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# NEW DIRECTION IN NUCLEAR PHYSICS ORIGINATED FROM THE NEUTRON ACTIVATION TECHNIQUE APPLICATION[*]

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The neutron activation technique is utilized to determine activation cross-section values for neutron-induced reactions on Lu, Tb, Dy, Er and Yb isotopes with application of in-home designed and manufactured neutron generator NG-300 and AMANDE facility within $3.5\div14.7$ MeV energy range of incident neutrons. Observation of the dineutron in the output channel of nuclear reaction on Tb is discussed. The cross-section estimate for the reaction with a dineutron escape for 6.85 MeV equals $75\pm30$ mb and is presented for the first time.

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## 1. Introduction

The neutron activation techniques have been widely used for decades to solve both fundamental and other tasks with application of neutrons of different energies. Among others, neutron generators represent a very convenient instrument to irradiate samples of interest with neutrons of certain energy to further analyze the neutron-induced nuclear reaction products due to interaction of neutrons with nuclei in the irradiated sample. The idea to use the fusion reaction between the deuterium and the tritium as a source of high enough energy neutrons was published in [1] for the first time and then was widely disseminated. Therefore, neutron generators based on utilization of ($d$–$d$) or ($d$–$t$) nuclear reactions to generate neutrons and determine a composition of a sample or cross section of nuclear reactions provide a basis to carry out research or to develop some practical tasks. The Department of Nuclear Physics of Taras Shevchenko National University of Kyiv,

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Ukraine, was established on September 1, 1945 by the prominent scientist Prof. A. Leipunsky, who initiated the development of neutron generators and physics of fast neutrons in Ukraine. In this paper, the results of the neutron activation technique application for the determination of the $(n,x)$ nuclear reactions cross sections on some rare earth elements are presented and discussed.

## 2. Experiments with 14-MeV neutrons

Several models of neutron generators were designed and manufactured at the Department of Nuclear Physics of Taras Shevchenko National University of Kyiv, Ukraine. One of them, NG-300, was developed to provide neutron output up to $10^{11}$ $n$/s with deuterium beam current up to 8 mA, and to serve as a neutron source. For the last ten years, we have studied neutron-induced nuclear reactions on rare earth elements with application of the neutron activation technique. Our elements of interest were Tb and Lu [2]. For the first of these two elements, the following reactions were thoroughly investigated: $^{159}\mathrm{Tb}(n,2n)^{158m+g}\mathrm{Tb}$; $^{159}\mathrm{Tb}(n,\alpha)^{156}\mathrm{Eu}$; $^{159}\mathrm{Tb}(n,p)^{159}\mathrm{Gd}$; $^{159}\mathrm{Tb}(n,n'\alpha)^{155}\mathrm{Eu}$. First and second reaction of listed above with cross sections 1,913 ± 60 mb (14.6 MeV) and 2.2 ± 0.3 mb (14.6 MeV) accordingly, were used as "the probing reactions" to make sure that all the steps of our neutron activation technique are implemented in a proper way. A very good correspondence of our cross-section results and the measurement results of other groups was used as a proof of correctness of our experimental technique [2].

For the other two reactions, the early available cross-section data were either uncertain or missing at all [2]. Therefore, our results contributed to filling in the corresponding gaps in nuclear data. Thus, our cross-section estimate for $^{159}\mathrm{Tb}(n,p)^{159}\mathrm{Gd}$ nuclear reaction allowed to clearly decide in favor of 4.8 ± 0.5 mb (14.6 MeV) value. As for $^{159}\mathrm{Tb}(n,n'\alpha)^{155}\mathrm{Eu}$ nuclear reaction cross section, our estimate in 40 ± 20 $\mu$b (14.6 MeV) was obtained for the first time and turned out to be about one order less of the lower level estimate available in EXFOR database.

Similarly, for Lu element, the reaction $^{175}\mathrm{Lu}(n,2n)^{174m,g}\mathrm{Lu}$ with corresponding cross sections proved the correctness of our experimental technique, and by the $^{176}\mathrm{Lu}(n,\alpha)^{173}\mathrm{Tm}$ nuclear reaction with our cross-section estimate in 1.63 ± 0.34 mb (14.6 MeV), we confirmed the evaluated data. For $^{175}\mathrm{Lu}(n,\alpha)^{172}\mathrm{Tm}$, we got an estimate of this reaction cross section which equals 1.00 ± 0.03 mb (14.2 MeV) for the first time.

Following our specific interest for rear earth elements, we expanded the area of our research to the even proton number nuclides of Dy, Er and Yb [3]. Our measurements of 14-MeV neutron-induced nuclear reaction cross sections resulted in a very good agreement for $^{156}\mathrm{Dy}(n,2n)^{155}\mathrm{Dy}$

and $^{158}\mathrm{Dy}(n,2n)^{157(m+g)}\mathrm{Dy}$ reactions with other experimental data available. For the reaction $^{156}\mathrm{Dy}(n,p)^{156}\mathrm{Tb}$, our estimate of the cross section equals 17.3 ± 6.0 mb (14.7 MeV) and was obtained for the first time [3].

