УДК 539.172:543.522

THE CROSS SECTIONS FOR (n, x) NUCLEAR REACTIONS ON TERBIUM AND LUTETIUM ISOTOPES

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Neutron cross sections have been measured for Lu and Tb isotopes with neutron activation method. Foils of natural lutetium and terbium were irradiated by neutrons produced by neutron generator NG-300/15. To ensure results accuracy and precision the coincidence summing and self-absorption effects have been taken into account. Calculations of efficiency and corrections have been performed with Monte Carlo simulations. The cross section results obtained for ^{175}Lu(n, α)^{172}Tm reactions were reported for the first time. Theoretical calculations of excitation functions were conducted with the Talys-1.0 code.

Introduction

At present time the knowledge of neutron cross sections is very important both in practical and theoretical area of activities. Requirements for neutron cross section values with high accuracy depend on enlargement of amount of nuclear data practical applications. Due to lack of universal nuclear reaction model such an approach with new and verified nuclear data may be considered as important for testing the applicability of the statistical model for description of (n, 2n) reactions on nuclides rather away from the stability line. Notwithstanding the fact that there are huge nuclear data bases which involve many neutron activation cross sections data for neutron energy about 14 MeV, some unsolved problems still remain in this area. Except incompleteness of nuclear data bases [1, 2] the discrepancy between existing results has been observed as well, what may lead to errors unrecognized during interpolation of experimental data and to influence the quality of estimated data (Figs. 1 and 2).

This paper is devoted to investigations of (n, x) nuclear reactions on lutetium and terbium isotopes. Regardless to requests [2] the most attention was paid to reaction ^{175}Lu(n, α)^{172}Tm due to lack of such cross-section data in literature. The reason for the choice of these nuclides for measurements deals also with their nowadays importance and practical applicability in human life. Terbium and lutetium are two rear earth elements which are interesting because of their complexity of β-branching and γ-spectra in this mass region. Besides that many of the data available has large error bars and often show gross disagreements between one and others.

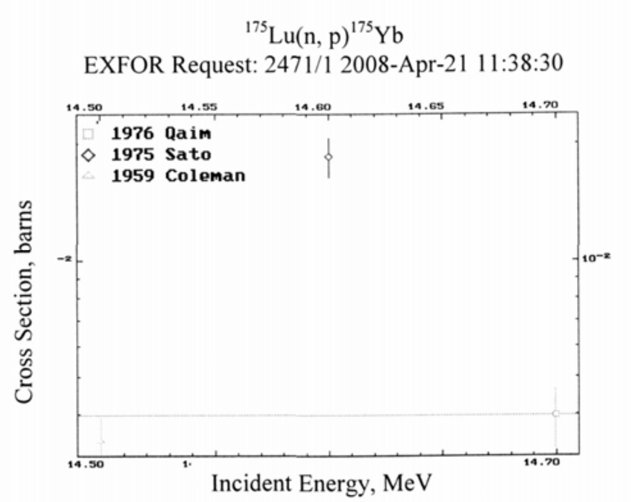

Fig. 1. EXFOR data for reaction ^{175}Lu(n, p)^{175}Yb.

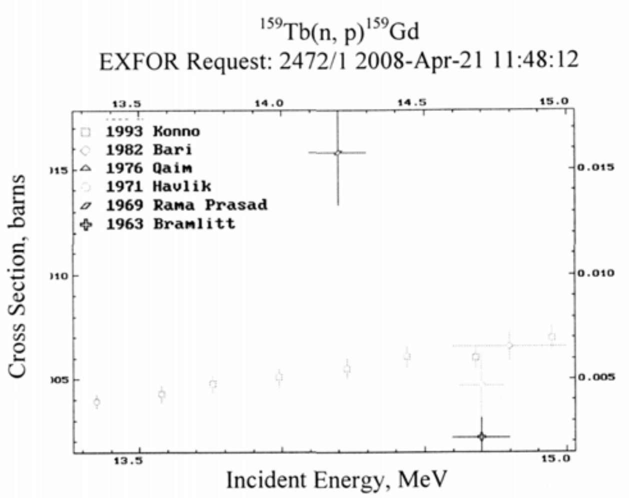

Fig. 2. EXFOR data for reaction ^{159}Tb(n, p)^{159}Gd.

