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Abstract

The accurate measurement of neutron-capture cross sections of the Eu isotopes is important for many reasons including nuclear astrophysics and nuclear diagnostics. Neutron capture excitation functions of ^{151,153}Eu targets were measured recently using a 4π γ-ray calorimeter array DANCE located at the Los Alamos Neutron Science Center for $E_n = 0.1 - 100$ keV. The progress on the data analysis efforts is given in the present paper. The γ-ray multiplicity distributions for the Eu targets and Be backing are significantly different. The γ-ray multiplicity distribution is found to be the same for different neutron energies for both ^{151}Eu and ^{153}Eu. The statistical simulation to model the γ-ray decay cascade is summarized.

Keywords: neutron capture, neutron resonances, statistical

PACS: 24.30.-v, 24.30.Gz, 24.30.Gd

I. INTRODUCTION

The accurate measurement of the neutron capture cross sections of ^{151,153}Eu is important for applied nuclear physics and modeling of stellar s- and r-processes in the mass A ~ 150 region. The s-process flow at ^{151}Sm and ^{157}Gd is not branched. Therefore the Sm-Eu-Gd region is contained and only the reaction rates within this region are important for a branching analysis. The neutron capture cross sections of stable Eu nuclei have previously been reported in several experiments, e.g. references [1-5]. The existing data in the 10-100 keV neutron energy regions are discrepant as much as 30-40 percent. In order to resolve this discrepancy, measurements of neutron-capture γ-rays on ^{151,153}Eu nuclei have been undertaken. In addition to obtaining a precise cross section, one can utilize the high granularity of the DANCE array to obtain the γ-ray multiplicity information and energy distribution of the decay. A brief description of the DANCE array and the experimental set-up is provided in the following section.

II. EXPERIMENTAL DESCRIPTION

The experiment was performed using the DANCE array located at the flight path 14 at Lujan Center at the Los Alamos Neutron Science Center (LANSCE). The DANCE array is a 4π γ-ray calorimeter that consists of 160 BaF_2 crystals. In order to reduce the scattered neutron background a shell of Li_6H is inserted between the target and the BaF_2 crystals. The initial design of the DANCE array is described in reference [6]. The various background and methods of background suppression are described in reference [7]. The description of the DANCE data acquisition system is given in reference [8]. The detailed description of the system is provided in two dissertations [9, 10]. The results from cross section measurements have been reported in various conferences see e.g. references [11, 12]. The white source of neutron beam with energy 10 meV - 100 keV with the repetition rate 20 Hz was provided by the spallation neutron source at LANSCE. The typical beam current is 100μA. The flight path length is 20 meter. The neutron energy for an event is determined by the time-of-flight technique. Although it was not crucial in the case of Eu where the capture cross section is large, the DANCE array is well suited for measurements of capture cross sections with radioactive and/or small samples. The stable ^{151,153}Eu targets with thicknesses 0.836 ± 0.040 mg/cm^2 and 1.06 ± 0.05 mg/cm^2 and enrichment 96.83 % and 98.76 %, respectively, were used. Both targets were mounted on a Be backing with a 0.5mil thickness. In the next section, the data analysis is described and the multiplicity distribution is considered in more detail.

III. DATA ANALYSIS AND RESULTS

Event by event data analysis was performed offline. The γ-rays detected by different crystals within a given time interval is considered to be an event. The neutron energy for an event is determined by the time-of-flight technique. The γ-ray multiplicity for an event is determined in terms of the "cluster multiplicity" where the cluster is defined such that a detector that is fired along with its nearest neighbors that are also fired forms a cluster. The true multiplicity of γ-rays following a neutron capture is more closely described by the cluster multiplicity because scattered neutrons that are captured in BaF_2 crystals give localized signals which give a low multiplicity. The summed energy of γ-rays of the same event peaks near the reaction Q-value. The most dominant cluster multiplicities around the summed energy peak are 3 and 4 in Eu.

All resonance energies previously known are identified in the present data and some new resonances above E_n = 90 eV are observed. Well known strong resonances in ^{152}Eu up to the neutron energy 10 eV are shown Fig. 1. The high quality of data is demonstrated by sensitivity to detect even the signal due to the small trace of ^{153}Eu in the target material. The resonance at 2.46 eV (denoted in red) is due to 3.17% ^{153}Eu trace in the main sample.

