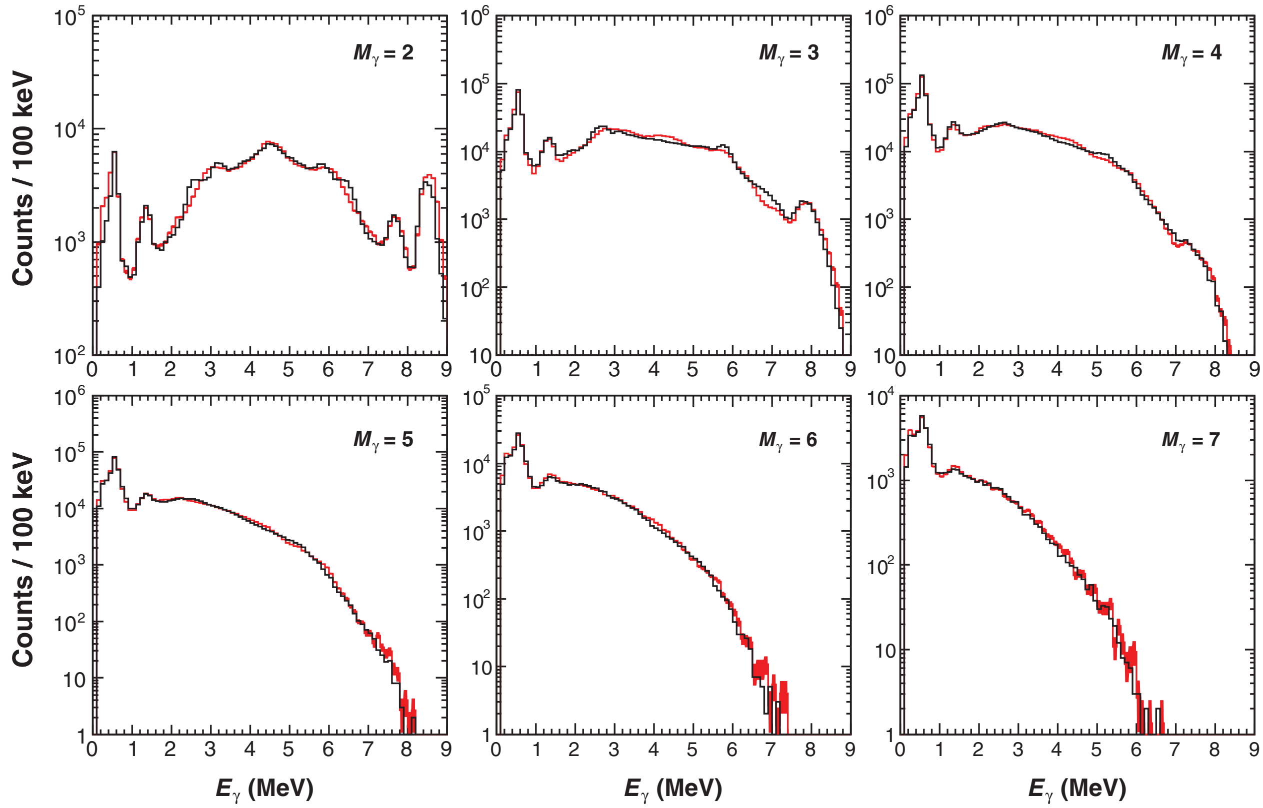

FIG. 1. (Color online) Measured γ-ray spectra with DANCE from the 0.178 eV resonance of the ^{113}Cd(n, γ) reaction for γ-ray multiplicities $M_\gamma = 2$ to 7. Predicted spectra corresponding to a DICEBOX realization which represents best the cascade transitions from the 0.178-eV resonance are shown in red.

efficiency for each crystal shape. The efficiency of DANCE for detecting a single photon with energy of 1 MeV was estimated to be 86% [8]. A 6-cm thick ^{6}LiH shell surrounding the target absorbs the scatted neutrons from the target, but it also reduces the DANCE efficiency for low-energy γ rays. A detailed description of the neutron facility at the Lujan Center and the properties of the beam can be found in Refs. [9,10].

