Formation and Measurement of the Thermal Neutron Beam at the Tandetron Accelerator

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Abstract

The neutron beams generated at accelerators using nuclear reactions with well-known parameters are widely used in neutron physics and in many practical applications. This paper is devoted to the formation of a thermal neutron beam and the measurement of its intensity and spatial distribution at an angle of 0° to the beam axis using an activation method and an ionization chamber with a solid boron radiator KNT-10 that is not sensitive to γ-radiation. The nuclear reaction of ^{7}Li(p,n) on metallic lithium installed in a cooled target device of the Tandetron accelerator was used as a neutron source.

Description of the experiment. The configuration of the Tandetron accelerator target device and the polyethylene block for slowing down the neutrons generated in the ^{7}Li(p,n) reaction is shown in Fig. 1.

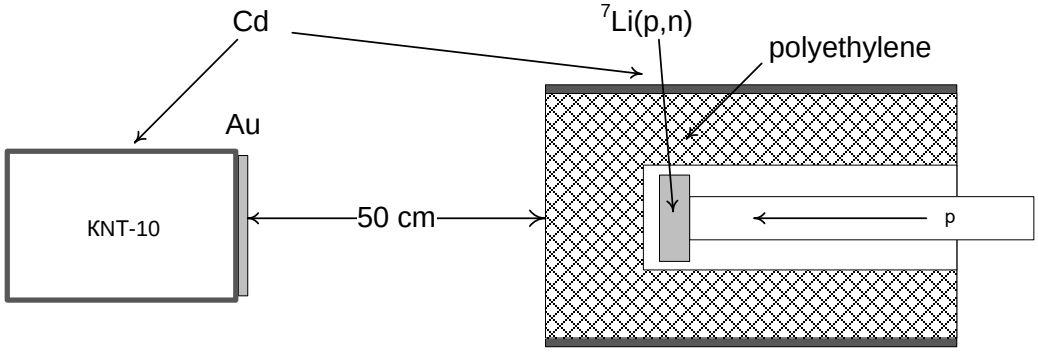

Fig. 1. Block diagram of measurement for determining the thermal neutron flux by the gold foil activation method and for determining the cadmium ratio using the camera KNT-10.

First, the gold foil was irradiated separately to determine the absolute neutron flux density, and then the number of pulses from the KNT-10 chamber installed at the same point as the gold foil was measured in a cadmium case and without a cadmium cover for determination of the cadmium ratio with the same accelerator and proton beam parameters.

The cadmium sheets 0.5 mm thick were used to reduce neutron leakage through the side surface of the cylinder. The distance from the lithium target to the end surface of the cylinder was 10 cm. The distance from the end surface of the cylinder moderator to the gold sample and to the KNT-10 chamber was 50 cm.

Measurement of cadmium ratio of the thermal beam. The absolute value of the thermal neutron flux was determined using activation analysis with thin gold foil as an indicator. The presence of resonant neutrons makes it difficult to interpret the activity induced in the gold foil.

The cadmium filters, which intensively absorb thermal neutrons, are used to separate the effects of activation from thermal and resonant neutrons. The cadmium neutron absorption

cross section is 2450 barn in the thermal region and decreases rapidly with increasing of the neutron energy. It decreases to 1 barn near the boundary of the thermal and resonant regions of the neutron energy. As a result, a 0.5 mm thick cadmium plate absorbs almost all thermal neutrons falling on it with an energy E <0.4 eV and passes resonant neutrons..

To determine the intensity ratio of thermal and resonant neutrons, we used the method of measuring the cadmium ratio

$$R_c = \frac{C_1\varphi_{th} + C_2\varphi_r}{C_2\varphi_r},$$

where C_1 and C_2 are the sensitivity of the detector, respectively, to thermal and resonant neutrons, φ_{th} is the thermal neutron flux, φ_r is the resonant neutron flux [1].

The following expression can be written for the cadmium ratio measurement in the case of a neutron detector with sensitivity proportional to 1/v

$$R_c - 1 = \frac{\varphi_{th}\sigma_{actth}}{\varphi_r \int\limits_{0.4}^{\infty} \sigma_r \frac{dE}{E}},$$

which takes into account the energy distribution of resonant neutrons *dE/E*.