For measurements on Er isotopes, again, our experimental results were helpful to disambiguate cross-section data for $^{170}\mathrm{Er}(n,p)^{170g}\mathrm{Ho}$ and $^{168}\mathrm{Er}(n,p)^{168(m+g)}\mathrm{Ho}$ nuclear reactions and to present a new estimate for the $^{162}\mathrm{Er}(n,p)^{162(m+g)}\mathrm{Ho}$ reaction cross section which equals 10.5 ± 3.2 mb (14.7 MeV) [3].

Beside the other very well proven results for 14-MeV neutron-induced reactions on Yb isotopes, we have conducted a measurement for $^{176}\mathrm{Yb}(n,n'\alpha)^{172}\mathrm{Er}$ reaction channel [3]. One of the available estimates for this reaction was published in [4] and reported as 0.7 ± 0.2 mb. Our very carefully performed measurement with many aspects of low-level measurements addressed gave us a chance to derive a value which is more than one order of magnitude lower and equals 0.015 ± 0.005 mb. The nuclear reaction $(n,n'\alpha)$ for rare earth elements is of specific interest due to the complex mechanism of this reaction and low values of reaction cross sections measured by us on $^{159}\mathrm{Tb}$ and $^{176}\mathrm{Yb}$ isotopes. Therefore, based on our experimental results, we used TALYS-1.2 code [5] to calculate the corresponding reaction cross-section values for 14-MeV neutrons in input channel and to fix the parameters of TALYS code to make estimates of reaction cross sections for other rare earth isotopes. This was done in our paper [6] with certain parameters of TALYS code.

Then, with these parameters set, we were able to very well reproduce our experimental results and to obtain some other reaction cross-section estimates. All the results are summarized in Table I below. From these results, it follows that the neutron activation technique developed at the Department of Nuclear Physics can be used for reliable determination of some reaction cross sections at the level of 10 $\mu$b and greater.

TABLE I

Cross-section data for $(n,n'\alpha)$ reactions on some rare earth isotopes.

| No. | Reaction | Our experimental data [mb] | Calculation result [mb] | Literature data [mb] |
|---|---|---|---|---|
| 1. | $^{159}\mathrm{Tb}(n,n'\alpha)^{155}\mathrm{Eu}$ | 0.04 ± 0.02 | 0.050 | $< 0.3$ [4] |
| 2. | $^{176}\mathrm{Yb}(n,n'\alpha)^{172}\mathrm{Er}$ | 0.015 ± 0.005 | 0.013 | $0.7 \pm 0.2$ [4] |
| 3. | $^{166}\mathrm{Ho}(n,n'\alpha)^{162}\mathrm{Tb}$ | — | 0.030 | $0.18 \pm 0.06$ [4] |
| 4. | $^{169}\mathrm{Tm}(n,n'\alpha)^{165}\mathrm{Ho}$ | — | 0.115 | N/A |

## 3. Experiments with lower energy neutrons

With a very well developed and validated neutron activation technique, another experiment was planned to measure reaction cross-section values for $^{159}\mathrm{Tb}(n,\gamma)^{160}\mathrm{Tb}$ nuclear reaction channel within 3.5–7.0 MeV neutron energy. Actually, neutron capture cross-section measurements are always difficult to carry out due to possible significant contribution of scattered and low-energy neutrons that may cause a significant systematic bias of the reaction cross-section estimates. To avoid as many as possible sources of potential errors, the measurements were conducted at AMANDE facility at IRSN, Cadarache [7]. This up-to-date neutron source is an excellent instrument to derive highly reliable reaction cross-section data to be further proved with TALYS calculations [8]. New reaction cross sections and corresponding TALYS calculation results are given in Table II below.

TABLE II

Measured and calculated cross-section data for the $^{159}\mathrm{Tb}(n,\gamma)^{160}\mathrm{Tb}$ nuclear reaction.

| No. | Neutron energy [MeV] | Our experimental data [mb] | Calculation result [mb] |
|---|---|---|---|
| 1. | 3.67 | $30.8 \pm 2.2$ | 29.54 |
| 2. | 4.28 | $21.8 \pm 1.8$ | 22.38 |
| 3. | 5.35 | $6.13 \pm 0.55$ | 8.20 |
| 4. | 6.85 | $2.14 \pm 0.83$ | 2.20 |

As one can see from neutron capture cross-section results on $^{159}\mathrm{Tb}$, the overall agreement between the model calculations and the experimental data is good. For the 6.85 MeV measurement of the reaction cross section, a Tb sample of 28.9 g mass was used because of low value of neutron capture reaction cross section.

