Isomeric ratio measurements for the radiative neutron capture ^{176}Lu(n,γ) at DANCE

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Abstract. The isomeric ratio for the neutron capture reaction ^{176}Lu(n,γ) on the $J^\pi = 5/2^-$, 761.7 keV, $T_{1/2}$=32.8 ns level of ^{177m}Lu, has been determined in the neutron energy range 8.5 eV-100 keV for the first time using the DANCE array at the Los Alamos National Laboratory.

1 Introduction

Neutron capture cross sections are of high interest in nuclear astrophysics to investigate the s-process in which the synthesis of heavy elements is dominated by neutron induced reactions. Some isotopes known as s-only nuclei are only produced by the s-process [1] and then give an access to specific characteristics of this nucleosynthesis process. Many investigations were performed on Lutetium isotopes [2–5] due to their great importance in the s-process. The s-only ^{176}Lu exhibits a thermally enhanced beta decay rate [6], making it a sensitive branch point, for estimating neutron density and temperature at the nucleosynthesis site [7]. Macklin [8, 9], Beer [10, 11], Bokhovko [12] and Wisshak [5] have performed various measurements on lutetium isotopes in the neutron energy region of astrophysical interest between 3 keV and 200 keV. Partial cross sections feeding the ground states or isomers are nevertheless particularly crucial in certain cases of the s-process nucleosynthesis [2, 7, 13], or of some astrophysical environments such as neutron stars or supernovae where reactions on the isomeric states can occur [14, 15]. Few measurements of these cross section branchings or of isomeric ratios, defined by the ratio of the isomeric/total cross sections, were performed by combining TOF (Time Of Flight) technic and a 4π array. Three methods were relevant up to now: activation method when lifetime are sufficiently long [16, 17], calorimetry method when excitation energy of isomeric states are sufficiently high compared to the detector energy resolution [18, 19] and combining time and calorimetry for short lifetimes and high excitation energy of isomeric states [20, 21].

In this paper we describe a new method using the high efficiency and granularity of the Detector for Advanced Neutron Capture Experiments (DANCE) array (Los Alamos National Laboratory) working with a digital data acquisition system. We have measured the isomeric ratio for a short lifetime isomer of ^{177}Lu formed by radiative capture reactions on ^{176}Lu.

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2 Experimental setup

2.1 The DANCE array

The experiment was conducted at the Los Alamos Neutron Science Center (LANSCE) of the Los Alamos National Laboratory. The neutron beam is produced by spallation reactions of the 800-MeV pulsed proton beam impinging on a moderated tungsten target [22]. The ^{176}Lu target is placed on the center of the DANCE detector which is located on the 20.25 m long flight path FP14 of the LANSCE [23]. This 4π array is composed of 160 barium fluoride (BaF$_2$) detectors and uses a digitizer acquisition system to record waveforms coming from theses ones. The DANCE array provides for each γ-cascade following the neutron capture, the γ-sum energy, the multiplicity of crystal hit and the γ-rays energies from each crystal. To take into account the Compton effect inside the ball array, a cluster of hits is defined as where at least one neighboring crystal is hit. Information is provided as cluster multiplicty and cluster γ-ray energies determined for each γ-cascade. A cluster time is also defined as a mean of all the crystal times which compose the cluster. In our case, the continuous mode of the DANCE acquisition system is used for neutron energy ranging from 8.5 eV up to 100 keV. More details about the DANCE detector and data analysis can be found in [24].

2.2 The targets

The ^{176}Lu target is unique as the isotopic enrichment reaches 99.95 % for a mass of 0.5 mg/cm^2 and a deposit diameter of 7 mm on a 1 μm aluminized Mylar foil. Enrichment was achieved using a mass spectrometer, SIDONIE available at the CSNSM laboratory (Orsay, France).

To evaluate the background due to neutron scattering on target backing, we have used a blank target which is composed of the same backing material than the Lu target.

