CROSS SECTIONS OF (n, p), (n, α), (n, 2n) REACTIONS ON ISOTOPES OF Dy, Er, Yb AT E_n= 14.6 MEV

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Abstract

The cross sections of the neutron reactions at E_n= 14.6 MeV on the isotopes of Dy, Er, Yb with emission of neutrons, proton and alpha-particle were studied by the use of new experimental data and different theoretical approaches. New and improved experimental data were obtained by the neutron-activation technique. Present experimental results and evaluated nuclear data from EXFOR, TENDL, ENDF data libraries were compared with different systematics and calculations within codes of EMPIRE 3.0 and TALYS 1.2. Contribution of pre-equilibrium decay was studied. The recommendations on validity of different systematics for estimations of cross-sections of considered reactions are given.

1. Introduction

Studies of the nuclear reaction cross sections induced by neutrons provides an opportunity to get information on the excited states of atomic nuclei and nuclear reaction mechanisms [1]. In addition, nuclear reaction cross section data are necessary in applied applications such as the design of fusion reactors protection and modernization of existing nuclear power plants [2, 3]. In particular, they allow to calculate the activity and the degree of radiation damage to structural elements of nuclear reactors [3]. Practical interest in cross sections of nuclear reactions caused by their wide use in experimental nuclear physics methods, such as the method of boundary indicators in measuring the spectrum of neutrons in the reactor core of a nuclear reactor, or neutron activation analysis. Despite of large amount of information [4, 5] concerning neutron interactions with nuclei there are still problems with ambiguities and disagreements between available experimental data, evaluated data, different systematics and theoretical calculation by the different codes. An additional problem is the difference in the experimental data presented by different experimental groups and sometimes by the same group at different years [6].

In this paper, both experimentally and theoretically defined cross sections of reactions (n, p), (n, α), (n, 2n) on dysprosium, erbium and ytterbium isotopes at neutron energies near 14.6 MeV were compared. Experimental work is an extension and refinement of research carried out in [7-10]. Experimental results are compared with theoretical calculations using EMPIRE 3.0 [11], TALYS 1.2 [12] codes and with data from the latest versions evaluated nuclear data libraries: ENDF/B-VII, TENDL-2010, JENDL-4.0. To evaluate the cross sections of reactions (n, p), (n, α), (n, 2n) with neutron energy near 14.6 MeV is currently widely used empirical and semi-empirical formulas and approaches based on the systematics of experimental data for cross sections nuclear reactions [13 - 20]. In most situations, the parameters of systematic relationships were identified involving relatively limited number of experimental data, particularly with large errors [21]. The reliability of using the systematics [13-20] that describe cross sections of the reactions (n, p), (n, α) and (n, 2n) on isotopes of dysprosium, erbium and ytterbium was analyzed considering new obtained values.

2. Experimental technique

Nuclear reaction cross sections were defined by the neutron activation method [22] and as a neutron source was a neutron generator NG-300 [23]. The maximum neutron flux density at radiation position was determined experimentally and has the value $5.2 \cdot 10^8$ (1/см^2·с). During the experiments for neutron generation the mixed (D^+ - D_2^+) component of the ion beam with a maximum energy of ~ 225 keV was used. The samples with a natural mixture of isotopes were used at the experiment. Measurements were performed on three samples of dysprosium. The first two samples were in the form of disk size Ø 15,4 × 0,07 mm and have weigh 132 mg. Before irradiation they were studied for the presence of impurities (presence of another elements) using mass spectrometry analysis. Such impurities as Gd – 1.21%, Sc – 0.039%, Cu – 0.017% were detected and taken into account during calculation the number of nuclei in the studied samples. The third sample of dysprosium had the form of a cylinder with dimensions Ø 17.68 × 1.23 mm and the mass of 2.5158 g. The average neutron energy and its error was 14.6 ± 0.2 MeV. Sample of erbium had the form of a parallelepiped with dimensions 8.5 × 7.3 × 2.1 mm and with weigh 1.022 g. And the ytterbium sample had a cylindrical shape with a diameter of 17.6 mm, a height of 1.2 mm, and with weigh 1.9669 g.

