Neutron capture reactions on Lu isotopes at DANCE

O. Roig for the DANCE collaboration
CEA, DAM, DIF, F-91297 Arpajon, France and LANL, Los Alamos, NM 87545, USA

Abstract

The DANCE (Detector for Advanced Neutron Capture Experiments) array located at the Los Alamos national laboratory has been used to obtain the neutron capture cross sections for ^{175}Lu and ^{176}Lu with neutron energies from thermal up to 100 keV. Both isotopes are of current interest for the nucleosynthesis s-process in astrophysics and for applications as in reactor physics or in nuclear medicine. Three targets were used to perform these measurements. One was ^{nat}Lu foil and the other two were isotope-enriched targets of ^{175}Lu and ^{176}Lu. The cross sections are obtained for now through a precise neutron flux determination and a normalization at the thermal neutron cross section value. A comparison with the recent experimental data and the evaluated data of ENDF/B-VII.0 will be presented. In addition, resonances parameters and spin assignments for some resonances will be featured.

1 Introduction

Neutron capture cross sections are of current interest in nuclear astrophysics and for the nuclear reaction models. Nuclear data for both topics are crucial for improving the predictive capabilities of the models. On the one hand, the synthesis of heavy elements is dominated by neutron induced reactions. Critical for understanding these reactions are the thermonuclear reaction rates. The reaction rates needed for s-process nucleosynthesis are particularly amenable to experimental investigation as the s process follows the valley of beta-stability, making most of the reactions of interest take place on stable isotopes. ^{175}Lu is an important waiting point while ^{176}Lu exhibits a thermally enhanced beta decay rate, making it a sensitive branch point, both for estimating neutron densities as well as temperatures at the nucleosynthesis site [1, 2]. Typically, the neutron capture reaction rates are obtained by measuring the neutron capture cross section using a neutron spectrum similar to a Maxwell-Boltzmann distribution at a given stellar temperature [3]. To get a complete set of such data between 5 keV and 100 keV stellar temperatures, we need to use cross sections for a neutron energy range as wide as possible [4]. On the other hand, this kind of experiments provides also the opportunity to further constraint reaction models obtaining nuclear structure information like resonance spin assignement and level density [5] or testing the gamma-rays strenght functions [6, 7]. To check the predictive capabilities of nuclear reaction models, we have envisaged to pursue performing such experiments on some Lu unstable isotopes as the ^{173}Lu.

By combining the capabilities of the Los Alamos Neutron Scattering CEnter (LANSCE) accelerators and the DANCE array, neutron capture measurements on ^{175}Lu and ^{176}Lu have been undertaken from thermal neutron energy to few hundred keV using isotope enriched targets. Here we report on the determination of the neutron capture cross sections on ^{175}Lu and ^{176}Lu and the resonance characterisation using a R-matrix code.

2 Experimental setup

2.1 The DANCE detector

The DANCE detector at the Los Alamos Neutron Science Center (LANSCE) flight path is located at 20 m from the white neutron source of the Lujan Center. This neutron production is based on spallation reactions on a tungsten target. The DANCE detector consists of 160 BaF_2 crystals in a 4π geometry. These crystals detect gamma-rays following neutron capture with high efficiency about 86% at 1 MeV.

The efficiency of gamma cascade is typically around 98%. Its high segmentation enables gamma multiplicity measurements and high counting rate. The fast timing allows precise gamma-gamma coincidence and time of flight measurements. Small or radioactive samples can be used. The acquisition system uses the technique of digitization to maximize the data available from the detector. For that, DANCE acquisition has high speed digitizer cards at 500 MSamples/s (1 point each 2 ns), managed by 14 frontend computers. An on-line analysis is performed to store reduced waveform consisting in the integrals of the slow and fast signal components, times and multiplicities for an acquired event [8].

2.2 The Lu targets

Four targets were used to perform these measurements. Characteristics of these targets are reported in the Table 1. Electrodeposition technic was used for most of these targets except the ^{176}Lu target for which a mass separator [9] was used to extract and to deposit the ^{176}Lu isotope.

Table 1: Characteristics of Lu targets used at DANCE.

Target	Form	Diameter	Backing	Purity	Mass (mg/cm^2)
^{nat}Lu	Metallic foil	25 mm	self-supported	99.90%	31
^{175}Lu	Deposit	6.35 mm	2.5 μm titanium foils	99.80%	1
^{176}Lu	Deposit	7 mm	1 μm aluminized mylar	99.95%	1
^{173}Lu	Deposit	6.35 mm	2.5 μm titanium foils	16%	21×10^{-3}

A ^{173}Lu target was exposed to the neutron beam at DANCE. This radioactive target of ^{173}Lu was produced at the Isotope Production Facility in Los Alamos following by a hot chemical separation. The data analysis concerning this target is under progress and will not present here.

