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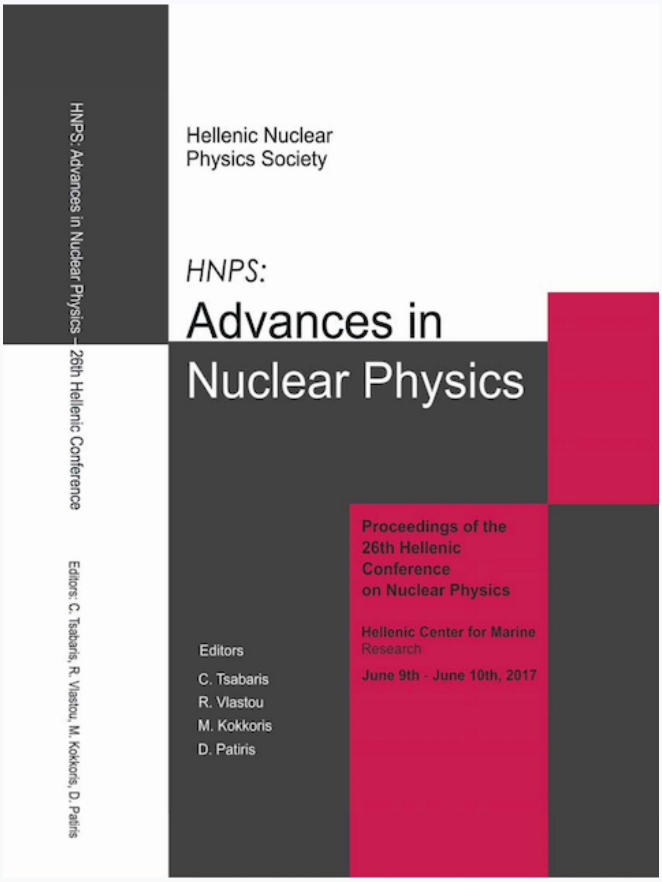

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Study of the ^{162}Er(n,2n)^{161}Er reaction from the reaction threshold up to 19 MeV neutron beam energy

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Abstract Within the present work the ^{162}Er(n,2n)^{161}Er reaction was studied. Experimental data were obtained by means of the Activation Technique for the first time at near threshold energies between 10.7-11.3 MeV, as well as at a higher energy region between 17.1-19.0 MeV. The quasi-monoenergetic neutron beam at the near threshold energies was produced by means of the ^{2}H(d,n)^{3}He reaction, whereas for the higher energies the ^{3}H(d,n)^{4}He reaction was used because of its higher Q-value. The primary deuteron beam was delivered in both cases from the 5.5 MV Tandem Van de Graaff accelerator of the Institute of Nuclear and Particle Physics at N.C.S.R "Demokritos". Along with the experimental determination of the cross section, theoretical calculations were performed with different statistical calculation codes, which show a rather reduced contribution, with respect the expected one, of the pre-equilibrium mechanism to the (n,2n) channel.

Keywords Activation Technique, quasi-monoenergetic neutron beam, cross section

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INTRODUCTION

Neutron induced reactions study and the comparison between experimental and theoretical calculations are important for basic research purposes as well as for the development and improvement of many applications.

In the domain of the Nuclear Physics Technology, the last decades it is an issue of concern the continuously increasing energy needs in combination with the imperative need for energy production with decreased Greenhouse gases emission [1]. Towards to this direction, nuclear energy can play a significant role, as nuclear reactors can substitute the fossil fuels and provide a long-term solution to the increasing future energy demands. Moreover, the 4th Generation fast neutron reactors and the ADS accelerators, which operate in the fast neutron spectrum, decrease the limitations of the nuclear energy use, as they lead to the incineration of the radioactive waste produced and to the decrease of a nuclear accident

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possibility [2-3]. Therefore, the upgrading of the existing nuclear data libraries at the fast neutron energies with accurate experimental information is of primary importance. Specifically, the reaction cross sections have to be accurately determined for alternative fissile isotopes as well as for reactor structural materials and neutron-economy control isotopes. Erbium along with other rare-earth elements is one of the possible neutron absorbers to be used in future nuclear energy systems.

The $^{162}Er(n,2n)^{161}Er$ reaction is still in a primitive stage of study. The only available experimental data, according to our knowledge, are limited in the energy range between 13.5-15 MeV and the discrepancies among them are even 30 % [4], fact which inhibits the accurate benchmarking of the theoretical calculations.