Irradiation of the samples was carried out at an angle of 0 deg with respect to deuteron beam axis at the distance of 10 mm from the titanium-tritium target. The magnitude of the neutron energy was averaged over the sample and its variation was determined on the basis of several approaches: the first - through kinematic calculations using software code DROSG [26], the second - on the basis of experimental Zr / Nb method [27], and the third - using Monte Carlo calculations. In all calculations the effect of backscattered fast neutrons from structural elements of the neutron generator and from the walls of the experimental hall was taken into account. For this purposes the model of neutron generator was developed and neutron spectrum shape was calculated by MCNP4C code [24],. The real geometry of experiment, the information about the components of structural materials, geometric dimensions of the sample and its position relative to the titanium-tritium target of neutron generator were taken into account.

The γ-ray spectra of induced activity were measured with HPGe spectrometer (detector volume ~ 110 cm3). The energy resolution was 2.0 keV for γ-rays with energy 1332 keV corresponding to ^{60}Co decay and 0.9 keV for γ-rays with energy 122 keV, corresponding to the decay of ^{57}Co. The measurement time of γ- spectra varied from 5 min to 36 h. The neutron flux density at the irradiation position was measured using the ^{27}Al(n, α)^{24}Na reaction. The cross sections for each of reaction studied were determined by referring to the standard ^{27}Al(n, α)^{24}Na reaction [28]. Each specimen was sandwiched between two Al foils with 16 mm diameter and 0.1 mm thickness. During irradiation the neutron flux deviation was kept within ± 5 %. The nuclear reaction cross sections with their errors at fixed neutron energy was determined in [7].

3. Results of measurements and calculations of reaction cross sections

Cross section of the (n, 2n) reaction at the incident neutron energy region of 14.6 MeV for the isotopes of Dysprosium was calculated by different systematics (Konobeyev, Lu and Fink) [13, 16], nuclear codes (EMPIRE 3.0 [11], TALYS 1.2 [12]) and was compared from the experimental data (EXFOR [7], data from this work [7-10]), evaluated data (TENDL-2010, ENDF/B-VII.0) are presented in Fig. 1. Calculations of the reaction cross section using the EMPIRE 3.0 code were carried out taking into account pre-equilibrium exciton model processes (PCROSS = 1,5) and without pre-equilibrium processes (PCROSS = 0). The nuclear level density was calculated by generalized superfluid model of the nucleus and the global optical potential of Koning-Delaroche [29] was used. In calculations using the TALYS 1.2 code the standard set of default parameters was used. Here and after, for greater clarity, the values of nuclear reaction cross sections were shows as a function of the number of neutrons. For some reactions also specified some residual nucleus such as ^{157g}Dy (disprosium in ground state) and ^{157m}Dy (disprosium in metastable state). The value of the measured nuclear reaction cross section for the isotope ^{158}Dy within errors coincides with the available experimental data. The cross section for the ^{156}Dy isotope is smaller, however, coincides with the value taken from the TENDL-2010 library. The values of the reaction cross section (n, 2n) for Dy isotopes increase with the increasing the number of neutrons. Determination of the nuclear reaction cross section (n, 2n) has one feature. Pre-equilibrium components reduce the value of nuclear reaction cross section (n, 2n) at the expense of increasing the likelihood of competing reactions.

Cross sections of the (n, p) reaction at the incident neutron energy region of 14.6 MeV for the isotopes of Dysprosium are shown Fig. 2.. Products of the nuclear reaction (n, p) such as ^{160}Tb, ^{162}Tb, ^{163}Tb were determined in this work. The value of the reaction cross section differs by five times for the case of calculations with and without pre-equilibrium process. Nuclear reaction cross section (n, p) increases in the case of the use pre-equilibrium process. Nuclear reaction cross section (n, p) decreases with the increasing of number of neutrons in the parent nucleus of dysprosium. Reaction cross sections calculated by EMPIRE 3.0 code using pre-equilibrium processes have better agreement with experimental data than the TALYS 1.2 code calculation with the default set of parameters. The systematic of Konobeyev has better agreement with experimental data than other ones.

Fig. 2 also contains new experimental cross section of the ^{156}Dy(n, p)^{156}Tb reaction, which absent at EXFOR database[6]. This value has a very good agreement with all systematic, evaluated data and theoretical calculation except of EMPIRE 3.0. This magnitude seems to be situated a little bit lower than other ones.