Experimental method

Determination of all cross sections was performed using neutron-activation method. Measurements were carried out with conventional, widely used scheme: irradiation – cooling -gamma counting. Samples in the shape of disc foils of natural terbium and lutetium isotopes have been irradiated with D-T neutrons. The neutron generator NG-300/15, which was designed and built at the Department of Nuclear Physics, University of Kyiv, has been used as a source of fast neutrons [4].

The maximum current of deuterium ions beam is 10 mA. To generate neutrons with energy ~ 14 MeV a molecular component of deuteron beam D_2^+ has been used. A diaphragm to form a beam with diameter 10 mm has been used to decrease disperse of neutron energy in ion-pipe that allows to use different parts of sample after every irradiated series. Location of deuteron beam axis has been defined from distribution of neutron flux density on the target by method of foil activation. The average neutron energy has been determined experimentally using Zr/Nb ratio method [5]. Stakes of niobium and zirconium foils have been irradiated simultaneously at different angels relative to the incident deuterium beam ($R(E_n) = \frac{\sigma_{Zr}(E_n)}{\sigma_{Nb}(E_n)}$). Contribution of scattered neutrons wasn't taken into account, because the threshold of specified nuclear reaction is above 2.8 MeV. The indium and cadmium foils were used as additional protection from scattered low energy neutrons.

Several series of experimental measurements have been conducted, gradually irradiated the samples Tb and then Lu. Samples had a natural composition, before irradiation they have been checked for the presence of impurities. For terbium the angel of the irradiation position with respect to the d^+ beam direction was 0 degrees on 75 mm distance from Ti-T target. The lutetium samples were irradiated under 0, 65, 135 degrees. The average neutron flux density was ~ 1.3 × × 10^8 neutrons/($cm^2 \cdot s$) and depended on the specimen position under irradiation. The neutron flux has been monitored using $^{93}Nb(n, 2n)^{92m}Nb$ reaction and kept constant with uncertainty ≤ 5 %.

For experiment optimization the neutron spectra were calculated also. It was taken into account both the real irradiation conditions, sample dimensions and position relative to the Ti-T target. At Fig. 3 a calculated neutron spectrum is presented for geometry when sample located under angel 0 degree at distance 5mm between sample and target [6].

Time of irradiation varied within (60 - 180) min to guarantee maximum reaction yields. Gamma rays emitted from the irradiated samples and the monitor foils were acquired with closed-end HPGe detector with sensitive volume of ~110 cm^3, placed in 50 mm thick lead shielding. Energy resolution was determined as 2.1 for γ1332 keV ^{60}Co and 1.2 for γ122 keV ^{152}Eu. Calibration procedure has been performed with a set of calibration point sources (^{133}Ba, ^{241}Am, ^{60}Co, ^{137}Cs). Cross sections have been determined by relative method and the reactions $^{27}Al(n, \alpha)^{24}Na$, $^{93}Nb(n, 2n)^{92m}Nb$ have been selected as monitor ones. The values of measured cross