EXPERIMENTAL SETUP AND METHOD

ACTIVATION TECHNIQUE

The $^{162}Er(n,2n)^{161}Er$ reaction cross section was determined at the 6 energies of 10.7 MeV, 11.0 MeV, 11.3 MeV, 17.1 MeV, 18.1 MeV and 19.0 MeV by means of the Activation Technique. The cross section formula is given via the equation:

$$\sigma = \frac{A}{N_T \Phi \varepsilon I_\gamma (1 - e^{-\lambda t_m}) e^{-\lambda t_w} f_b}$$

where A is the induced Activity in the erbium sample, Φ is the neutron beam flux, ε is the detector efficiency at the γ-ray energy emitted by the activated nucleus, I is the intensity of the γ-ray and N_T is the initial number of nuclei in the sample. The t_m and t_w parameters correspond to activity measuring time and the waiting time between the end of the irradiation and the start of the activity measurement. The correction factor for the simultaneous decay and production of the activated nuclei is denoted as f_b.

For the flux determination of the neutron beams three reference reactions were used: $^{27}Al(n,\alpha)^{24}Na$, $^{197}Au(n,2n)^{196}Au$ and $^{93}Nb(n,2n)^{92m}Nb$. These reactions have well-known cross sections at the energies of interest, so that the flux Φ was determined as the inverse solution of the previous formula.

The unstable nuclei produced by the reactions, their half-life times, the γ-ray energies emitted and their respective intensities are summarized in Table 1 [5]:

Target-nucleus	**Product-nucleus**	**$T_{1/2}$**	**Eγ (keV)**	**I (%)**	**σ_I (%)**
^{162}Er	^{161}Er	3.21 h	826.6	64	4
^{27}Al	^{24}Na	14.997 h	1368.626	99.9936	0.0015
^{197}Au	^{196}Au	16.1669 d	333.03	22.881	0.946
^{93}Nb	^{92m}Nb	10.15 d	934.44	99.15	-

Table 1. Decay characteristics of the product-nuclei.

IRRADIATION SETUP

The six irradiations were performed at the 5.5 MV Tandem Van de Graaff accelerator of the Institute of Nuclear and Particle Physics at N.C.S.R "Demokritos".

The quasi-monoenergetic neutron beam at the near threshold energies of 10.7, 11.0 and 11.3 MeV was produced via the $^{2}H(d,n)^{3}He$ reaction (Q-value=3.26 MeV). The deuterium beam was directed and focused to a deuterium gas target with beam current between 2.5-3 μA. During the irradiations the gas target pressure was kept constant at 1250 mbar. The samples were placed at the distance of the 7 cm from the gas target and at 0^{o} with respect to the primary deuterium beam.

The production of neutron beams with energies equal to 17.1, 18.1 and 19.0 MeV was achieved via the $^{3}H(d,n)^{4}He$ reaction (Q-value=17.6 MeV). The deuterium beam bombarded a solid tritium titanium target (TiT). Tritium was absorbed by the titanium layer with nuclei ratio T/Ti=1.543. The use of a Cu foil backing the tritium target served the heat conduction purposes. The samples were situated in the distance of 2 cm from the solid target and at 0^{o} with respect to the primary deuterium beam.

In order to detect the neutron intensity fluctuations a BF_3 detector was placed at the distance of 3 m from the D_2 gas and the TiT solid targets respectively. The BF_3 detector is a proportional gas counter. The pulses generated were recorded by a Multi-channel-Scaler every 60 s. The BF_3 detector was placed inside a paraffin barrel so as moderate the neutrons and enhance the detector's efficiency. The history files recorded were used for the accurate estimation of the f_b correction factor.

Each irradiation lasted about 10 hours so as to cover the 3 half-life times of ^{161}Er decay (=3.21 h).

Two erbium samples were used at the irradiations of 1 gr in mass, 13 mm in diameter and 2 mm in thickness. The Er was present in the samples in the powder form of Er_2O_3 with its natural composition. The pellets consisted of a mixture of 90% Er_2O_3 and 10% Cellulosepulver for mechanical support.

γ-RAY ACTIVITY MEASUREMENTS

After the end of the irradiations the induced activity of the erbium sample was measured in a dedicated off-line γ-ray detection set-up.