In Fig. 2, the cluster multiplicity distribution for different neutron energy regions for ^{151,153}Eu is shown for the γ-summed energy gate 4.7-6.3 MeV. For ^{151}Eu, the first neutron energy region 0.25-0.63 eV contains two resonances at 0.32 eV and 0.46 eV. The second region is around the resonance at 1.05 eV. The third region 200 – 500 eV is in the overlapping resonance region. For ^{153}Eu, several resonances are summed in order to obtain high statistics. The first region 2-10 eV contains six well-resolved resonances, the second region 10-20 eV contains ten well-resolved resonances. The third region 200-500 eV is in the overlapping resonance region. The compound states near the neutron binding energy are dominated by the s-wave strength in these two nuclei because Eu is near the maximum of the 4s neutron strength function. Therefore, the compound nuclear states which are the initial states are very similar. The ground state of ^{152,154}Eu are $J^\pi = 3^-$. However, the effective final state spin for the decay is not the just ground state spin but is averaged over levels with energies within the detector resolution. Since the level densities in the odd-odd compound nuclei ^{152,154}Eu are extremely large, there are many levels with energies within the DANCE energy resolution of a few hundred keV.

At higher energies, there is more averaging over the initial states, since the resonances are no longer resolved. Thus the energy independence of the multiplicity distribution is physically very reasonable. For both ^{151,153}Eu, the distribution peaks near cluster multiplicity 3 and 4, and are very similar. From the multiplicity distribution one can deduce that in these nuclei, the percentage of the total counts with multiplicities 3 – 7 is 85±1 % and the percentage of the counts with multiplicity 1 and 2 is 15±1 %. The contribution from multiplicities 8 and higher is negligible.

In contrast to this picture, consider the multiplicity distribution from the beryllium backing. Be has a very low neutron capture cross section. The dominant cross section is elastic scattering. The scattered neutrons that are captured in the crystals produce a localized signal of low multiplicity. The multiplicity distribution from the Be backing and from the ^{151}Eu sample are compared in Fig. 3.

The multiplicity distribution for ^{151}Eu target is shown in red and for the Be backing in black. As expected, the highest cluster multiplicity from the Be backing is 1. More than 90 percent of the total counts in the Be spectrum is for multiplicity 1 and 2, in contrast to the Eu samples. The constancy of the multiplicity distribution as a function of neutron energy can be useful for the background subtraction in the higher incident neutron energy region where the multiplicity summed γ-ray signals from Eu and from scattered neutrons are comparable. The background is subtracted using the spectra with multiplicity 3 and higher. The ratio between the Eu and Be counts is determined from the summed energy region above the reaction summed energy peak. Because of the presence of the leak through for multiplicities higher than 3 at strong resonances, the multiplicities 1 and 2 are used for the determination of the ratio between the Eu sample and Be backing spectra. The analytic dead time correction is performed for the sample and Be spectra separately prior to the background subtraction. For the determination of the cross section the systematic uncertainties are being examined.

In addition to the cross section measurement, experimental data obtained from the DANCE detector can be used for the detector response function (and investigation of nuclear statistical properties). In order to do that the results from the DANCE data are compared with DICEBOX and GEANT simulations. The Monte Carlo code DICEBOX [13] generates γ-ray cascades initiating at the neutron capturing state, in our case an s-wave resonance, and terminating at the ground state following the rules of the extreme statistical model. The nuclear levels and the associated decay scheme are simulated assuming phenomenological models for the level-densities and γ-ray strength functions for different types of transitions. Each set of the generated level structure and the decay scheme are called a nuclear realization. The level structure below the excitation energy about 400 keV in odd-odd Eu nuclei is taken from literature and kept fixed [14]. Above that energy, the level density and decay scheme are assumed to follow statistical rules. The Porter-Thomas fluctuation is taken into consideration and the uncertainty in the simulation is determined by generating a large number of nuclear realizations. Conversion electrons are a considerable factor for the decay of Eu nuclei. Therefore the internal conversion is included for the calculation. Cascades produced by the DICEBOX code in the list mode serve as an input for a GEANT simulation of the detector response to these cascades. Simulation and data for sum-energy spectra and γ-ray spectra for events for various multiplicities with deposited sum-energy peak are compared.

Comparisons between data from the Eu experiments at DANCE and simulation provided an excellent agreement for the simulated and measured the multiplicity distribution

IV. CONCLUSIONS

The 4π γ-ray calorimeter DANCE is utilized for the measurement of the neutron capture cross section on stable Eu targets. The high granularity of the detector allows the determination of the multiplicity distribution as a function of neutron energy. The multiplicity distributions for ^{151,153}Eu were nearly independent of neutron energy. This independence can be employed for the accurate background subtraction. Comparison between data from DANCE and the statistical simulation using DICEBOX and GEANT confirmed the independence of the multiplicity distribution in these nuclei on the neutron energy..

