Measurement of the Energy Distributions of Neutrons from ^{7}Li(d,n)^{8}Be Reaction at Deuteron Energy 2.9 MeV by Activation Method

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Abstract

The neutron beams generated at the electrostatic accelerators using nuclear reactions T(p,n)^{3}He, D(d,n)^{3}He, ^{7}Li(p,n)^{7}Be, T(d,n)^{4}He, ^{7}Li(d,n)^{8}Be, ^{9}Be(d,n)^{10}B are widely used in neutron physics and in many practical applications. Among these reactions the least studied reactions are ^{7}Li(d,n)^{8}Be and ^{9}Be(d,n)^{10}B. The present work is devoted to the measurement of the neutron spectrum from ^{7}Li(d,n)^{8}Be reaction at 0° angle to the deuteron beam axis on the electrostatic accelerator EG-1 (JSC "SSC RF – IPPE") using activation method and a stilbene crystal scintillation detector. The first time ever ^{7}Li(d,n)^{8}Be reaction was measured by activation method. The target was a thick lithium layer on metallic backing. The energy of the incident deuteron was 2.9 MeV. As activation detectors a wide range of nuclear reactions were used: ^{27}Al(n,p)^{27}Mg, ^{27}Al(n,α)^{24}Na, ^{113}In(n,n')^{113m}In, ^{115}In(n,n')^{115m}In, ^{115}In(n,γ)^{116m}In, ^{58}Ni(n,p)^{58m}Co, ^{58}Ni(n,2n)^{57}Ni, ^{60}Ni(n,p)$^{60m+g}$Co, ^{197}Au(n,γ)^{198}Au, ^{197}Au(n,2n)^{196}Au, ^{197}Au(n,γ)^{198m}Au, ^{59}Co(n,p)^{59}Fe, ^{59}Co(n,2n)$^{58m+g}$Co, ^{59}Co(n,α)^{56}Mn, ^{59}Co(n,γ)$^{60m+g}$Co. Measurement of the induced gamma-activity was carried out using HPGe detector Canberra GX5019[1]. The up-to-date evaluations of the cross sections for these reactions were used in processing of the data. The program STAYSL was used to unfold the energy spectra. The neutron spectra obtained by activation detectors is consistent with the corresponding data measured by a stilbene crystal scintillation detector within their uncertainties.

Activation method

The activation method of measuring neutron spectra uses a link between the induced activity of detector-monitors and neutron flux. The reaction are divided into two groups by the nature of the interaction of neutrons with substances: those reactions which are more sensitive to low-energy neutrons - (n,γ), (n,f) and reactions that are essential for neutron energies above a certain value called the energy threshold of the reaction (reaction threshold). The main threshold reactions are reactions of neutron capture with emission of a charged particle (n,p) and (n,α), inelastic neutron scattering (n,n'), the neutron capture reaction with the emission of two neutrons (n,2n) and fission reaction (n,f).

Upon irradiation activation monitors at a constant power the number of pulses in the total absorption peak of the analyzed gamma line, $S(E_\gamma)$, and the reaction rate, R, related by:

$$R = \frac{S(E_\gamma)\cdot\lambda_M}{n\cdot F\cdot I(E_\gamma)\cdot\varepsilon(E_\gamma)\cdot k_\mu\cdot k_\tau\cdot k_s\cdot Y\cdot(1-e^{-\lambda_M t_O})\cdot(1-e^{-\lambda_M t_U})\cdot e^{-\lambda_M t_\theta}}, \quad (1)$$

if the analyzed gamma-line in the spectrum produced by the decay of the parent nuclei. In the case when the analyzed line in a gamma spectrum is due to the decay of daughter nuclei, the ratio between the reaction rate R and the measured value $S(E_\gamma)$ is given by:

$$R = \frac{S(E_\gamma)\cdot(\lambda_D - \lambda_M)}{n\cdot F\cdot I(E_\gamma)\cdot\varepsilon(E_\gamma)\cdot k_\mu\cdot k_\tau\cdot k_s\cdot Y\cdot[C_1(1-e^{-\lambda_M t_u})\cdot e^{-\lambda_M t_в} - C_2(1-e^{-\lambda_D t_u})\cdot e^{-\lambda_D t_в}]}, \quad (2)$$