3 Isomeric ratio measurement

The isomeric cross-section ratio $R_{iso}(E_{iso})$ of the isomer located at an exitation energy of E_{iso} is written as:

$$R_{iso}(E_{iso}) = \frac{N_{iso}(E_{iso})\,\epsilon_{casc}}{N_{casc}\,\epsilon_{iso}(E_{iso})} \tag{1}$$

where $N_{iso}(E_{iso})$ is the number of detected isomers, N_{casc} is the number of detected γ-cascades, ϵ_{casc} is the cascade detection efficiency and $\epsilon_{iso}(E_{iso})$ is the isomer detection efficiency. The different terms of the equation (1) are described below.

3.1 Selection of the isomers

Our method to determine isomeric cross section ratios consists in a careful study of γ-cascades using the time information of each γ-ray of the cascade. In a large coincidence window of 250 ns, all the γ rays following the neutron capture are recorded. All the γ-rays of this window located in the first 20 ns define the prompt γ-cascade. The others γ-rays are assigned as delayed γ-rays. The time of the prompt cascade is defined as a mean of the cluster times associated to the γ-rays which compose this cascade. The selection of events with particular number of delayed γ-rays highlights particular isomer decays. This selection is illustrated in figure 1.

In this figure, the following γ-ray spectra for the Lu target are presented: the spectrum with no time selection (energies of the prompt and delayed γ-rays), the spectrum with only one γ-ray for the Lu and blank target and the spectrum with two delayed γ-rays.
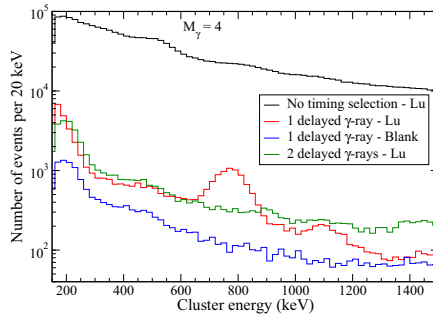
Figure 1: γ-ray spectra obtained with the DANCE array after a $M_\gamma = 4$ γ-cascades including all the prompt and delayed γ-rays (no timing selection), only one delayed γ-ray for the Lu and the blank targets and two delayed γ-rays for the Lu target.

The spectrum which represents the events with only one delayed γ-ray (three prompt γ-rays for $M_\gamma = 4$) exhibits two peaks located at 762 keV and at 1.1 MeV. In this paper, we will focus on the first one. This peak is not present in the case of the blank target which indicates that it is associated to the ^{177}Lu decay. This peak is related to the de-excitation of the $T_{1/2} = 32.8$ ns isomer to the ground state. It proceeds mainly by the emission of only one γ-ray at 761.7 keV (γ intensity of $I_\gamma(761.7) = 70.5 \pm 2.8$ %). That why It disappears when two delayed γ-rays are selected.

On the spectrum with one delayed γ-ray, energy gates, which take into account the BaF_2 energy resolution, are defined around the full energy peak at 761.7 keV to obtain the time decay of the isomers. In figure 2, the spectra which represent the difference between the time of the prompt γ-cascade and the delayed γ-ray are plotted for $M_\gamma = 4$ and in the cases of the Lu and blank targets.
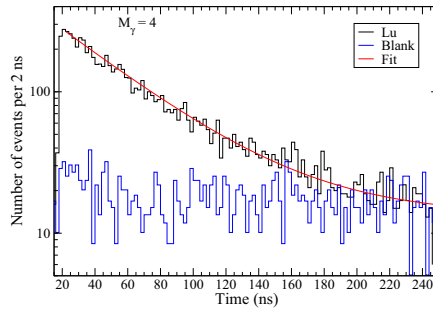

Figure 2: Time spectra for $M_\gamma = 4$ and for the $T_{1/2} = 32.8$ ns isomer obtained by applying energy gates on energy spectra with one delayed γ-ray for the Lu and blank targets. The exponential fits used to obtain the detected isomer number is also plotted.

The isomer exponential decay is clearly visible for the Lu target whereas the time spectrum is flat for the blank target. An exponential fit, $f(t) = A_0 \exp\left(-\frac{\ln 2}{T}t\right) + B$ is performed to extract the number of formed isomers. The fit parameters are reported in table 1 for multiplicities ranging from 3 to 6.

Table 1: Results of the fits performed for the $T_{1/2} = 32.8$ ns isomer and for different cluster multiplicities.

