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14.5-MeV NEUTRON CAPTURE CROSS-SECTION MEASUREMENTS IN ^{160}Gd WITH ACTIVATION TECHNIQUE

CHR. NECHEVA, N. NENOFF, M. VLASAREV*,
A. KIROV and D. KOLEV

Faculty of Physics, Sofia University
Sofia, Bulgaria
**Institute for Plant Protection*
Kostinbrod, Bulgaria

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Activation cross-sections for neutron capture have been measured at an energy of 14.5 MeV for ^{160}Gd, relative to $\sigma(^{160}\text{Gd}(n,2n)^{159}\text{Gd}) = 1975$ mb. Gamma-ray spectra of the product nuclei were measured with a HP Ge-detector. By systematically varying the geometrical arrangement the corrections due to the influence of lower energy neutrons could be determined. The corrected activation capture cross-section at 14.5 MeV is found to be 1.0 ± 0.2 mb.

1. Introduction

The activation technique is a relatively simple method to measure fast neutron cross-sections. Applied to (n,γ) cross-sections appear to be difficult primarily due to accompanying background neutron sources. On the average, the background neutrons are of a much lower energy than the primary neutrons. Even a small contamination by background neutrons can seriously disturb the measurements, because the (n,γ) cross-section generally increases rapidly with decreasing neutron energy [1–5]. This contamination would be particularly serious for deformed nuclei, for which even a 1 % fraction of low energy neutrons can disturb the activation results considerably [6].

The neutrons with lower energy than the primary neutrons, are produced primarily by (n,n'), (n,pn) and $(n,2n)$ reactions in the sample and in the surrounding material in the target–sample assembly. This type of neutrons are called secondary neutrons and their influence was first established experimentally by Valkonen and Kantele [2]. In measurements, where we have utilized the reaction $\text{T}(d,n)^4\text{He}$ for the production of monoenergetic 14 MeV neutrons, the projectiles may also generate a background of low-energy primary neutrons from $\text{D}(d,n)^3\text{He}$ reactions. The influence of this type lower-energy neutrons would be serious when an old T-target is used for a long time by which the d-contamination could achieve a high value.

14.5–MeV neutron capture cross-sections in ^{160}Gd have been measured with activation technique by Kantele and Valkonen and have been found to be 1.0±0.4 mb

[3]. The purpose of our experiment is to measure the same cross-section with another type activation technique, a Water-cooling Neutron Generator, type NA-3 (made in Hungary) and present measuring counting techniques.

The reaction $^{160}Gd(n,\gamma)^{161}Gd$ is suitable for investigation of the effects of low-energy neutrons. ^{160}Gd is a deformed nucleus and has a high capture cross-section for neutrons with low energy. The influence of low-energy background neutrons has been studied by systematically varying the target–sample arrangement.

2. Experimental arrangement and procedure

The experiment was carried out at the NA–3 Neutron Generator at the Institute for Plant Protection, Kostinbrod, Bulgaria, which produces neutrons with an energy of 14.5 MeV through the reaction $T(d,n)^4He$. We have used tritiated titanium targets (2 mg/cm^2) on a 0.4 mm thick molibdenum backing. The deuterons were accelerated to 120 keV. Beam currents around 1 μA were used. The beam spot diameter was typically 4 mm. The relative time variation of the neutron flux during the irradiation was measured and the activation results were corrected for the time variation effects.

The target is of rotating type and cooling is provided by water, which is in contact with all backing of the target. The target holder is made of stainless steel. The target head is made of aluminium. Consequently, because of existing constructive conditions, the minimal possible layer of cooling water is 1.3 mm; the Al layer between the target and samples is 2.7 mm; the minimal distance between the target and samples is 4.5 mm.

The samples of pressed Gd_2O_3 were made with a diameter of 8 mm in all cases and different thicknesses (260 mg/cm^2–670 mg/cm^2). Measurements of the activation cross-section for gadolinium were performed with various target–sample geometries. Irradiation times are generally 11 min with beam currents of typically 1 μA. The various irradiations were performed with new targets with the purpose to reduce the deuteron contamination of the targets.