Introducing the dependence of the cross section on the neutron energy, we obtain

$$R_c - 1 = \frac{\varphi_{th} \frac{1}{\sqrt{0.025}}}{\varphi_r \int\limits_{0.4}^{\infty} \frac{dE}{E^{3/2}}} = 2\frac{\varphi_{th}}{\varphi_r}.$$

Thus, the cadmium ratio provides the information on the fluxes of thermal and resonant neutrons at the point at which measurements are being made. The cadmium covers are used not only in the activation method. Any small neutron detector not sensitive to γ-radiation can be placed in a cadmium cover. When the thermal neutrons are absorbed in cadmium, a capture γ-radiation arises, the registration of which distorts the cadmium ratio.

In this experiment, an ionization chamber with a solid boron radiator KNT-10, which is not sensitive to γ-radiation, was used to measure the cadmium ratio. KNT-10 is an ionization two-electrode chamber with a solid boron (^{10}B) coating [2]. It is known that the reaction cross section ^{10}B(n,α) obeys the 1/v law. Therefore, the above expression for estimating the intensity of thermal and resonant neutrons based on measurements of the cadmium ratio is quite correct for analyzing the results for both the KNT-10 ionization chamber and the activation of the gold indicator.

For the experimental determination of the cadmium ratio, the neutron flux was measured using a KNT-10 ionization chamber, which is not sensitive to gamma radiation, in and without the cadmium cover under the same experimental conditions indicated above in Figure 1. Figure 2 shows the neutron spectra measured during irradiation of a KNT-10 camera in and without a cadmium cover at a distance of 50 cm from the end of the moderator.

Integrating these spectra and dividing the obtained values one by one, we obtain the average flux ratio 29.9898, from which we determine the cadmium ratio: R_{Cd} = 58.9796. The obtained sufficiently high value of the cadmium ratio allows us to further neglect the effects of resonant neutrons.

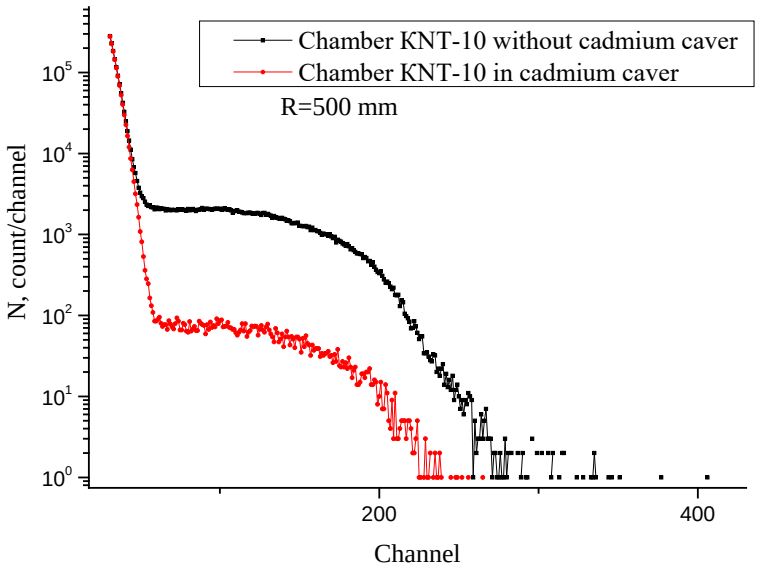

Fig. 2. The neutron spectra measured by a KNT-10 ionization chamber at a distance of 50 cm from the moderator with cadmium caver and without it.

The measurement of the spatial distribution of the thermal neutron flux. The KNT-10 ionization chamber was used to measure the spatial distribution of the thermal neutrons generated in the Tandetron target using the ^{7}Li(p,n) nuclear reaction. The range of distances from the target was varied from 10 cm to 250 cm. The experiment procedure consisted in measuring the amplitude distribution of the ionization chamber KNT-10 and the number of counts of the proton current integrator of the target. At each point 5 measurements were taken. Then, when the ion current was turned off, the neutron background was measured. Fig. 3 shows the results of measuring the amplitude distribution of neutrons with the current on the accelerator target and the background of neutrons corresponding to this point measured with the accelerator current turned off.