For the activity measurements of the erbium sample two HPGe detectors with 100 % relative efficiency were used. The detectors were carefully gain matched, so as to operate as one detection system, and were placed face to face at the close distance of 2 cm. The erbium sample was placed at the middle of this distance in order to cover a 4π solid detection angle. The close detection geometry was instrumental, given the minimal abundance of ^{162}Er (0.139 %), so as to maximize the γ-ray detection efficiency. Despite the close detection geometry it has to be underlined that the coincidence summing effects were negligible, due to the fact that the 826.6 keV γ-ray emitted by the ^{161}Er is the strongest one and it goes directly to the ground state (multiplicity=1within 99%).

The detectors were calibrated by means of the monoenergetic point source of ^{54}Mn. ^{54}Mn was adopted as a calibration source because it decays by emitting a γ-ray at 834.8 keV. This energy is very close to the 826.6 keV, which is the γ-ray energy emitted by ^{161}Er, so as to can be considered that the detectors efficiencies at these two energies are almost equal. Also being a monoenergetic and weak source, no coincidence summing, as well as dead-time and pile-up effects needed to be handled.

The reference foils activity was measured using a HPGe detector with 16% relative efficiency. The reference foils were placed at the distance of 7 cm with respect to the detector's window. In this way it was ensured that the measurements were free from coincidence summing effects.

The efficiency calibration of the 16% relative efficiency HPGe detector was achieved using a ^{152}Eu point source, which decays by emitting γ-rays in a wide energy range. In this way the detection needs for the used reference foils were covered.

DATA ANALYSIS

The neutron flux at the erbium target was determined as the mean value of the neutron fluxes at the front and back foil, whereas its uncertainty was 7%. The results are concluded in Table 2.

En (MeV)	Φ (n/cm^2)	σ_Φ (n/cm^2)
10.7	1.29E+10	0.09E+10
11.0	7.50E+10	0.53E+10
11.3	1.09E+10	0.08E+10
17.1	1.23E+10	0.09E+10
18.1	1.07E+10	0.07E+10
19.0	0.95E+10	0.07E+10

Table 2. Neutron beam flux at the erbium target for each irradiation.

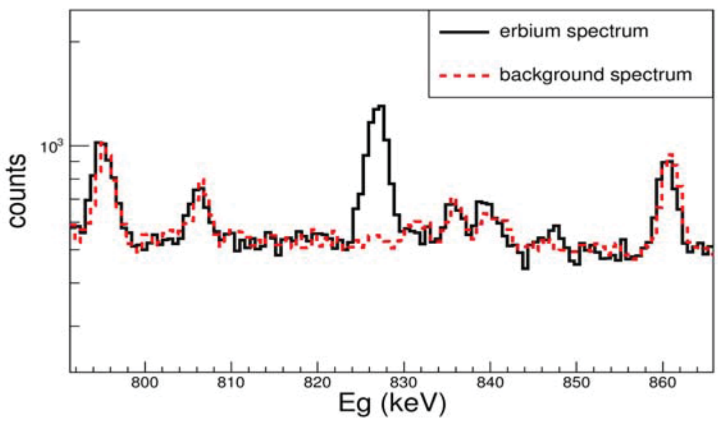

Fig. 1. Erbium spectrum for En=11.0 MeV and 10 h of measurement along with the respective background spectrum.

The ^{161}Er activity was determined through the photo-peak at the 826.6 keV. In Fig. 1 one characteristic spectrum of the peak for the irradiation of 11.0 MeV neutron energy and for 10 h of activity measurement is presented along with the respective background spectrum. By the comparison of these two spectra it can be concluded that the 826.6 keV is free of contaminations.

RESULTS

The (n,2n) reaction cross section on ^{162}Er was measured for a first time at the energies of 10.7 MeV, 11.0 MeV, 11.3 MeV, 17.1 MeV, 18.1 MeV and 19.0 MeV. The results along with the previous experimental data are presented in Fig. 2.