A sample of CdO, enriched to 96.3% in ^{113}Cd, was mounted at the center of DANCE at a distance of 20.25 m from the water moderator of the spallation neutron source. The mass of the target was of tens of 10^{-9} grams to ensure an acceptable counting rate for DANCE and the reduction of pile-up events. The two-dimensional spectrum $A(E_\gamma,M_\gamma)$ was collected for neutrons with energies from 0.165 to 0.190 eV, which gives the maximum cross section for the strongest resonance of the ^{113}Cd(n, γ) reaction at 0.178 eV. Projections of the $A(E_\gamma,M_\gamma)$ spectrum, corrected for the off-resonance background, are shown in Fig. 1 for $M_\gamma = 2$ to 7.

The signal from each detector is split and analyzed by two Acqiris DC265 digitizers for 250 μs each. The delays of the digitizers with respect to the time when a proton bunch struck the spallation target can be set independently. In our experiment, one of the cards was analyzing the events of neutron capture from the resonance at 0.178 eV, while the other card the events of capture from 0.73 to 1.0 eV, which we considered as background. The two neutron-energy regions from which we collected the data are shown in Fig. 2(a).

A γ ray emitted from the target, placed at the center of the DANCE array, can scatter from one crystal to another creating a cluster of fired detectors. All neighboring crystals, which fired within 10 ns, were considered as members of the cluster and the sum of their registered energies we considered as the energy E_γ of the detected γ ray. Events for which a photon scatters across DANCE or a fired crystal is separated from a cluster by not fired detectors were not considered to originate from a single incident photon because those events may correspond to detection of two γ rays in coincidence. The number of created clusters was used as multiplicity of the γ-ray cascade M_γ.

The sum energy of all γ rays detected in one neutron-capture event is considered as the total energy of the γ-ray cascade $E_\gamma^{\text{total}} = \sum_{i=1}^{M_\gamma} E_\gamma^i$. This sum energy equals to the Q value of a given neutron-capture reaction for events when all γ rays were fully absorbed in DANCE crystals. A plot of E_γ^{total} from the ^{113}Cd(n, γ)^{114}Cd reaction is shown in Fig. 2(b). To ensure that all detected events are from the ^{113}Cd(n, γ) reaction and to reduce the background from other reactions [7] a Q value gate was applied to the E_γ^{total} from 8.8 to 9.2 MeV. The narrow Q-value gate ensures also that the detected γ rays have not been attenuated providing the highest sensitivity when compared to the predicted spectra.

The energy calibration is of great importance when a Q-value gate is applied because the incorrect calibration of any of the detectors will cause E_γ^{total} of a cascade to be different

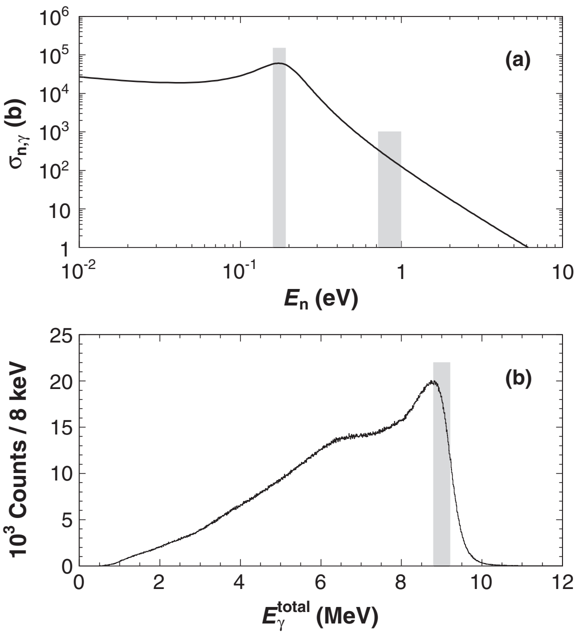

FIG. 2. Cross section for the ^{113}Cd(n,γ) reaction (a) taken from the ENDF-6 evaluation with gray rectangles indicating the time-of-flight intervals for which the emitted γ rays were registered by DANCE. Measured spectrum (b) of E_γ^{total} of the same reaction. The spectrum was collected under the condition at least three γ rays to be detected by DANCE. The Q value of the reaction is visible in the spectrum as a bump around 9 MeV. The gray rectangle represents the E_γ^{total} gate applied in the data analysis.