In the above relations (1) and (2):

n – the number of nuclei of the target isotope contained in the monitor;

$\varepsilon(E_\gamma)$ – the efficiency of the full absorption of gamma rays with energy E_γ by HPGe detector;

$I(E_\gamma)$ – yield per one decay of nucleus by analyzed gamma product (Eγ) or X-ray lines (E_R);

λ_M and λ_D – correspondingly, the decay constants of the parent and daughter nuclei;

t_o – radiation time of monitors (detectors);

$t_в$ – delay time;

t_u – measuring time of the irradiation monitor on the spectrometer;

k_μ – correction for the absorption of gamma rays with an energy E_γ in the monitor material;

k_τ – correction for counting pulses in the spectrometer;

k_s – correction for gamma quanta pulse summation emitted in a cascade;

F – coefficient taking into account the self-shielding and the scattering of neutrons in the monitor detector material;

Y – yield per one act of parent (daughter) nuclei reaction;

parameters C1 and C2 are respectively equal to:

$$C_1 = \frac{\lambda_2}{\lambda_1}\cdot(1-e^{-\lambda_1 t_o}); \quad C_2 = \frac{\lambda_1}{\lambda_2}\cdot(1-e^{-\lambda_2 t_o})$$

Parameter Y is a cumulative yield of studied isobaric chain, when measuring the rate of fission reaction.

The amendment to the sum of pulses of gamma rays emitted in a cascade, k_s, depends on the value of the solid angle between the measured monitor and the HPGe detector. The solid angle smaller the correction less. The amendment is easily measured experimentally. Studies show that the correction coefficient k_s is close to 1,000, when the gamma spectra of irradiated monitor's diameter of 3 to 10 mm measured at a distance of 10 to 12 cm from the HPGe detector cap with a working volume of about 60 to 80 cm^3. The continuous monitoring of gamma background is necessary requirement for measuring the rate of nuclear reactions.

Rate of monitor reactions, R_i, proceeding from the equations (1) and (2) are determined by RRC program [2]. An algorithm allowing in both cases to determine the rate of reactions by irradiating monitors on unsteady ion current also was implemented in the RRC program. In this case, the time dependence of the ion current is approximated by a piecewise linear function normalized to unity. The decay data for radioactive nuclei are included into the program EFGL and RRC from the library decay.lib. The values of half-life, $T_{1/2}$, gamma ray energy, Eγ, and yields per a decay, I(Eγ), shows for each radioactive nucleus in this library from [3], [4]. Constant decay of radioactive nuclei, λ, is calculated by programs from the ratio $\lambda = \ln 2/T_{1/2}$. The data on the cross sections of all monitor reactions were taken from the international dosimetry file IRDF-2002 [5].

The efficiency of HPGe-detector Canberra GX5019

The energy dependence of the efficiency of Ge(Li) gamma-spectrometer $\varepsilon(E_\gamma)$ was determined on the basis of experimental data for discrete values of the energy and intensity of gamma rays. The calibration of the spectrometer efficiency of total absorption of gamma rays was carried out using the standard gamma-ray sources "OSGI": ^{54}Mn (E_γ=834,85 keV), ^{57}Co (E_γ=122,08 keV, 136,47 keV), ^{60}Co (E_γ=1173,23 keV, 1332,49 keV), ^{137}Cs (E_γ=661,66 keV) etc. The distance between the standard source and Ge (Li) detector and the diameters of the standard source and activation monitors were identical.