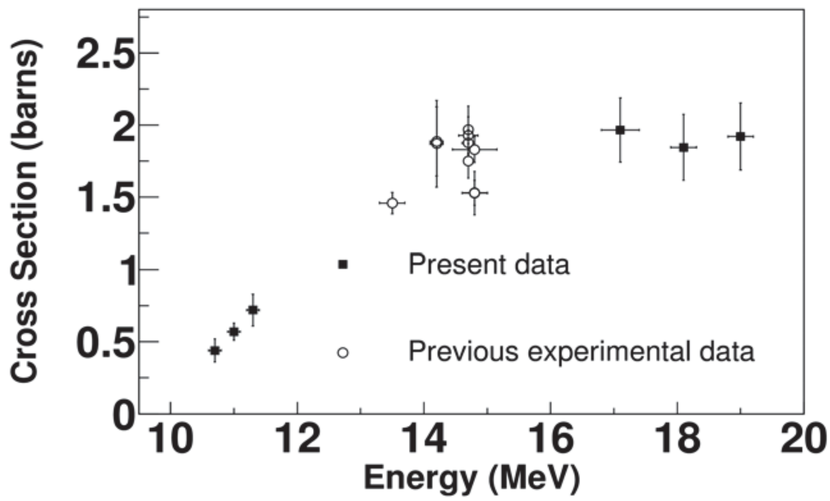

Fig. 2. The experimental data accrued from this work along with previous experimental data.

THEORETICAL CALCULATIONS

For the theoretical estimation of the ^{162}Er(n,2n)^{161}Er reaction cross section extended theoretical calculations have been performed with Talys [6] and Empire [7] nuclear reactions simulation softwares, as well as with the code MECO [8].

In the neutron interaction with the ^{162}Er nucleus the Compound Nucleus Mechanism prevails. In the Talys code the Compound Nucleus cross section calculations were performed in the framework of the Hauser-Feshbach theory. For the optical model potential the parameterization of Koning and Delaroche was used [9]. The Constant temperature and Fermi Gas model was implemented for the density model parametrization. The theoretical calculations have been performed for global parameters as well as by making a fit to the data by changing the global value of the shell effects damping parameter γ. The γ parameter has a global value about equal to 0.43 and it was changed to 1. For this value the theoretical calculations reproduce the experimental data. Both calculations correspond to totally deactivated pre-equilibrium contribution, as this choice describes better the high energy part of the excitation function.

The calculations with the Empire code were performed for the optical model potential of Varner [10] and the Generalized Superfluid Model for the level densities. In the calculations the contribution of the pre-equilibrium mechanism was considered reduced so as to describe better the high energy part.

In the code MECO neutron absorption from the ^{162}Er target was calculated with the optical model using the parameters reported by Koning and DeLaroche [9]. The compound nucleus deexcitation was calculated according to the Weisskopf formalism. Level densities were calculated with the composite formula of Gilbert and Cameron [11]. Emission of neutrons, protons and alphas was taken into account with transmission coefficients derived from optical model calculations with global parameters from Refs. [12-14]. Pre-equilibrium neutron emission was not considered, since it seemed to play a minor role in the calculated cross sections in accordance with the previously mentioned calculations as well as with the experimental data.

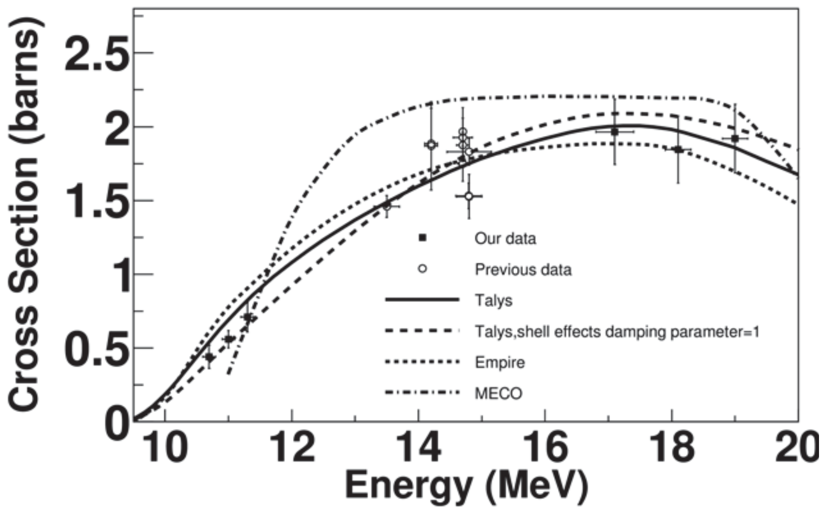

Fig. 3. The experimental data accrued from this work and the previous experimental data along with the theoretical calculations.

CONCLUSIONS

The experimental data along with the theoretical calculations map for the first time the excitation function of the ^{162}Er(n,2n)^{161}Er reaction. Through the comparison of the experimental data with theoretical calculations it can be concluded that the role of the pre-equilibrium reaction mechanism in the (n,2n) reaction is reduced.

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