2.3 Data analysis

Each experiment have taken 10 days of beam. The goal of the data analysis was to get the cross section $\sigma_{(n,\gamma)}$ according to this formulae 1

$$\sigma_{n,\gamma}(E_n) = \frac{M}{N_A \times \rho_S} \times \frac{N_{(n,\gamma)}(E_n)}{\epsilon(E_n)\phi(E_n)S} \quad (1)$$

where N$_{(n,\gamma)}$ is the yield of the neutron capture events at one neutron energy bin. To determine the absolute cross section, we extracted the detection efficiency ϵ from GEANT4 using an input file from a gamma cascade code [10] [11]. Some cuts were applied on our data. To correct these selections, the cut efficiencies have been determined . A BF_3 beam monitor was used to get the neutron flux $\phi(E_n)$. This flux was normalized using a gold sample placed at the target position. The data analysis for a DANCE experiment is well described in reference [12]. Following results presented in this paper are normalized cross sections at E_n=0.0253 eV from the reference [13].

3 Results and discussion

3.1 The ^{176}Lu isotope

The results on ^{176}Lu(n,γ) cross section are shown on the figures 1 and 2. The R-matrix SAMMY code [14] is used to fit the experimental data using the ENDF/B-VII.0 evaluated data base. A very good agreement with DANCE data is found in the resonance region. The figure 1 shows that the background subtraction was very efficient in the resonance region. The table 2 presents some resonances parameters extracted from the SAMMY code. In the present work the resonance energies are better determined than in the previous work [15].

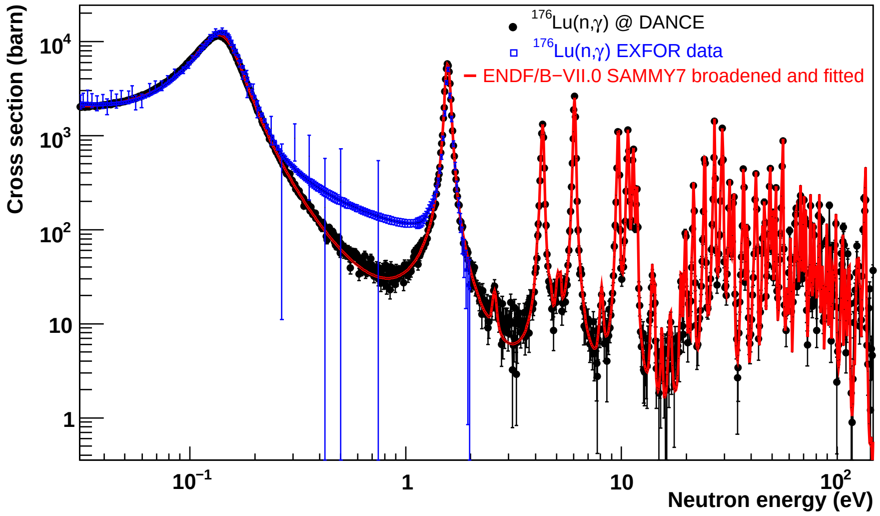

Fig. 1: Neutron capture cross section on ^{176}Lu in the neutron energy range between 0.02 eV and 140 eV measured with the DANCE array (black circles). Red line represents a SAMMY fit using the ENDF/B-VII.0 evaluated data base. Blue markers represents existing experimental data from EXFOR data base.

Table 2: Some preliminary resonance parameters for ^{176}Lu(n,γ)

Mughabghab (2007)			This work		
Energy (eV)	Γ_γ (meV)	Γ_n (meV)	Energy (eV)	Γ_γ (meV)	$2g\Gamma_n$ (meV)
9.73 (3)	-	1.370 (12)	9.71 (1)	78 (3)	1.34 (1)
10.79 (4)	72 (2)	1.600 (17)	10.78 (1)	81 (4)	1.89 (1)
11.44 (4)	68 (8)	1.072 (73)	11.43 (1)	70 (5)	1.03 (3)
11.88 (5)	69 (8)	0.442 (15)	11.87 (1)	71 (6)	0.437 (17)

Figure 2 shows the cross section measured at higher energy with the evaluated data from ENDF/B-VII.0. DANCE cross section normalized only at the thermal neutron energy agrees well with previous data from H. Beer [16], K. Wisshak [3] and the evaluated cross sections.