M_γ	A_0 (counts/ns)	T (ns)	B (counts/ns)
3	173.9 (77)	39.0 (22)	66.7 (24)
4	199.3 (67)	33.8 (11)	13.5 (11)
5	106.8 (45)	34.6 (14)	2.7 (7)
6	38.8 (33)	28.4 (19)	1.1 (3)

The half-life obtained by the fits are compatible at 2σ with the previous measured ones: $T_{1/2} = 32.8 \pm 2.4$ ns. The number of detected isomer $N_{iso}(E_{iso})$ is deduced from the fits by:

$$N_{iso}(E_{iso}) = \sum_{M_\gamma} \frac{A_0(E_{iso}, M_\gamma) T(E_{iso}, M_\gamma)}{\ln 2 \, I_{1\gamma}(E_{iso})} \tag{2}$$

where E_{iso} is the energy of the considered isomer and $I_{1\gamma}(E_{iso})$ is the probability that this isomer is detected by only on delayed γ-ray by taking into account the DANCE energy threshold. In the case of the 761.7 keV isomer, we have: $I_{1\gamma}(761.7) = I_\gamma(761.7) = 70.5 \pm 2.8$ %.

3.2 Number of detected cascades

The number of detected cascades N_{casc} is summed for cluster multiplicities ranging from 3 to 6. It is determined, for each multiplicity, by integrating the total energy spectrum between 3.5 and 7.5 MeV. Background obtained with the blank target is subtracted before the integration.

3.3 Detection efficiencies

The cascade detection efficiency ϵ_{casc} is calculated with GEANT4 simulations of the DANCE detector [25] thanks to a γ-cascade obtained with the Monte-Carlo code EVITA, which is based on Hauser-Feshbach formalism [26]. This code is able to reproduce a γ-cascade event using all available information for each nucleus involved in a capture reaction. Ingredients used by EVITA are based on the TALYS code [27] and optimized on the specified available information on the desired isotope and reaction. ϵ_{casc} is defined as the ratio of the number of detected cascade for $M_\gamma \in [\![3, 6]\!]$, which is calculated by integrating the total energy spectrum in the energy range $[3.5 - 7.5]$ MeV, and the total number of initial cascades obtained with EVITA. In our case, we obtain $\epsilon_{casc} = 60.2$ %.

The isomer detection efficiency $\epsilon_{iso}(E_{iso})$ is also calculated with GEANT4 simulations using EVITA. It is defined as the ratio of the full energy peak integral of the γ-rays used to evaluate $N_{iso}(E_{iso})$ summed over the multiplicities indicated in the table 1 and the total number of the same γ-rays in the initial cascades calculated with EVITA. $\epsilon_{iso}(E_{iso})$ takes into account the geometric efficiency, the photopeak efficiency and the multiplicity cut. We have: $\epsilon_{iso}(761.7) = 32.9$ %.

4 Results and discussions

Experimentally, we obtain: $R_{iso}(761.7) = 11.3 \pm 0.8$ %. This experimental value can be compared with a TALYS calculation. In this calculation, we have used the Gilbert and Cameron model for the level density, the Enhanced Generalised LOrentzian (EGLO) model for the E1 strength function and

the dispersive and global spherical optical potential developed by Morillon and Romain [28]. The calculated isomeric ratios are: $R_{iso}(761.7) = 4.1$ %. Large discrepancies are observable between experimental and evaluated isomeric ratios. They may indicate that the γ-ray cascades which lead to the isomers are not properly modelled in our Hauser-Feshbach calculations. Further investigations must be done on level scheme and γ-strength function models.

5 Conclusion

In conclusion, we have obtained for the first time an isomeric ratio of the radiative capture reaction ^{176}Lu(n,γ) for an isomer of the ^{177}Lu compound nucleus, at 761.7 keV (J$^\pi$ = 5/2$^-$, T$_{1/2}$ = 32.8 ns), integrated over all neutron energies. This isomeric ratio was extracted from TOF experiment at DANCE. Comparisons with Hauser-Feshbach prediction have shown large discrepancies.

Acknowledgments

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