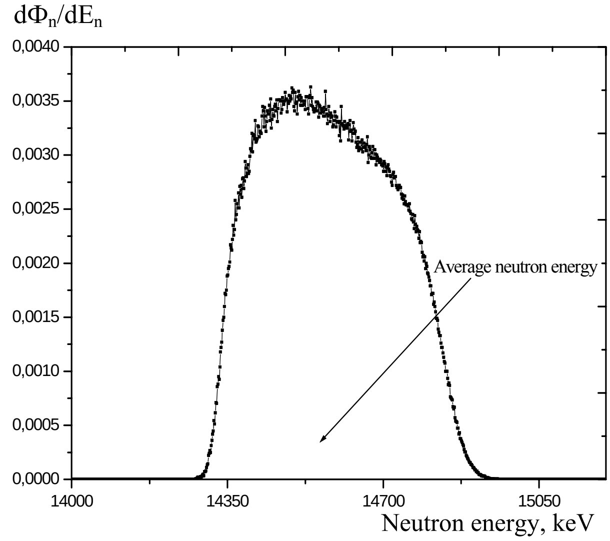

Fig. 3. Calculated spectrum of d-t neutrons irradiated from Ti-T target.

sections were determined for different gamma-lines energies with subsequent weighted averaging. In order to deduce reliable cross-section values, all the sources of biases were thoroughly considered. Because of big thickness (up to 2 mm) and high density of irradiated samples it was necessary to take into account self-absorption effects as well. A modeling approach has been used with Monte Carlo simulations. Correction factor was taken as the ratio of detector efficiency in cases of point and volume radiation sources. The efficiency of point and volume sources (activated foils) was calculated with MCNP 4C code [6], correction factors for coincidence summing have been calculated by Nuclide Master+ code [7] as well. The input parameters for these calculations were the information about nuclear structure from estimated data base ENSDF and geometry of measurements.

Results of measurements

The neutron induced reactions (n, p), (n, α) and (n, 2n) were studied at the average neutron energy of 14.6 MeV for the terbium and lutetium isotopes. Cross section values were measured and presented in Tables 1 and 2. Each value is based on several independent measurements. The available literature cross section values [1] for incident neutron energies around 14 MeV is given in the same tables for comparison. As a confirmation of accurate using of measurement technique applied it can be considered the fact that for some reactions we reached rather very good agreement with previously measured data (see Tables 1 and 2).

Theoretical calculations of excitation functions have been performed with code Talys-1.0 [8]. Evaluated data have been taken from ENDF B/VI data base. At neutron energies higher then 8 MeV pre-equilibrium processes do predominate, therefore in calculations of excitation functions two-component exiton model [8] was used. For reaction ^{175}Lu(n, p)^{176}Yb, ^{159}Tb(n, n)^{158}Tb and ^{159}Tb(n, α)^{156}Eu acceptable agreement observed between results of measurements and calculations (Figs. 4. - 6).

Table 1. **Measured cross sections for terbium at neutron energy 14.56 MeV**

Nuclear reaction	Half-live	E_γ, keV	Cross section, mb	EXFOR [1]
^{159}Tb(n, p)^{159}Gd	18.48 h	363.54	4.8(0.5)	6.6(0.7)
^{159}Tb(n, α)^{156}Eu	15.19 d	1153.67	2.2(0.3)	2.2(0.5)
^{159}Tb(n, 2n)^{158}Tb	180 y	944.18	1913(60)	1909(82)

Table 2. **Measured of cross sections for lutetium**

Nuclear reaction	Half-life	E_γ, keV	Neutron energy, MeV	Cross section, mb	EXFOR [1]
^{175}Lu(n, 2n)^{174m}Lu	142 d	992.07	13.47	480(63)	–
			14.2	382(59)	515(36)
			14.56	567(60)	627(52)
^{175}Lu(n, 2n)^{174g}Lu	3.31 y	1241.85	13.47	1896(250)	1890(124)
			14.2	1473(219)	1670(159)
			14.6	1860(190)	1900(162)
^{175}Lu(n, p)^{175}Yb	4.19 d	396.32	13.47	10.7(0.7)	–
			14.2	9.8(0.7)	–
			14.6	13.2(0.9)	18.5(2.2) 3.4(0.5)
^{175}Lu(n, α)^{172}Tm	63.6 h	1093.59	13.47	0.7(0.1)	–
			14.2	1(0.03)	–
			14.6	1.5(0.2)	–
^{176}Lu(n, α)^{173}Tm	8.24 h	398.9	14.6	1.63(0.34)	2.3(0.6)

