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Neutron capture cross section on Lu isotopes at DANCE

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The DANCE (Detector for Advanced Neutron Capture Experiments) array at the LANSCE spallation neutron source in Los Alamos has been used to measure 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 s-process nucleosynthesis. ^{175}Lu is an important waiting-point in the s-process and ^{176}Lu is a sensitive s-process thermometer. Three targets were used to perform these measurements. One was a natural Lu foil of 31 mg/cm^2 and the other two were isotopically enriched targets of ^{175}Lu (99.8%, ~1 mg/cm^2 electro-deposited on Ti) and ^{176}Lu (99.9%, ~1 mg/cm^2 mass separator deposited on aluminized mylar). The data analysis is in progress. Preliminary cross sections have been obtained by normalizing the data to the known thermal cross sections. A comparison of these data with recent experimental data of K.Wisshak *et al.* and the evaluated data of ENDF B-VII will be presented.

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1. Introduction

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.

Lutetium-175 is an important waiting point while Lutetium-176 exhibits a thermally enhanced beta decay rate [1], making it a sensitive branch point, both for estimating neutron densities as well as temperatures at the nucleosynthesis site [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. 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. By combining the capabilities of the Los Alamos Neutron Scattering CEnter (LANSCE) accelerators and the DANCE array, neutron capture measurements on ^{176}Lu and ^{175}Lu have been undertaken from thermal neutron energy to few hundred keV using isotope enriched targets. On top of data for astrophysics, resonance characterization, level densities and γ-cascade information will be extracted to further constrain reaction model calculations.

2. Experimental details

2.1 The DANCE array

DANCE is a 4π gamma-detector array composed of 160 BaF2 scintillators. DANCE provides the total γ-ray calorimetry and the multiplicity information of the γ-cascade following neutron capture. High granularity, high neutron flux and a fast digitized data acquisition system enable measurements with small samples of ~1 mg or less and/or radioactive targets with activities up to around 1 GBq. The DANCE array is located on a 20 m neutron flight path (FP14) at the Lujan Center at LANSCE.

2.2 The beam line at LANSCE

The white neutron source of the Lujan Center is based on spallation reactions on a tungsten target using a pulsed 800-MeV proton beam. The beam is accumulated in the proton storage ring and delivered to the target in ~200 ns long bunches with a repetition rate of 20 Hz and an average beam intensity of 100 μA to facilitate neutron time-of-flight experiments.

Three monitors located ~2 m downstream of the DANCE target provide a measurement of the neutron beam flux. The first monitor uses a ^{6}LiF foil and a silicon detector to measure the ^{6}Li(n,t)α reaction. The second is a BF_3 gas proportional counter that utilizes the ^{10}B(n,α)^{7}Li reaction. The third monitor is a ^{235}U fission chamber. A typical flux measurement using the BF_3 monitor can be found in reference [4].

2.3 The targets: The Lu isotopes: ^{175}Lu and ^{176}Lu

Three lutetium targets were used at DANCE (target details are given in table 1).

Target	***Form***	***Diameter***	***Backing***	***Purity***	***Mass*** *(mg/cm^2)*
^{nat}Lu	*Metallic foil*	*25 mm*	*self-supported*	*99.90%*	*31*
^{175}Lu	*Deposit (electro-deposition)*	*6.35 mm*	*sandwiched between two 2.5 μm titanium foils*	*99.80%*	*~1*
^{176}Lu	*mass separator deposit (SIDONIE [3])*	*7 mm*	*one 1 μm aluminized mylar*	*99.95%*	*~1*

Table 1 Characteristics of Lu targets used at DANCE.

3. Results and discussion

Experimental data analysis was performed as described in reference [4]. The yield of neutron capture cascade was obtained after applying multiplicity selection (number of BaF_2 detector hits), Q-value gate (total energy, $E_{\gamma\ sum}$, deposited in all BaF_2 detectors), dead time correction and background subtraction. In this paper, only the preliminary results for ^{176}Lu(n,γ) are presented. DICEBOX was used to simulate γ-cascade following the ^{176}Lu(n,γ) reaction. The DICEBOX output was used as an input for a GEANT4 simulation of the DANCE response to such events [5-7].

3.1 DANCE Response Characterization

For each multiplicity, the Lu data are compared to DICEBOX-GEANT4 simulation for J=13/2 and J=15/2 resonances after background subtraction. The measured total γ-ray energy distributions for different multiplicities are compared with the simulation and a good agreement has been found. The deduced capture cascade detection efficiency extracted from these calculations gives a total efficiency of 99.7% (i.e. for the detection of at least one gamma-ray in the cascade). The cross section data has been obtained after applying a total γ-ray energy gate of $E_{\gamma\ sum}$= 4.2-7.3 MeV, a multiplicity gate of $M_\gamma \geq 4$ and subtracting background as described in reference [4]. For multiplicities of 4 and larger, no efficiency dependence on the spins for different resonances is found.