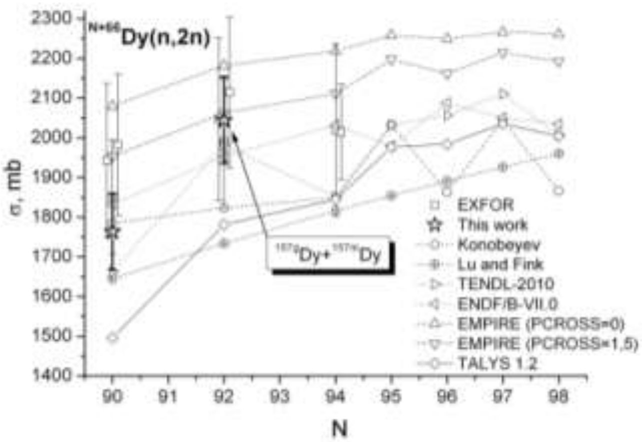

Fig. 1 The (n, 2n) reaction cross sections for the isotopes of Dysprosium

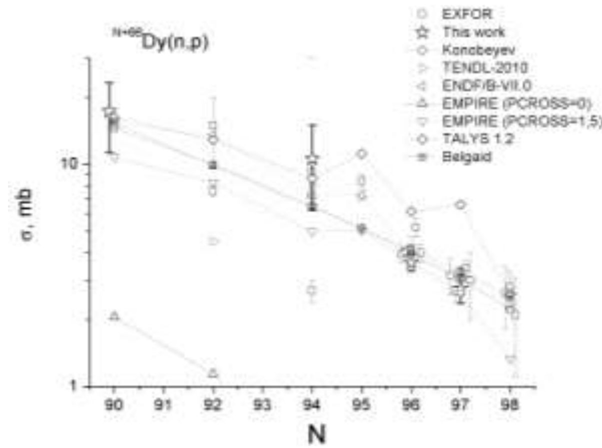

Fig. 2 The (n, p) reaction cross sections for the isotopes of Dysprosium

Cross section of the (n, α) reaction at the incident neutron energy region of 14.6 MeV for the isotopes of Dysprosium are shown on Fig. 3. Cross section of the ^{164}Dy is located between the available experimental data values of the cross sections. This discrepancy between the experimental data is making difficulty to produce the evaluated nuclear data bases, their systematics and requires further analysis. Nuclear reaction cross section (n, α) increases in the case of the use pre-equilibrium process. Nuclear reaction cross section (n, α) decreases with the increasing of number of neutrons in the parent nucleus of dysprosium.