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FIGURE 1. Resonances in the ^{151}Eu(n,γ) reaction between E_n = 0.1 – 10 eV. The spectrum with the γ-ray cluster multiplicity 3 is shown.

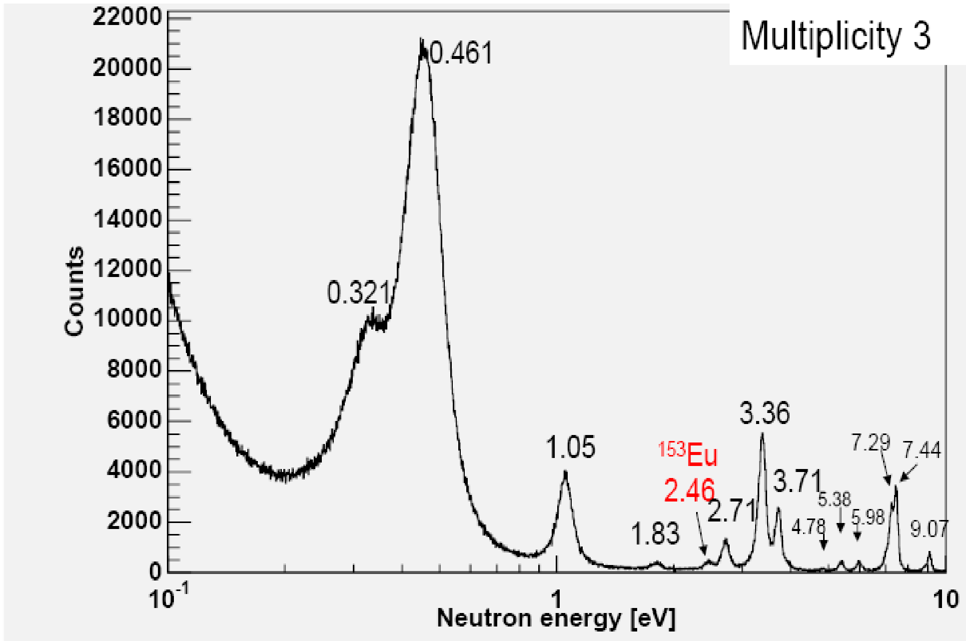

FIGURE 2. The γ-ray multiplicity distribution for ^{151,153}Eu(n,γ). The curves for the incident neutron energy cuts overlap.

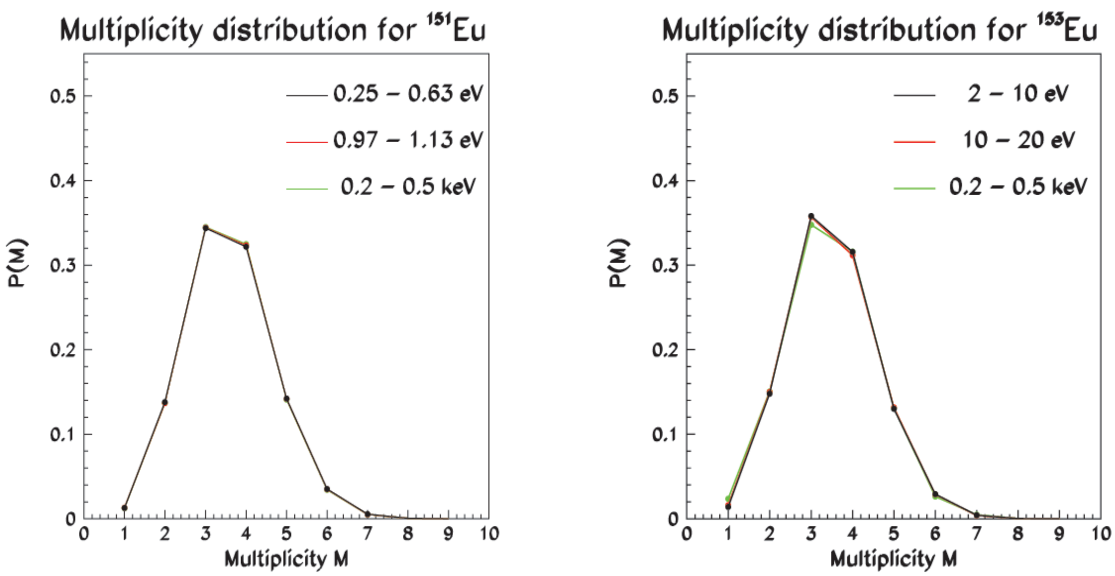

FIGURE 3. The comparison of the γ-ray multiplicity distribution for the ^{151}Eu target and Be backing.

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