The value of the efficiency $\varepsilon(E_\gamma)$ of the total absorption of gamma rays with energy E_γ was determined from the equation:

$$\varepsilon\left(\mathrm{E}_\gamma\right) = S_S(E_\gamma) / (A_S \cdot e^{-\lambda \cdot t_d} \cdot I(E_\gamma) \cdot t_m) \ ,$$

where $S_S(E\gamma)$ – counts at the peak of total absorption of gamma rays with energy E_γ, registered during time interval t_m ;

A_S – absolute activity of standard source at the time of certification;

λ - decay constant of standard source;

$I(E_\gamma)$ - the yield of gamma rays with energy E_γ per a decay of a radioactive nucleus of standard source;

t_d – elapsed time from the moment of certification of the source to the beginning of measuring quantities $S_S(E\gamma)$.

The efficiency of the total absorption of gamma rays with energy $E\gamma$ were calculated on the basis of the measured values $S_S(E_\gamma)$ and parameters A_S, $I(E_\gamma)$, λ, t_d, t_m. The function $\varepsilon(E_\gamma)$ was determined by fitting the experimental data for different E_γ . The results of determination of the efficiency of Ge(Li) detector were shown in figure 1.

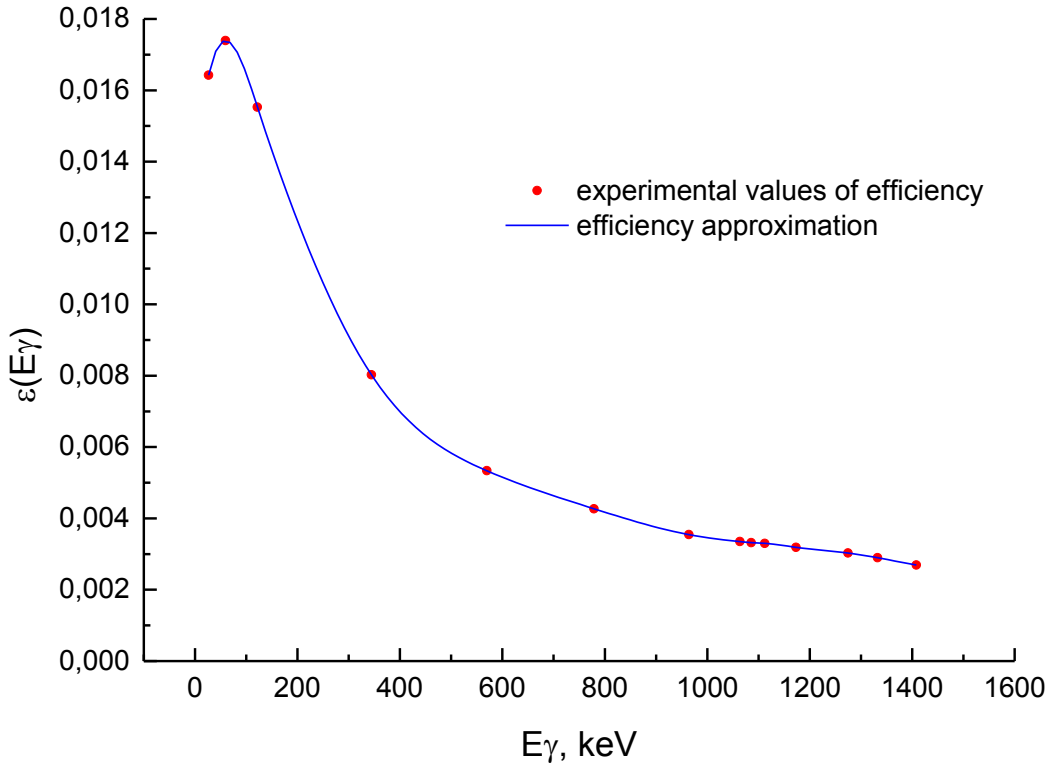

Figure 1 – The efficiency of HPGe gamma spectrometer.