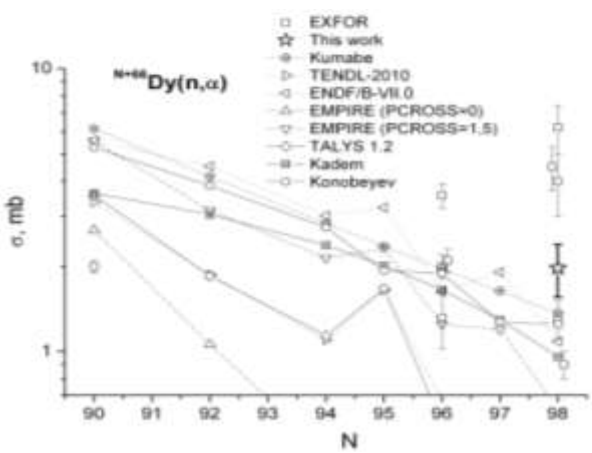

Fig. 3 The (n, α) reaction cross sections for the isotopes of Dysprosium

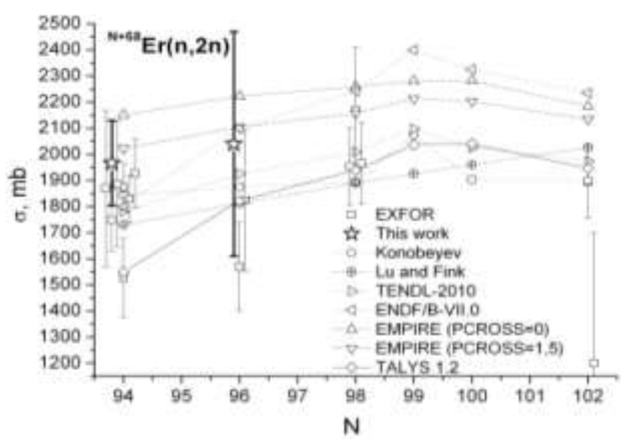

Fig. 4 The (n, 2n) reaction cross sections for the isotopes of Erbium

Cross section of the (n, 2n) reaction at the incident neutron energy region of 14.6 MeV for the isotopes of Erbium is shown on Fig. 4. Reaction (n, 2n) for the Er isotopes is analogical for the case of reaction (n, 2n) on Dy isotopes. There is a good agreement between our nuclear reaction cross sections and data of other authors, evaluated data, the results of calculations (by EMPIRE 3.0 code), systematics.

Cross section of the (n, p) reaction at the incident neutron energy region of 14.6 MeV for the isotopes of Erbium is shown on Fig. 5. Measured cross section for ^{162}Er(n, p)^{162}Ho nuclear reaction is to be considered as original data and could be used for nuclear databases updating. Cross sections for ^{167}Er(n, p)^{167}Ho, ^{168}Er(n, p)^{168}Ho nuclear reactions were measured with higher precision than previous ones defined.

Cross section of the (n, α) reaction at the incident neutron energy region of 14.6 MeV for the isotopes of Erbium is shown on Fig. 6. Nucleus, product of the (n, α) reaction, ^{165}Dy have been measured in metastable ^{165m}Dy and ground ^{165g}Dy states both separately and together ^{165m}Dy +^{165g}Dy.

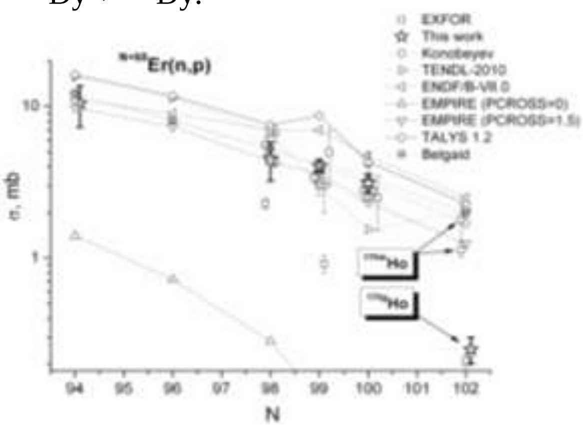

Fig. 5 The (n, p) reaction cross sections for the isotopes of Erbium

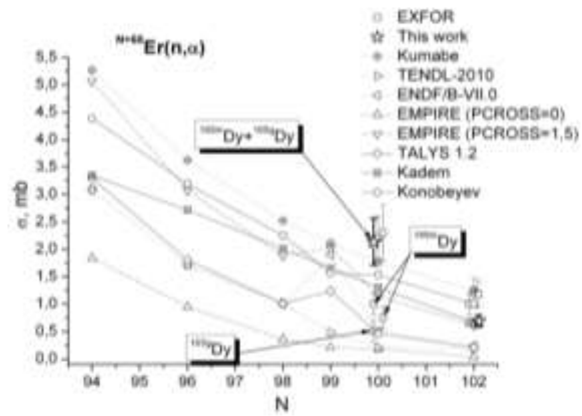

Fig. 6 The (n, α) reaction cross sections for the isotopes of Erbium

Cross section of the (n, 2n) reaction at the incident neutron energy region of 14.6 MeV for the isotopes of Ytterbium is shown on Fig. 7. Acceptable agreement between experimental data on the ^{168}Yb and ^{170}Yb isotopes was observed. But for the nucleus ^{176}Yb the difference between experimental and evaluated nuclear reaction cross section is presented.

Cross section of the (n, p) reaction at the incident neutron energy region of 14.6 MeV for the isotopes of Ytterbium is shown on Fig. 8. New cross section for the reaction ^{172}Yb(n, p)^{172}Tm is presented. There is no such experimental data at EXFOR database. This new cross section is located closer to the calculation of the EMPIRE 3.0 with pre-equlibrium processes, also close to the systematics of Konobeyev and Belgaid.