3.2 Cross section for neutron energy [0.02 eV, 400 keV]

Preliminary cross sections were obtained by normalizing the data to the thermal cross section of 2020±70 b [8]. A good agreement between these DANCE data and ENDF/B-VII is found up to a limited value of ~50 keV where background subtraction becomes problematic. Several new resonances below 700 eV have been observed. A SAMMY fit is in progress. The Wisshak *et al.* [9] data (black squares) are also shown for ^{176}Lu(n,γ). A full paper on these results with absolute cross section determinations is in preparation.

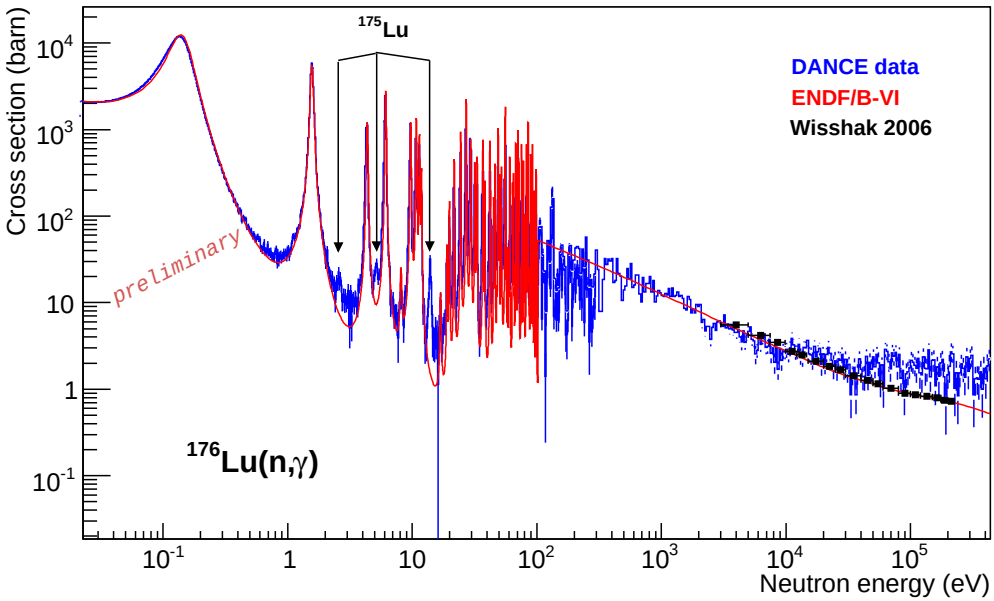

Figure 1 Preliminary neutron capture cross section normalized for ^{176}Lu(n,γ) are shown for neutron energies from 0.02 eV up to 400 keV. These data have been normalized to the thermal cross sections given in [8].

The Maxwellian-averaged (n,γ) cross sections (MACS) in a stellar plasma of thermal energy *kT* is defined as in reference [10]. Since cross sections have been measured over a wide energy range, these preliminary MACS can be defined as a sum of three integrals. The first integral I_1 is extracted from these DANCE data according to the formula (1) between thermal energy and 3 keV including the resonance region. The other two integrals, I_2 and I_3, are taken from reference [9].

$$I_1 = \frac{2}{\sqrt{\pi}} \frac{1}{(kT)^2} \sum \sigma_{(n,\gamma)} E_i \exp(-E_i/kT) \Delta E_i \qquad (1)$$

The calculated MACS for the ^{176}Lu(n,γ) reaction at various *kT* values is given in Table 2. Resonances have an increasing influence at low temperatures.

MACS (n,γ) ***kT* (keV)**	**This work+[9] (mb)** ***Preliminary***	**Ref. [9] (mb)**	**Percentage of resonance region**
8	3487 ± 52	3586 ±62	17.00%
10	3041 ± 38	3109 ± 44	12.00%
15	2383 ± 25	2421 ± 27	7.00%
20	2024 ± 19	2046 ± 20	5.00%
25	1791 ± 16	1806 ± 17	4.00%
30	1629 ± 14	1639 ±14	3.00%

Table 2 Maxwellian-averaged cross section given in mb for various *kT* values for ^{176}Lu(n,γ) reaction.

4. Conclusion and outlook

The neutron capture cross sections on ^{175,176}Lu isotopes over a wide neutron energy range have been measured at DANCE. Preliminary cross sections for ^{176}Lu(n,γ) that are normalized at thermal energy are found to agree correctly with previous data and ENDF/B-VII. Absolute cross section will be published once the accurate target thicknesses will be determined. The Maxwellian-averaged (n,γ) cross sections are in good agreement with the results of Wisshak *et al* [9]. Further analysis to assign spins for each resonance is in progress using multiplicity information and the methods outlined in reference [11-12].

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