Experiment and neutron spectrum from the ^{7}Li(d,n)^{8}Be

The rate values of the following nuclear reactions were measured by activation method to determine the energy spectrum generated in the lithium target by deuterons with 2.9 MeV: ^{27}Al(n,p)^{27}Mg, ^{27}Al(n,α)^{24}Na, ^{113}In(n,n')^{113m}In, ^{115}In(n,n')^{115m}In, ^{115}In(n,γ)^{116m}In, ^{58}Ni(n,p)^{58m}Co, ^{58}Ni(n,2n)^{57}Ni, ^{197}Au(n,γ)^{198}Au, ^{197}Au(n,2n)^{196}Au, ^{197}Au(n,γ)^{198m}Au, ^{59}Co(n,p)^{59}Fe, ^{59}Co(n,2n)$^{58m+g}$Co. The irradiation of the activation monitors by neutrons from the reaction of Li(d,n) was carried out at 0° to the axis of the beam in an accelerator of EG-1 IPPE. The energy of the incident deuteron was 2.9 MeV. Setup scheme is shown in Figure 2.

All activation detectors (monitors) used for measuring the rates of these reactions were produced in the form of discs with a diameter of 10 to 12.2 mm. Geometrical thickness of monitors was in the range of 0.6 to 3.5 mm. All monitors used for measuring the rate of threshold reactions were made of chemically pure metal of the corresponding elements. Main characteristics of monitors are shown below in Table 1.

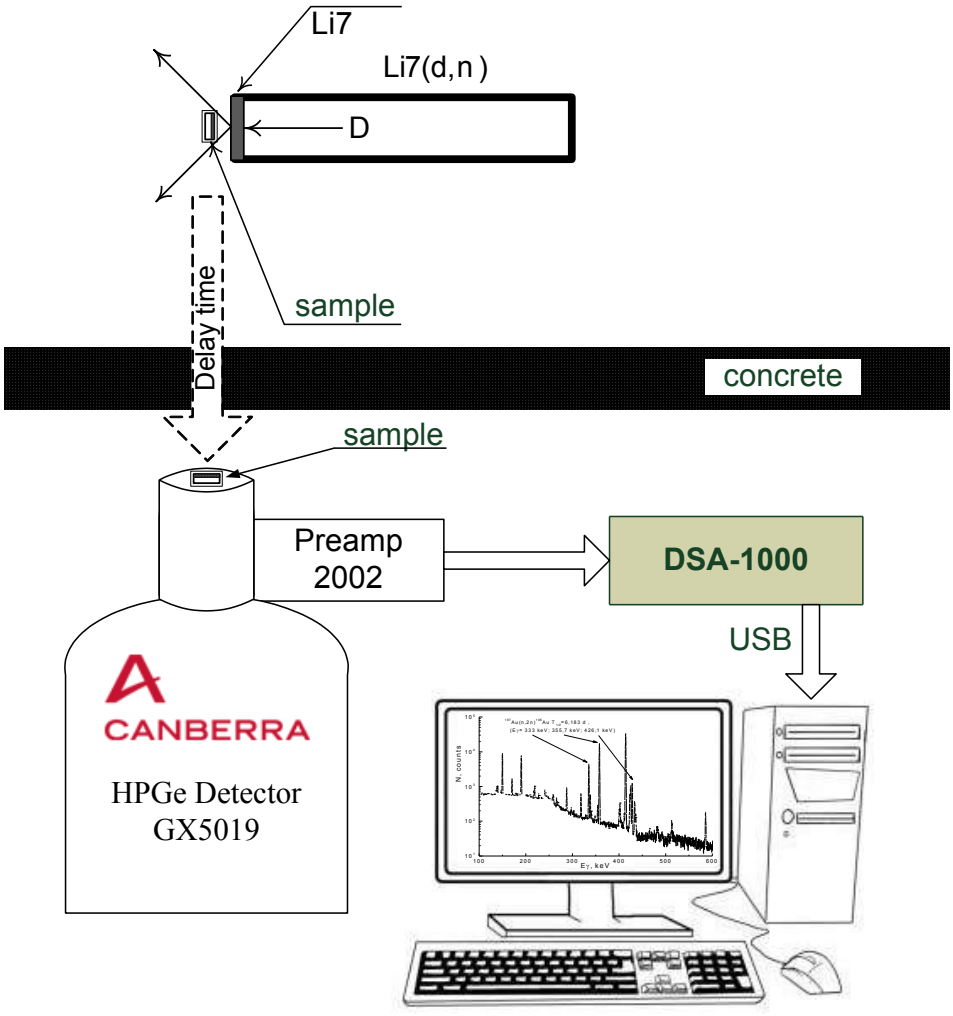

Figure 2 – Scheme of the experimental setup.