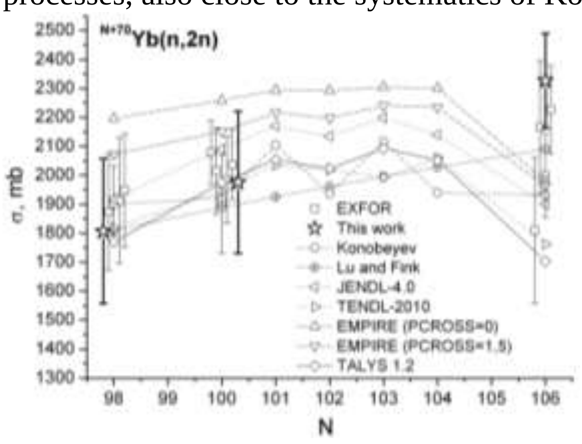

Fig. 7 The (n, 2n) reaction cross sections for the isotopes of Ytterbium

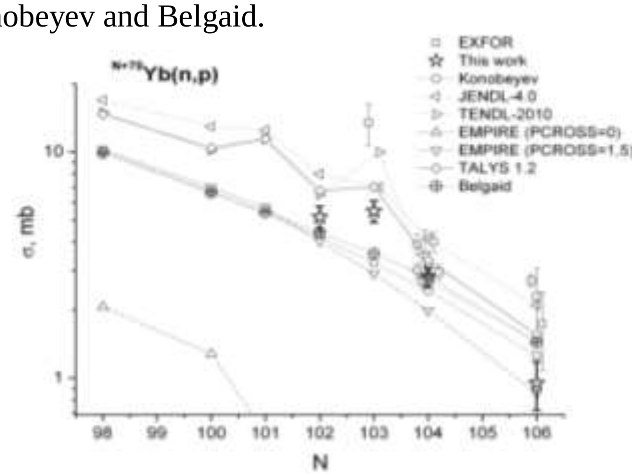

Fig. 8 The (n, p) reaction cross sections for the isotopes of Ytterbium

Cross section of the (n, α) reaction at the incident neutron energy region of 14.6 MeV for the isotopes of Ytterbium is shown on Fig. 6. Our results of the nuclear reaction cross sections were measured with higher precision and they are in accordance with systematics of Konobeyev and Kadem.

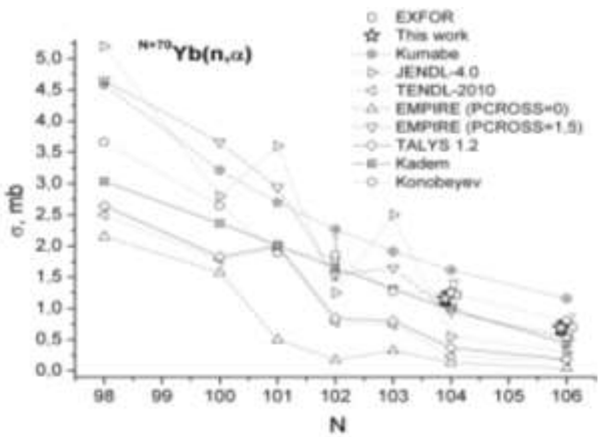

Fig. 9 The (n, α) reaction cross sections for the isotopes of Ytterbium

4. Conclusions

Cross section of the nuclear reactions (n, p), (n, α), (n, 2n) were measured on isotopes of dysprosium, erbium and ytterbium at the neutron energies 14.6 ± 0.2 MeV. Obtained results were compared with available experimental data, evaluated nuclear data and the results of theoretical calculations. In most cases, the measured in this work data agreed within errors with the available experimental data. Calculated values of the reaction cross sections using EMPIRE 3.0 code with considering pre-equilibrium processes better describe experimental data than the calculations using TALYS 1.2 code with default set of parameters, therefore, for estimation of the nuclear reaction cross section in this masses nuclei region can be recommended EMPIRE 3.0 code calculation. Konobeyev and Belgaid systematics are the most agreed with available experimental data and recommended for use. Presented results can be utilized in the field of nuclear energy applications as well as in a testing of nuclear reaction models.

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