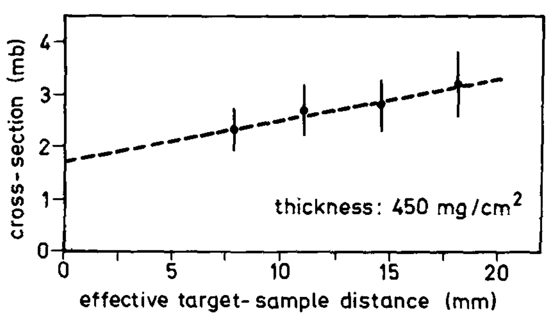

Fig. 1. Dependence of the apparent activation cross-section on the effective distance between the target and the sample. Statistical uncertainties are given

The gamma rays from the induced activity were measured by a HP Ge-detector "ORTEC" with an active volume of 166 cm^3 and a resolution of 1.9 keV for the 1332.5 keV γ-line of ^{60}Co. The strongest gamma-ray line 360.9 keV (I_γ = 60.6 ± 6.0 %) in the decay of ^{161}Gd ($T_{1/2}$ = 3.7 min) was used [8]. Like a monitor reaction we used ^{160}Gd$(n, 2n)^{159}$Gd reaction, known to have a cross-section of 1975 ± 185 mb [7]. The strongest gamma-ray line 363.3 keV (I_γ = 10.8 ± 1.0 %) in the decay of ^{159}Gd ($T_{1/2}$ = 18.56 h) we used is very close to the 360.9 keV line from the decay of ^{161}Gd, but the two lines are well resolved in the spectra. The ^{161}Gd activity measured typically 11 min, but ^{159}Gd activity measured around 1 hour. Several sets of measurements were performed and the results show good consistency.

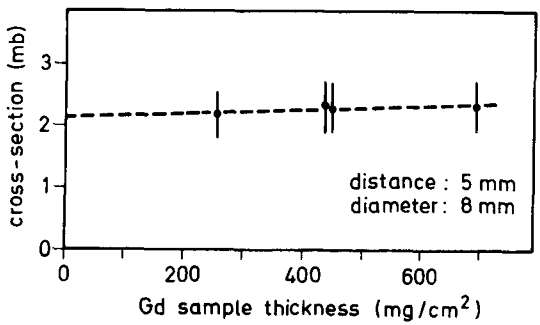

Fig. 2. Dependence of the apparent activation cross-section on the Gd-sample thickness. Statistical uncertainties are given

3. Experimental results

The results from measurements with various target–sample arrangements are shown in Figs 1–4. We have used the same representation as Valkonen and Kantele: "apparent cross-section", which means the value obtained from comparison with the known cross-section of ^{160}Gd$(n, 2n)^{159}$Gd reaction at 14.5 MeV neutron energy. The latter reaction has a cross-section which decreases rapidly with decreasing neutron energy and was used as monitor. Several sets of measurements were performed to establish the influence of primary low-energy neutrons from $d(d, n)^3$He reactions. The results show that we use a new T-target for one or two irradiations, the background of these neutrons does not influence the value of measured cross-sections. Thus, the geometrical effects observed on the apparent activation cross-section would then be caused by secondary neutrons.

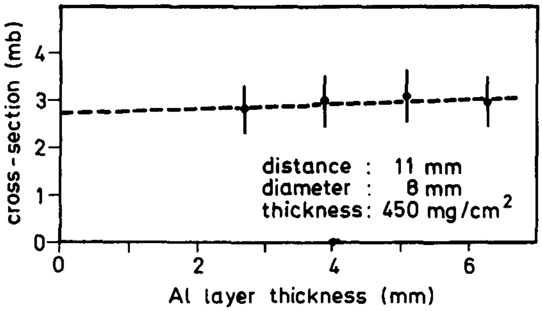

Fig. 3. Dependence of the apparent activation cross-section on the thickness of Al layer between the target and the sample. Statistical uncertainties are given

3.1. Dependence of apparent activation cross-section on effective target–sample distance

The influence of secondary neutrons, produced in materials surrounding the target and the sample or room-scattered neutrons can be studied through an investigation of the dependence of the total observed activation yield on effective target–sample distance. The total observed activation yield, $Y(n, \gamma)$, can roughly be described by

$$Y \sim \sigma_{14} \cdot \phi_{14} + \sigma_0 \cdot \phi_0 + \sigma_1 \cdot \phi_1, \qquad (1)$$

where σ_{14} is the cross-section to be measured, σ_0 is the effective capture cross-section for room-scattered neutrons, σ_1 is the effective capture cross-section for secondary neutrons. Here ϕ_{14}, ϕ_0 and ϕ_1 are corresponding neutron fluxes.