**Observation of the dineutron**. One year after the last 6.85 MeV neutron irradiation, the same Tb sample was placed on HPGe detector for about two weeks instrumental spectrum acquisition. In this spectrum, among the background and some still remaining $^{160}\mathrm{Tb}$ decay gammas, a peak was detected with 944.2 keV gamma energy [9]. A thorough analysis of possible interfering reactions, contaminants and Tb sample impurities allowed to unambiguously conclude about the presence in the output channel of 6.85 MeV neutron induced reaction on $^{159}\mathrm{Tb}$ of $^{158g}\mathrm{Tb}$ isotope ($T_{1/2} = 180$ years) as a product of $^{159}\mathrm{Tb}(n,x)^{158g}\mathrm{Tb}$ nuclear reaction. Then by "$x$" we could assume only two neutrons, but the threshold of the $^{159}\mathrm{Tb}(n,2n)^{158g}\mathrm{Tb}$ nuclear reaction is 8.18 MeV [10] and about 1.3 MeV greater. Again, some ideas from [1] were very helpful since this paper was the pioneering one, in which an assumption about a possibility of a dineutron existence was reported for the first time: "The existence of the dineutron has been discussed but no evidence for their existence has been found. If they do exist, then important knowledge concerning the binding energies can be obtained ..." [1]. Therefore, the only possible suggestion for "$x$" in our particular case would be the dineutron — ${}^{2}_{0}n$ — a particle, consisting of the two bound neutrons. Then the energy aspects of a dineutron emission in nuclear reaction would be similar to emission of the deuteron below the threshold of the corresponding nuclear reaction with the neutron and proton in the output channel. The interval estimates for the binding energy and half-life value for the dineutron are obtained and presented in [9]. From our measurement, it was also possible to derive a point estimate for the ${}^{159}\mathrm{Tb}(n,{}^{2}_{0}n)^{158(m+g)}\mathrm{Tb}$ nuclear reaction cross section for 6.85 MeV neutron energy only. To make this estimate, the following expression has been used:

$$\sigma(\mathrm{mb}) = \frac{S\lambda}{\nu F f_n N_x \varepsilon_d I_\gamma 10^{-27}\left(1-e^{-\lambda T_{\mathrm{irr}}}\right)e^{-\lambda T_{\mathrm{c}}}\left(1-e^{-\lambda T_{\mathrm{meas}}}\right)}\,,$$

where $\nu$ is the isotopic abundance, $F$ is the neutron flux, $f_n$ is the self-absorption factor for 944.2 MeV gammas in Tb sample; $N_x$ is the number of nuclei in Tb sample under irradiation; $\varepsilon_d$ is the source to detector efficiency for 944.2 MeV gamma energy; $I_\gamma$ is the quantum yield of 944.2 gamma line due to ${}^{158g}\mathrm{Tb}$ decay; $\lambda$ is the decay constant of ${}^{158g}\mathrm{Tb}$ nuclide; $T_{\mathrm{irr}}$ is the time of Tb sample irradiation; $T_{\mathrm{c}}$ is the cooling time; $T_{\mathrm{meas}}$ is the time of Tb sample measurement; $S$ is the 944.2 keV peak area.

More details about the experimental technique and cross-section determination are available in [8]. From the expression above, the cross section for a dineutron emission in the ${}^{159}\mathrm{Tb}(n,{}^{2}_{0}n)^{158(m+g)}\mathrm{Tb}$ nuclear reaction with 6.85 MeV neutrons in input channel is $\boldsymbol{\sigma} = \mathbf{75 \pm 30}$ **mb** with major statistical contribution to the total uncertainty. This value is reported in this paper for the first time.

A possibility for the two neutrons to exist as a single particle was predicted by Migdal in [11], where two interacting particles were considered to become bound in a potential well due to the presence of the heavy nucleus. Concerning the mechanism of this reaction, one could assume that the interaction of the incident neutron with the two paired-up neutrons near Fermi level takes place with subsequent movement of the two paired-up neutrons as a single particle from the nucleus in the direction of its $z$-axis. Then the paired-up neutrons as the dineutron escape from the nucleus but not from the potential well of residual nucleus. This leads to capturing the dineutron at Migdal level within (100÷400) keV energy range near the surface of the nucleus — product of the nuclear reaction and a presence of this energy level provides the binding mechanism for the two neutrons to exist as a single particle — the dineutron.

## 4. Conclusions

The neutron activation technique for decades has remained a very powerful instrument both for practical applications and for new fundamental findings. With this tool, we were able to obtain a new nuclear data to make cross-section estimates more precise and accurate and to confirm some of available cross-section data for $(n,x)$ nuclear reactions on Tb, Lu, Dy, Er and Yb rare earth elements. Moreover, an application of this technique gave us a chance to observe a dineutron emission in the $^{159}\mathrm{Tb}(n,{}^2_0n)^{158g}\mathrm{Tb}$ nuclear reaction according to Migdal's prediction [11]. 70 years after the theoretical foundation of the dineutron in [1], the evidence for a dineutron existence as a bonded particle was provided in [9]. This event opens up the new direction in Nuclear Physics: physics of the dineutron, or dineutron physics. In the same time, it may happen that the dineutron is not the only complex system that may exist in a close proximity to the nucleus — residual product of a similar nuclear reaction. Thus, the following statement deserves some additional attention: "One might think that an analogous mechanism leads to bound states which are more complicated than the dineutron" [11]. The diproton would be a very good candidate as the next more complicated state than the dineutron. Therefore, by proper selection of target nuclide and by application of the nuclear activation technique, one could assume an escape of the diproton under the similar conditions described above as a possible explanation of the effect observed some time ago [12], but not firmly explained yet.

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