Cross Sections of Neutron Reactions \((n, p)\), \((n, \alpha)\), \((n, 2n)\) on Isotopes of Dysprosium, Erbium and Ytterbium at \(\sim 14\) MeV Neutron Energy

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The cross sections of the nuclear reactions induced by neutrons at \(E_n = 14.6\) MeV on the isotopes of Dy, Er, Yb with emission of neutrons, proton and alpha-particle are studied by the use of new experimental data and different theoretical approaches. New and improved experimental data are measured by the neutron-activation technique. The experimental and evaluated data from EXFOR, TENDL, ENDF libraries are compared with different systematics and calculations by codes of EMPIRE 3.0 and TALYS 1.2. Contribution of pre-equilibrium decay is discussed. Different systematics for estimations of the cross-sections of considered nuclear reactions are tested.

I. INTRODUCTION

Studies of the nuclear reaction cross sections induced by neutrons provide information on the properties of excited states of atomic nuclei and nuclear reaction mechanisms [1]. Data on nuclear reaction cross section are also needed in applications, specifically, such as the design of fusion reactor protection and modernization of existing nuclear power plants [2, 3]. Despite of a large amount of information [4] on observed characteristics of neutron interactions with nuclei, there are disagreements between existing experimental data and evaluated data both within different systematics and calculations by the different codes.

In this contribution, experimental and theoretical cross sections of reactions \((n, p)\), \((n, \alpha)\), \((n, 2n)\) on Dy, Er and Yb isotopes at neutron energies near 14.6 MeV are determined and compared. Neutron generator (NG-300), installed in Nuclear Physics Department of Taras Shevchenko National University of Kyiv, was used as a source of neutrons with \(E_n = 14.6 \pm 0.2\) MeV. The neutron activation method was applied for measurements of the cross-sections (see [5, 6] for details). Theoretical calculations were performed by the EMPIRE 3.0 and TALYS 1.2 codes [7, 8]. The experimental cross-sections were also compared with data from the latest versions of evaluated neutron data libraries: ENDF/B-VII, TENDL-2010, JENDL-4.0. The reliability of the different systematics [9-15] for estimation of the nuclear reaction cross-sections on isotopes of Dy, Er and Yb was analyzed.

II. RESULTS OF MEASUREMENTS AND CALCULATIONS

Figure 1 shows cross sections of the \((n, 2n)\), \((n, p)\), \((n, \alpha)\) reactions on the isotopes of Dy as a function of the number of neutrons \(N\) and metastable \(m\) states. The residual nuclei are additionally indicated on this and next figures. Calculations of the nuclear reaction cross sections by the EMPIRE 3.0 code were performed with and without including pre-equilibrium processes (PCROSS = 1.5 and 0). For nuclear level density, the generalized superfluid model was taken. In calculations by the TALYS 1.2 code default parameters were set. It can be seen, that the measured \((n,2n)\) cross section on the \(^{158}\)Dy \((N=92)\) with allowance for uncertainties coincides with the available experimental data. The measured \((n,2n)\) cross section on the \(^{156}\)Dy \((N=90)\) is less than previous ones, but it coincides with evaluated value from the TENDL-2010 library. The \((n, 2n)\) cross sections on Dy isotopes increase with the neutron number increasing.

The allowance for pre-equilibrium processes leads to strong increasing the \((n, p)\) cross sections (approximately in five times). A behavior of the \((n, 2n)\) cross sections is opposite, and pre-equilibrium emission reduce the values of these cross sections mainly due to increase cross-sections of competing binary reactions with emission of charge particles.

On the whole, the results of calculations by EMPIRE 3.0 code with allowance for pre-equilibrium processes are in best agreement with experimental data. For calculations using different systematics, the results according to [11] are more suited for description of the experimental data.
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Cross sections of the \((n, 2n)\), \((n, p)\) and \((n, \alpha)\) reactions on the isotopes of Dysprosium.

FIG. 1. Cross sections of the \((n, 2n)\), \((n, p)\) and \((n, \alpha)\) reactions on the isotopes of Dysprosium.

Cross sections of the \((n, 2n)\), \((n, p)\), \((n, \alpha)\) reactions on the Er isotopes are given on figure 2. Cross sections of \((n, 2n)\) reaction on the Er isotopes have the similar peculiarities as on Dy. There is a rather good agreement between presented measurements and the results of other authors.

Figures 3-5 show cross section of the \((n, 2n)\), \((n, p)\), \((n, \alpha)\) reactions the isotopes of Yb. Rather good agreement between experimental data for the \(^{168}\text{Yb}\) and \(^{170}\text{Yb}\) isotopes (\(N = 98\) and \(100\)) is observed for \((n,2n)\) reaction, but presented cross section on \(^{176}\text{Yb}\) (\(N = 106\)) is placed higher. The cross section of the reaction \(^{172}\text{Yb}(n, p)^{172}\text{Tm}\) \((N=102)\) calculated by the EMPIRE 3.0 with pre-equilibrium processes is agree better with measured value. The results of calculation using systematics from [10, 12] is also closer to measured one. The cross sections of the \((n,\alpha)\) reaction were measured with higher precision and they agree better with calculation by systematics from [14, 15].

III. CONCLUSIONS

The results of measurements of the cross sections of the nuclear reactions \((n, p)\), \((n, \alpha)\), \((n, 2n)\) on isotopes of Dy, Er and Yb at the neutron energy \(14.6 \pm 0.2\) MeV...
FIG. 3. Cross sections of the (n, 2n) reaction on the isotopes of Ytterbium.

FIG. 4. Cross sections of the (n, p) reaction on the isotopes of Ytterbium.

FIG. 5. Cross sections of the (n, $\alpha$) reaction on the isotopes of Ytterbium.

are presented. They were compared with available experimental data, evaluated nuclear data and the theoretical calculations by the EMPIRE and TALYS codes. In the most cases, the presented data correlate well with available experimental data. On the whole, the cross sections calculated by the EMPIRE 3.0 code with pre-equilibrium processes agree better with experimental data than the results obtained by TALYS 1.2 code with default set of parameters. Amongst the systematics, the cross section values calculated by expressions from [10, 12] are more consistent with measured cross-sections.

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