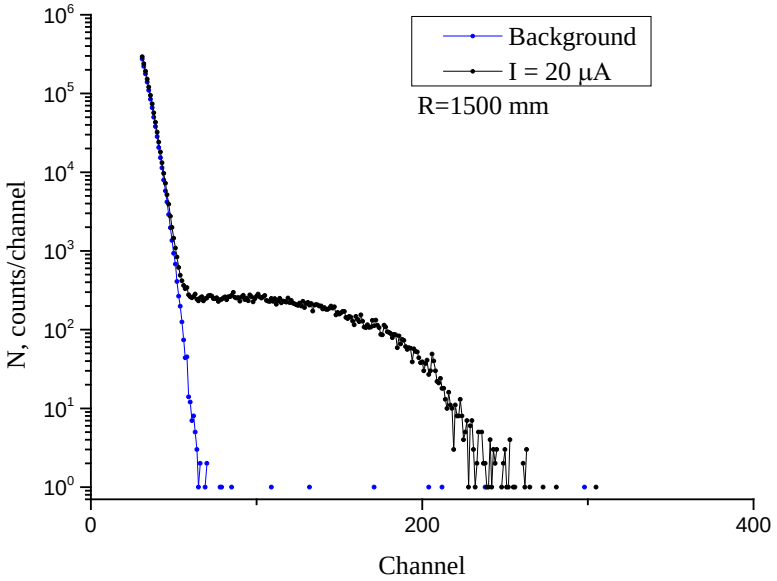

Fig. 3. The amplitude distribution of the ionization chamber KNT-10 with the accelerator current turned on and off. The current on the accelerator target was 20 μA.

This procedure was performed at each point of the investigated range of distances. The dependence of the number of the camera counts on the distance to the moderator was obtained after subtracting the neutron background, integrating the amplitude spectrum of the KNT-10 ionization chamber and normalizing it to the value of the current integrator. The results are presented in Fig. 4.

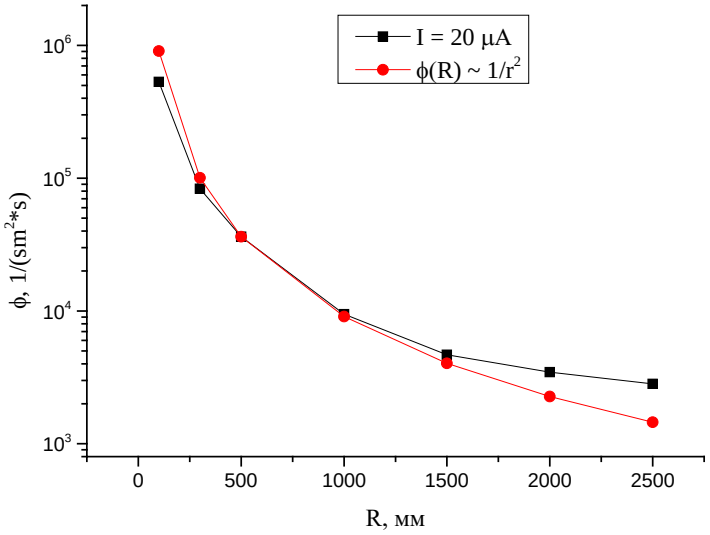

Fig.4. The spatial distribution of thermal neutron flux at the Tandetron accelerator.

Fig. 4 shows that in the range of 0.5 to 1.5 m the dependency of the neutron flux obeys the $1/R^2$, which is valid for a point source. At the distances less than 0.5 m, the discrepancy of the observed dependence on the law $1/R^2$ is due to the fact that the source is different from the point source. At the distances of more than 1.5 m, the distorting factor is the neutrons reflected from the walls of the experimental hall of the Tandetron accelerator.

Absolute neutron flux. The absolutization of the neutron flux was carried out using an activation method for measuring the neutron spectra, which uses a link between the induced activity of detector-monitors and the neutron flux density [3]. This link is expressed by the following equation:

$$S_{peak} = \frac{m}{\lambda \cdot A} \cdot \varepsilon_\gamma \cdot f \cdot g \cdot N_a \cdot (1 - e^{-\lambda \cdot t_{irr}}) \cdot e^{-\lambda \cdot t_d} \cdot (1 - e^{-\lambda \cdot t_m}) \cdot \Phi \cdot \sigma , \qquad (1)$$

S_{peak} – the peak area of specific gamma-line
m – mass of the activation of the monitor in grams,
λ – decay constant,
A – atomic weight of the monitor,
ε_γ – Ge detector efficiency for a particular gamma-line,
f – isotopic purity of the monitor,
g – the intensity of the particular gamma-line,
N_a – Avogadro constant,
t_{irr} – irradiation time of the monitor,
t_d – delay time of the monitor,
t_m – measurement time of the monitor,
Φ – the energy spectrum of neutrons (neutron/cm^2·s),
σ – cross section of reaction (barn).