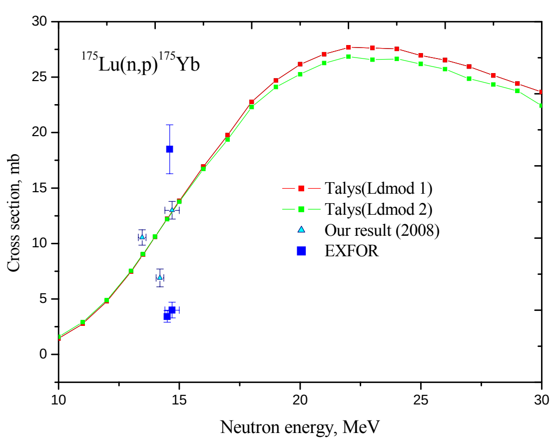

Fig. 4. Comparison of experimental results for reaction ^{175}Lu(n, p)^{175}Yb with calculations.

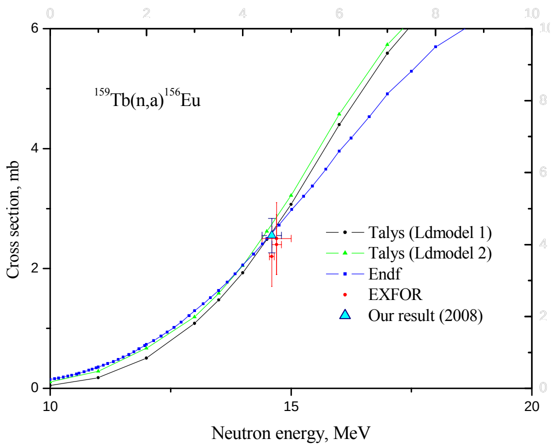

Fig. 5. Comparison of experimental results for reaction ^{159}Tb(n, a)^{156}Eu with calculations.

Considering the fact that at 14 MeV neutron energy the cross section is rather sensitive to pre-equilibrium process, but for alpha-particles an emission is not simple and exiton model only does not work. It is well-known that for nuclear reactions involving alpha-particles, mechanisms like stripping, pick-up, brake-up and knock-out do play an important role and these direct-like reactions are not covered by the exciton model. The cross section of (n, α) reaction near threshold is sensitive to the stripping reaction. In Talys-1.0 for that reason two phenomenological models are developed. The stripping, pick-up, brake-up and knock-out contributions can be adjusted with the Cstrip keyword. It has been provided an excellent agreement with experiment (Fig. 7).

Calculations also demonstrated that cross sections in specific cases are insensitive for level density parameters (see Figs. 4 and 5). This result obtained confirmed again that behavior of nuclear reaction excitation functions for deformed nuclei are not simple and do not belong to one systematic.

Measured cross section for ^{176}Lu(n, a)^{173}Tm reaction is in well agreement with results provided in paper (T. Sato, K. Kanda, 1975 [1]) .

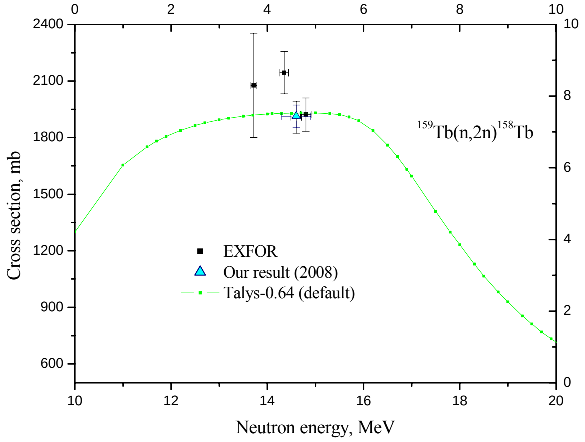

Fig. 6. Comparison of experimental results for reaction ^{159}Tb(n, 2n)^{158}Tb with calculations.