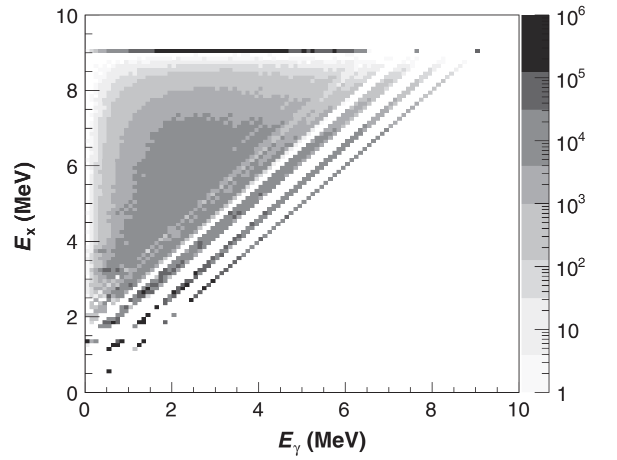

FIG. 3. Gamma-ray transition intensities, simulated with DICEBOX, as a function of the excitation energy (E_x) representing the cascades transitions in ^{114}Cd deexciting the resonance at 0.178 eV in the reaction ^{113}Cd(n,γ). The binning of E_x and E_γ is 100 keV/channel. The gray scale represents the transition intensity for 10^7 neutron captures. The numerical values are listed in the Supplemental Material [14].

than the Q value of the reaction and thus the cascade will not be considered. Therefore, incorrect energy calibration leads to a reduction of the overall DANCE efficiency when a Q-value gate is applied.

Each DANCE detector was calibrated to energy using ^{22}Na (0.511 and 1.275 MeV), ^{88}Y (0.898 and 1.836 MeV), and PuBe sources. The PuBe source emits 4.438-MeV γ rays from the reaction ^{9}Be$(\alpha,n)^{12}$C, where the α particles are provided by ^{239}Pu. Additionally, we measured in-beam the reaction ^{10}B$(n,\gamma)^{11}$B to extend the calibration at higher energies. The measurement was carried out for 22 hours with a 0.17-g boron target enriched to 96% in ^{10}B.

The measured two-dimensional spectrum $A(E_\gamma, M_\gamma)$ is a convolution of the incident γ-ray distribution $I_\gamma(E_\gamma, M_\gamma)$ emitted from the target and the DANCE detection response. Due to the finite efficiency and the 4π geometry of DANCE, the spectrum contains events which cannot easily disclose the incident γ-ray distribution, for example, a single γ ray emitted from the target can create an event with detected more than five photons because of scatterings in the ball. The opposite, three γ rays emitted from the target, for example, could lead to detection of one photon because of absorption in the ^{6}LiH shell, insufficient efficiency, or the detection of two photons in neighboring crystals being considered as one due to the add-back procedure.

We extracted the γ-ray intensity distribution of the ^{113}Cd(n,γ) reaction by comparing predicted spectra with the measured one. The predicted spectra were produced by simulating the transition intensities with the code DICEBOX [11] and using these intensities as input to GEANT4 simulations of the DANCE response [12]. The same definitions described above for quantities M_γ and E_γ^{total} for the measured spectra were applied to the predicted spectra. The models for the photon-strength functions and level densities needed for the statistical-model simulations with DICEBOX were adopted from Ref. [4]. Each nuclear realization created by DICEBOX generated a set of partial widths for transitions from the capture state to all lower-lying levels following the Porter-Thomas fluctuations [13] analogously to the partial widths from one particular capture state in the real nucleus. We created 10 000 nuclear realizations and generated simulated spectra with GEANT4 for 10^7 cascades from each realization. The predicted spectrum which described best the measured one, i.e., for which χ^2 had the lowest value, is shown in Fig. 1, and the intensity distribution of the cascade transitions from this particular realization is depicted in Fig. 3 with binned data available in the Supplemental Material [14].

In summary, we measured the $A(E_\gamma, M_\gamma)$ spectrum from the 0.178-eV resonance in the ^{113}Cd(n,γ) reaction with the DANCE array. A DICEBOX nuclear realization representing best the cascade γ-ray transitions in ^{114}Cd was selected by folding the cascade transitions with the DANCE detector response and comparing it with the measured spectrum. The intensity distribution of the cascade transitions shown in Fig. 3 can be used for the generation of γ-ray cascades in Monte Carlo transport codes for simulating the conversion of thermal neutrons to γ rays by ^{113}Cd. The representation of the cascades as a table of γ-rays energy (E_γ) versus excitation energy (E_x) (cf. Fig. 3) allows building a random generator which uniquely reproduces the cascades.

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[14] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevC.88.057602 for data for Fig. 3 with binning of E_x and E in 10 keV/channel.