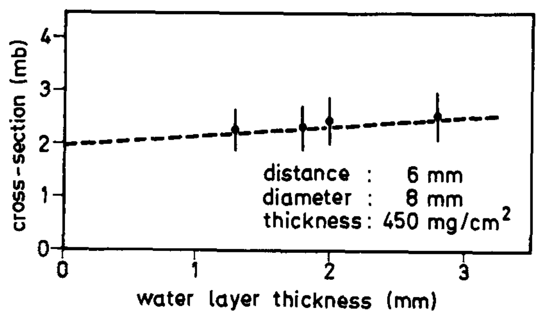

Fig. 4. Dependence of the apparent activation cross-section on the thickness of water layer between the target and the sample. Statistical uncertainties are given

We define an apparent cross-section for σ_{app} by

$$Y \sim \sigma_{app} \cdot \phi_{14}.$$

Thus,

$$\sigma_{app} = \sigma_{14} + \sigma_0 \cdot \frac{\phi_0}{\phi_{14}} + \sigma_1 \cdot \frac{\phi_0}{\phi_{14}}. \tag{2}$$

The distance dependence from a point source is

$$\phi_{14} \sim \frac{1}{r^2}.$$

The room-scattered neutron flux is assumed to be uniformly distributed, i.e.

$$\phi_0(r) = \text{constant}.$$

The secondary neutrons must have a distance dependence between these two extremes. Thus, we can roughly write

$$\sigma_{app} \sim \sigma_{14} + a \cdot f(r) + b \cdot f(r^2). \tag{3}$$

The influence of room-scattered neutrons and secondary neutrons from sources outside the sample itself can be determined by a measurement of the distance dependence of the apparent cross section and extrapolation to zero distance. In view of the fact that neutron source and samples are not points and have defined sizes, a change of these sizes is also a change of "effective" distance between the target and the sample [5]. The effective distance is defined by

$$\langle r \rangle = \frac{\int\int r \cdot ds_1 \cdot ds_2}{\int\int ds_1 \cdot ds_2}, \tag{4}$$

were ds_1 and ds_2 are area elements of the sample and the beam spot, respectively, and r is the distance between the two elements. Integration is carried out over the sample and beam spot areas.

The measurements were performed with samples 450 mg/cm^2 thick and 8 mm in diameter and the result are shown in Fig. 1.

3.2. Dependence on gadolinium sample size

The influence of secondary neutrons produced in the sample itself can be studied by observing the dependence of sample diameter and thickness on the apparent activation cross-section. The influence of activation sample diameter is taken into account in the target–sample effective distance (see 3.1). The effect of sample thickness was studied by varying it. The measurements were performed at a target–sample distance of 5 mm and samples with a diameter of 8 mm and various thicknesses. The experimental results are shown in Fig. 2.

3.3. Dependence on target-head thickness and cooling water

The target head is made of aluminium and there are a 2.7 mm Al layer and a 1.3 mm cooling water layer between the target and the sample. Aluminium is a material which has a small $(n, 2n)$ cross-section (< 0.17 mb [7]), but water is one of the major sources of secondary neutrons from (n, n') reactions. To study the effects of these layers the apparent activation cross-section was measured with various thicknesses of aluminium and water between the target and the sample. The measurements were performed with samples 8 mm in diameter and a thickness of 450 mg/cm^2 and constant target–sample distance. The results are shown in Figs 3 and 4.

The molibdenum target backing is another source of secondary neutrons primarily from $(n, 2n)$ reactions, but in our experiment the influence of molibdenum backing on the apparent activation cross-section is not taken into account.

3.4. Determination of the activation capture cross-section

The capture cross-section for the reaction ^{160}Gd$(n, \gamma)^{161}$Gd has been determined from Figs 1–4. The results indicate a linear dependence of the apparent cross-section and the lines through the experimental points have in all cases been determined by least-squares fitting. Extrapolation of the line in Fig. 1 to zero effective distance gives an apparent cross-section value corrected for both distance and diameter dependences. After that, this value was corrected for the dependences of sample, aluminium layer and cooling water thickness, respectively, taken from Figs 2–4. Thus, we obtain a corrected value of the 14.5 MeV neutron capture cross-section in ^{160}Gd of 1.0 ± 0.2 mb.

In determining the accuracy of the cross-section value, the following sources of error were taken into account:

- statistical counting error of the ^{161}Gd and ^{159}Gd activities;
- uncertainties in the least-squares fitting of the experimental results;
- uncertainties in the gamma-ray intensities in the decay of ^{161}Gd;
- uncertainties in the monitor reaction.

4. Conclusions

The 14.5–MeV neutron capture cross-section is found to be 1.0 ± 0.2 mb and this value is in good agreement with previous results obtained with activation and spectrum methods, 1.0 ± 0.4 mb and 0.9 mb, respectively [3,6]. These results indicate that the Neutron Generator with water cooling can be used for the determination of neutron activation capture cross-sections at 14–15 MeV with an accuracy of $\sim 20\%$. The accuracy can be even better, depending on the decay and half-life of produced nuclei, the monitor and counting technique.

A comparison with previous activation measurements indicates that in the present experiment there is an additional serious source of low-energy neutrons, namely the cooling water. For more accurate measurements, the contribution of secondary neutrons can be decreased by using a gas cooling, thin aluminium backing and smaller beam spot.

Acknowledgement

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