Considering only s-wave resonances, the compound nucleus formed by the (n,γ) reaction on the J^π=7^- ^{176}Lu ground state can have resonance spins of 13/2 or 15/2. A preliminary study of the averaged γ multiplicity distribution shows that we are able to distinguish between spins of s-wave resonances. The figure 3 shows the difference of the averaged multiplicity. Spins indicated on the figure 3 are from the reference [13]. The spins of unassigned resonance could be attributed. At higher neutron energies, methods proposed by S. Sheets $et\ al.$ [5] and P. Koelher $et\ al.$ [17] should be more accurate and would be appropriate for applying to Lu isotopes data.

3.2 The ^{175}Lu isotope

Figure 4 shows cross sections concerning the natural Lu neutron capture reaction. As the natural Lu isotopes is mostly compound of the ^{175}Lu isotope (97.41%), cross section could be extract for the ^{175}Lu(n,γ) reaction. Corrections should be necessary to subtract contribution from ^{176}Lu and ^{181}Ta. ^{181}Ta was found as pollutant of the natural foil. However, the SAMMY code can determine the proportion of each constituant and fit the measured cross section. There is a good agreement between DANCE data and fits from SAMMY using the ENDF/B-VII.0 evaluated data base.

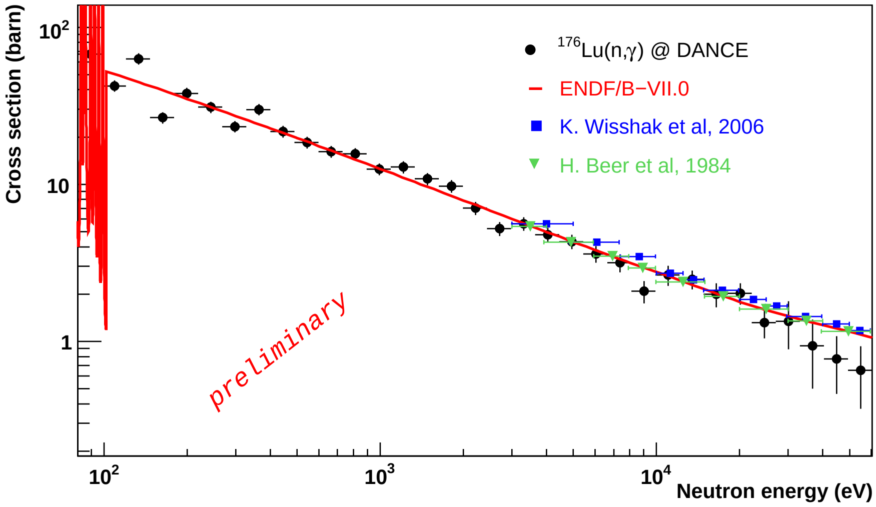

Fig. 2: Neutron capture cross section on ^{176}Lu in the neutron energy range between 100 eV and 100 keV measured with the DANCE array (black circles). Red line represents evaluated data from ENDF/B-VII.0 data base. Blue and green markers represent existing experimental data from H. Beer $et\ al.$ [16] and K. Wisshak $et\ al.$ [3] respectively.

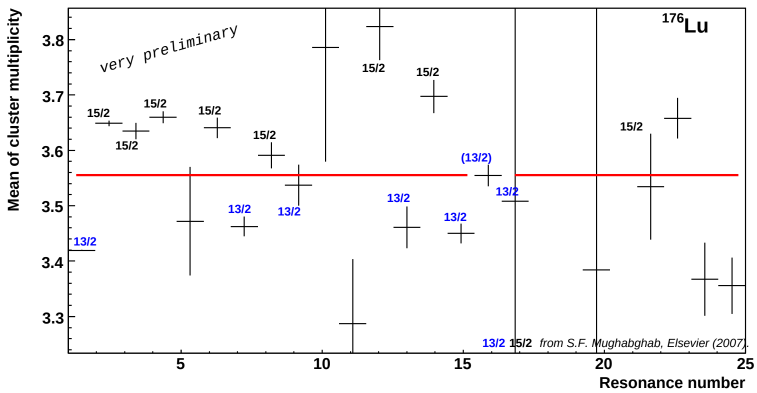

Fig. 3: Average multiplicity for the 25st resonances of the ^{176}Lu(n,γ) reaction. Black and blue values are spins of s-wave resonances known from Mughaghab [13].