As was already shown above, there is a negligible number of neutrons with energies above 0.025 eV, that is, the epithermal neutrons, because the cadmium ratio was 58.9796.

Figure 5 shows a comparison of two exactly identical activation samples (weight, size, thickness, chemical purity of gold) irradiated with the same parameters, only one was in a cadmium case, and the second without a cadmium case.

It is clearly seen from the figure that epithermal and resonant neutrons were not registered in the activation sample, which was irradiated in a cadmium case.

On this basis, the $^{197}Au(n,\gamma)^{198}Au$ reaction cross section was taken equal to 98.8 barn with a neutron energy of 0.025 eV to determine the neutron flux.

The energy dependence of the efficiency $\varepsilon(E_\gamma)$ of a Ge(Li)-gamma spectrometer was determined on the basis of experimental data for discrete values of the energies of gamma ray. The spectrometer was calibrated according to the efficiency of the total absorption of gamma ray using the reference gamma ray sources (OSGI). The distance between the reference source and the Ge(Li) detector, the diameter of the reference source when calibrating the spectrometer and measuring the activity of monitors were the same.

The absorption efficiency of gamma ray with the energy of 411.8 keV was 0.07016 for a Ge (Li) gamma spectrometer.

The activation sample was irradiated at the IPPE Tandetron accelerator. The monitor was irradiated continuously for 1 hour at a proton energy of Ep = 2.3 MeV and a current of 20.6 μA. The reaction $^{7}Li(p,n)$ was used to generate the neutron flux. The activation sample was made of chemically pure gold weighing 1.0415 g.

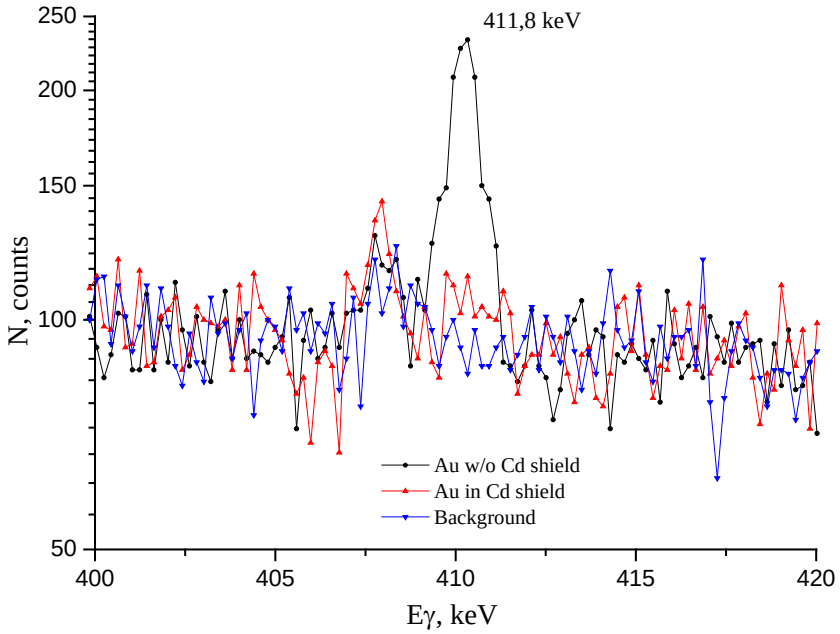

Fig. 5. Two Au samples irradiated in the Cd cover and without the Cd cover in comparison with background measurement.

The Canberra GX5019 HPGe detector was used as the spectrometer for measuring the induced gamma activity [4]. Figure 6 shows the apparatus spectrum of gamma rays of the $^{197}Au(n,\gamma)$ ^{198}Au reaction products in a gold sample after its irradiation in the neutron flux.

A number of counts at the peak of the gamma ray total absorption for the 411.8 keV gamma rays energy were obtained as a result of the Au monitor measurements and the subsequent processing of the gamma ray spectra. The 5 irradiations were carried out under the same conditions of the 5 activation monitors to increase the statistical accuracy of the determination of the induced activity.