An apparatus spectrum of gamma rays originated from ^{197}Au(n,2n)^{196}Au reaction in Au sample after irradiation by the neutron flux is shown in Figure 3.

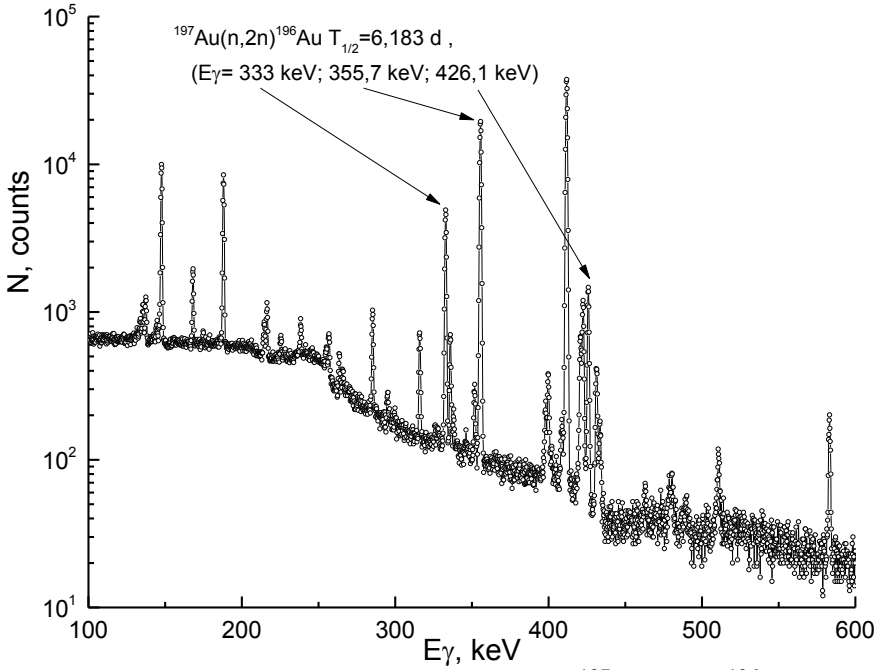

Figure 3 – Apparatus spectrum of gamma rays from ^{197}Au(n,2n)^{196}Au reaction in the Au activation monitor after irradiation by the neutron flux.

Table 1 – List of nuclear reactions used for activation analysis

Element	Isotope	Reaction	$T_{1/2}$	E_{thr}, MeV	E_γ, keV	I_γ, %	Weight, g	Number of nuclei
Ni	^{58}Ni	^{58}Ni(n,p)^{58m}Co	70.8 d	0.0	511.17	29.8	0.49	$0.0342\cdot10^{23}$
					810.76	99.45		
		^{58}Ni(n,2n)^{57}Ni	35.6 h	12.429	1377.71	81.7		
					1919.99	12.3		
In	^{113}In	^{113}In(n,n')^{113m}In	99.476 min	0.395	391.7	64.94	0.2	$0.00045\cdot10^{23}$
	^{115}In	^{115}In(n,n')^{115m}In	4.486 h	0.339	336.24	45.8		$0.01\cdot10^{23}$
		^{115}In(n,g)^{116m}In	54.29 min	0.0	1097.27	58.5		$0.01\cdot10^{23}$
					1293.69	84.8		
Au	^{197}Au	^{197}Au(n,g)^{198}Au	2.69 d	0.0	411.8	95.62	1.15	$0.0352\cdot10^{23}$
		^{197}Au(n,2n)^{196}Au	6.183 d	8.114	333.03	22.9		
					355.73	87		
					426.1	6.6		
		^{197}Au(n,g)^{198m}Au	2.272 d	0.0	333.82	18		
Co	^{59}Co	^{59}Co(n,p)^{59}Fe	44.495 d	0.796	1099.25	56.5	1.35	$0.1381\cdot10^{23}$
					1291.59	43.2		
		^{59}Co(n,2n)$^{58m+g}$Co	70.86 d	10.633	810.76	99.45		
Al	^{27}Al	^{27}Al(n,p)^{27}Mg	9.458 min	1.896	843.76	71.8	0.09	$0.0201\cdot10^{23}$
		^{27}Al(n,a)^{24}Na	14.997 h	3.250	1368.6	99.99		