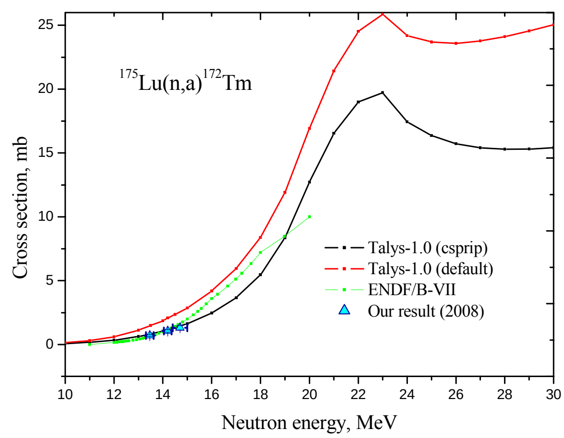

Fig. 7. Comparison of experimental results for reaction ^{175}Lu(n, a)^{172}Tm with calculations.

The cross sections values are measured with up to 10 % uncertainty, though in few cases the error bars are even larger. For many applications such an accuracy may be considered as acceptable and the cross section values themselves as quite reliable since nuclear constants, interfering reactions, contaminations, neutron flux normalization, energy determination, energy spread, energy attenuation in the sample for irradiation to be detected and instrumental factors with necessary corrections have been taken into account.

Conclusions

The cross section values obtained can be considered in the process of evaluated data calculation to provide more correct assessment of cross section values for these reactions.

Seven values of new cross sections for and ^{175}Lu(n, α)^{172}Tm nuclear reactions were measured. Effectiveness and correctness of using the neutron-activation method were confirmed by good agreement of our results with results of other research groups. Obtained results could be useful to avoid ambiguity in values of cross sections for ^{75}Lu(n, p)^{176}Yb nuclear reaction. Presented results can be used in the process of estimated data calculation and provide more correct cross section values for testing of nuclear reaction models. One can stress that it is necessary to use an individual approach in theoretical calculations for certain reactions.

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ПЕРЕРІЗИ ЯДЕРНИХ РЕАКЦІЙ (n, x) НА ІЗОТОПАХ ТЕРБІЮ ТА ЛЮТЕЦІЮ

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Виміряно нейтронні перерізи для ізотопів тербію та лютецію з використанням нейтронно-активаційного методу. Фольги з природного тербію та лютецію опромінювалися нейтронами з нейтронного генератора NG-300/15. Для забезпечення прецизійності отриманих результатів було враховано ефекти каскадного додавання гамма-квантів та самопоглинання. Розрахунки ефективності та коригуючих факторів виконано із застосуванням симуляції за методом Монте-Карло. Отримані результати для реакції ^{175}Lu(n, α)^{172}Tm представлено вперше. Теоретичні розрахунки функцій збудження виконано з використанням коду Talys-1.0.

СЕЧЕНИЯ ЯДЕРНЫХ РЕАКЦИЙ (n, x) НА ИЗОТОПАХ ТЕРБИЯ И ЛЮТЕЦИЯ

Н. Р. Дзисюк, И. Н. Каденко, В. К. Майданюк, Г. И. Применко, Р. В. Ермоленко

Измерены нейтронные сечения для изотопов тербия и лютеция с использованием нейтронно-активационного метода. Фольги из природного лютеция и тербия облучались нейтронами из нейтронного генератора NG-300/15. Для обеспечения прецизионности результатов были учтены эффекты каскадного суммирования и само-поглощения. Расчеты эффективности и поправочных факторов выполнены и использованием симуляции по методу Монте-Карло. Полученные результаты для реакции ^{175}Lu(n, α)^{172}Tm представлены впервые. Теоретические расчеты функций возбуждения выполнены с использованием кода Talys-1.0.

Received 27.06.08,
revised - 23.07.08.