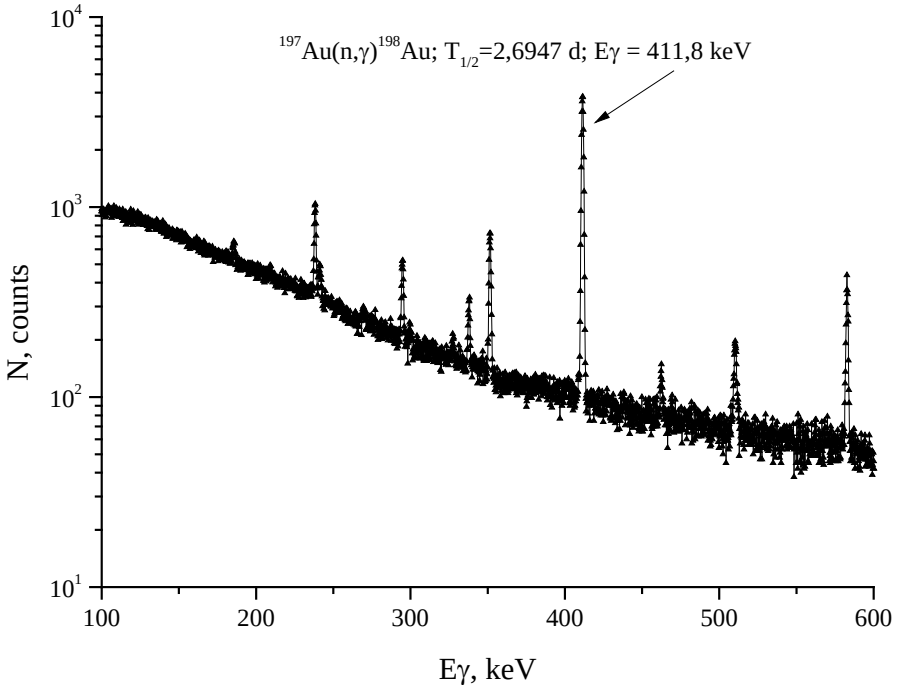

Fig. 6. The apparatus spectrum of gamma rays of the ^{197}Au(n,γ)^{198}Au reaction products in the gold sample after its irradiation in the neutron flux.

Thus, all the parameters of equation (1) are defined, namely, the characteristics of the monitor, the characteristics of the gamma ray spectrometer, the times of irradiation, exposures and measurements, as well as the cross section of the ^{197}Au(n,γ) ^{198}Au reaction.

Then the neutron flux density Φ can be determined using the expression

$$\Phi = \frac{S_{peak}}{\frac{m}{\lambda \cdot A} \cdot \varepsilon_\gamma \cdot f \cdot g \cdot N_a \cdot (1 - e^{-\lambda \cdot t_{irr}}) \cdot e^{-\lambda \cdot t_d} \cdot (1 - e^{-\lambda \cdot t_m}) \cdot \sigma} \qquad (2)$$

The thermal neutron flux density is determined by the following formula

$$\Phi_{th} = \Phi \cdot \frac{(R_{cd} - 1)}{R_{cd}} \qquad (3)$$

The average thermal neutron flux Φ_{th} was obtained as a result of analyzing the activation gamma spectra of the irradiated Au monitor by the neutron flux from the ^{7}Li(p,n) reaction on a thick target bombarded by protons with an energy Ep = 2.3 MeV and at a current of 20.6 μA. The average thermal neutron flux Φ_{th} is equal **$3.63 \cdot 10^4$** neutrons/(cm^2·s) at the distance of 50 cm from the moderator.

Based on the obtained absolute value of the thermal neutron flux and the measured spatial distribution of the thermal neutron flux, it can be concluded that the scale of the

change of the absolute value of the thermal neutron flux at the Tandetron accelerator using this neutron moderator design and the ^{7}Li(p,n) reaction varies from the maximum value of **$5.31 \cdot 10^{5}$** n/(cm^2·s) at the proton current of 20 μA at the distance of 100 mm from the target to the minimum value of **14.12** n/(cm^2·s) at the proton current of 0.1 μA at the distance of 2500 mm from the target.

References

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