3.3 Conclusion

The DANCE detector provides us a very complete data set for the neutron capture study that can be used to improve reaction models. We can directly compare our results to the reaction models results in the keV region. In the resonance region, we are able to obtain valuable nuclear structure information from spin assignments. All of these results are relevant to fundamental nuclear properties and important input parameters for reaction models. For the first time, we have obtained over a large neutron range the neutron capture cross sections on the ^{176}Lu and the ^{175}Lu isotopes. A very good agreement between the evaluated data for the ^{176}Lu and the ^{175}Lu and measurements is found.

4 Acknowledgements

This work has benefited from the use of the Lujan Center at the Los Alamos Neutron Science Center, funded by the DOE Office of Basic Energy Sciences and Los Alamos National Laboratory funded by the

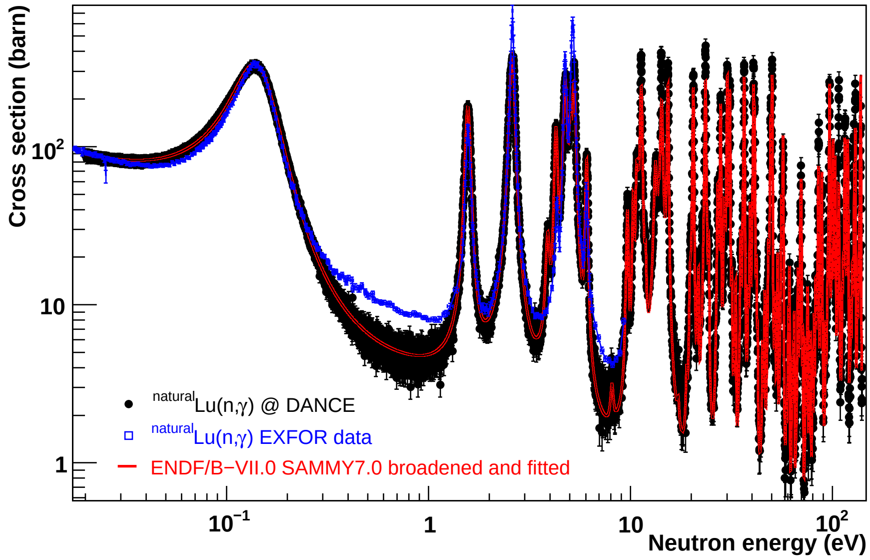

Fig. 4: Neutron capture cross section on ^{nat}Lu in the neutron energy range between 0.02 eV and 140 eV measured with the DANCE array (black circles). Red line represents a SAMMY fit using the ENDF/B-VII.0 evaluated data base. Blue markers represents existing experimental data from EXFOR data base.

Department of Energy under contract W-7405-ENG-36.

References

[1] K. Takahashi and K. Yokoi, At. Data Nucl. Data Tables **36**, p.375 (1987).

[2] N. Klay, F. Käppeler, H. Beer, and G. Schatz, Phys. Rev. C **44**, 2839 (1991).

[3] K. Wisshak, F. Voss, F. Käppeler, L. Kazakov Phys. Rev. C **73**, 015807 (2006).

[4] O. Roig and A. Couture, in proceedings of "10th Symposium on Nuclei in the Cosmos", PoS(NIC X)077 (2008).

[5] S. A. Sheets *et al.*, Phys. Rev. C **76**, 064317 (2007).

[6] S. A. Sheets *et al.*, Phys. Rev. C **79**, 024301 (2009).

[7] D. Dashdorj *et al.*, in proceedings of "the Twentieth International Conference of application of accelerators in research and industry", AIP Conf. Proc. **1099**, p.704 (2009).

[8] Jan M. Wouters *et al.*, IEEE Transactions on nuclear science, **Vol. 53**, 3 (2006).

[9] N. Chauvin, F. Dayras, D. Le Du, and R. Meunier, Nucl. Instrum. and Meth. A **521**, pp. 149-155 (2004).

[10] F. Bečvàr, Nucl. Instr. and Meth. A **417**, p.434 (1998).

[11] L. Pangault, PhD thesis, University of Lyon, (1998).

[12] M. Jandel *et al.*, Phys. Rev. C **78**, 034609 (2008).

[13] S. F. Mughabghab, Atlas of neutron resonances, Elsevier Science (2007).

[14] N. M. Larson, SAMMY, ORNL/TM-9179/7 (2006).

[15] S.M. Kalebin *et al.*, Atomnaya Energiya, **42**, Iss. 6, p. 506 (1977)

[16] H.Beer, G.Walter, R.L.Macklin, P.J.Patchett, Physical Review C **30**, p.464 (1984)

[17] P. E. Koehler *et al.*, Phys. Rev. C **76**, 025804 (2007).