The obtained spectra of all nuclear reactions were processed in order to obtain the total absorption peak areas of the gamma rays of certain energy. The obtained values were used to calculate the rate of the corresponding reactions. Preliminary estimate of the neutron spectrum at 0° to the beam axis from the reaction of ^{7}Li(d,n) on the accelerator of EG-1 (IPPE) on the basis of these data was performed using STAYSLF program [6]. The Bayesian

approach is the basis of the neutron spectrum unfolding method based on the reaction rate of the data used in STAYSLF program. Figure 4 shows the result of unfolding of the spectrum obtained by activation method in comparison with the spectrum obtained by a spectrometer on the basis of the stilbene crystal.

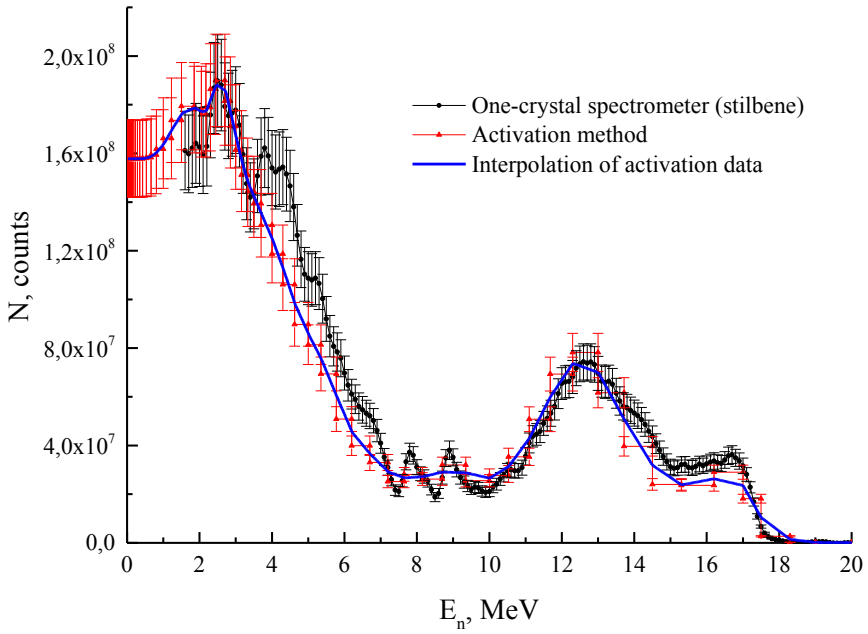

Figure 4 – Comparison of the spectra obtained by the activation method and the spectrometer with a stilbene crystal.

Thus, as a result of the performed work, the spectrum of the neutrons from the ^{7}Li(d,n)^{8}Be reaction at an angle of 0° to the beam axis was measured by activation method that uses a link between induced activity of detectors and flux of neutrons. It is worth noting that ^{7}Li(d,n)^{8}Be reaction was measured by activation method for the first time ever. The advantage of this method over other methods is that the measurement of neutron spectrum can be carried out in the presence of high intensity gamma radiation. Figure 4 shows a good agreement in the range from 7 to 18 MeV between the activation spectrum and the spectrum obtained by using single-crystal spectrometer based on stilbene crystal. At the present time the studies on the possible reasons for the some discrepancy of neutron spectra obtained by activation method and the scintillation spectrometer in the range from 3 to 7 MeV are carrying out.

References

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