EXPERIMENTAL INVESTIGATION OF NEUTRON SPECTRA GENERATED IN A COPPER TARGET BY 10 MeV PROTONS

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The intensity and energy spectra of neutron radiation arising as a result of interaction of the accelerated proton beam with a copper target were measured at a proton energy of 10 MeV. The neutron spectrum was measured using two different techniques: i) with pulse-shape discrimination of gamma-background, and ii) by activation detectors. The neutron yield from the (p,n) reaction was estimated. For the copper target, the neutron yield per accelerated proton of energy 10 MeV was $(3.5 \pm 1.0)\cdot10^{-3}$.

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The aim of the present work has been to measure the intensity and energy spectra of neutron radiation resulting from the interaction of an accelerated proton beam with a copper target. The measurements were performed at the U-12 accelerator at an energy of 10 MeV at different positions inside and outside the hall, where the accelerator is located. The neutron spectra were measured by two different methods: i) using the stilbene crystal-based spectrometer NS-2 with the pulse shape discrimination of gamma-background, and ii) by means of activation detectors. In the last case, the neutron spectrum is reconstructed by the method of effective threshold cross- sections. The data obtained by different methods are in good agreement. To obtain information on time characteristics of neutron radiation, the neutron spectrum was measured simultaneously in the mode of continuous build-up and in the modes of on and off periods. Neutron yields from the (p,n) reaction were estimated. For the copper target, the neutron yield per 10 MeV accelerated proton was estimated to be $(3.5 \pm 1.0)\cdot10^{-3}$.

1. MEASUREMENT OF SPECTRAL AND TIME CHARACTERISTICS OF NEUTRON RADIATION BY MEANS OF NS-2 SPECTROMETER

The energy spectra of neutron radiation resulting from the interaction of an accelerated proton beam with the target were measured at the U-12 accelerator at an energy of 10 MeV at different positions inside and outside the hall, where the accelerator is located. A stilbene crystal-based spectrometer NS-2 with pulse shape discrimination of gamma-background was used to detect neutrons. The apparatus spectra of neutrons were processed with a microprocessor of the analyzer LP-4900B. Fig.1 shows the processed data on neutron spectra obtained at location 5 (see Fig.1 of [1]) being at a distance of 0.5 m from the target at a height of 1.5 m relative to the hall floor. The measurement time was 1.5 h, the accelerated proton beam energy was 10 MeV, the frequency was 1 Hz. Fig.2 and 3 show the neutron spectra measured at the on and off periods, respectively. The neutron spectrum exhibits an exponential character of intensity decrease with time, the total duration being 10 ms.

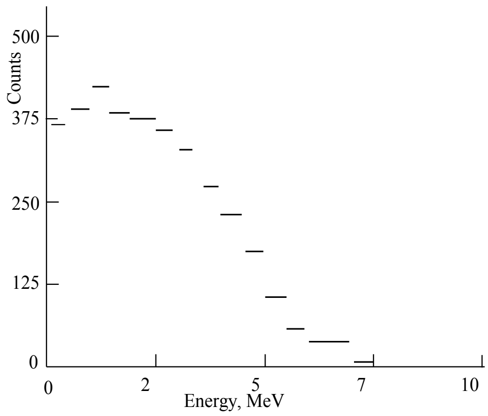

Fig.1. Neutron energy spectrum measured by the NS-2 at point 5 at a proton energy of 10 MeV

The count information in the neutron channel of the NS-2 spectrometer was used for measuring the space distribution of neutrons in the accelerator hall. The values obtained on the neutron field intensity at certain locations of NS-2 spectrometer represent the total intensity of prompt and latent neutrons. The results of neutron flux intensity measurements (in relative units) are given in Table 1, which also lists the values of the distance from the target, R, and the height H (in meters).

Table 1

Place of measuring	R, m	H, m	Φ_n (relative)
1	3	0	1.0
2	5	1.5	0.06
3	2	1.5	0.11
4	3	1.5	0.06
5	0.5	1.5	2.0
6	2.5	0	0.9

The energy spectrum of neutrons measured at point 1 is mainly contributed by neutrons scattered from structural elements and walls of the canyon. The average energy of neutrons detected at point 4 behind the shield is somewhat higher than the one at point 3 located before the shield. This is explained by the fact that the cross section for the interaction of neutrons with the concrete shield elements decreases with an increasing energy. Therefore, the low-energy part of the neutron spectrum is attenuated to an appreciably greater extent as opposed to the high-energy part that carries information on the proton beam energy.

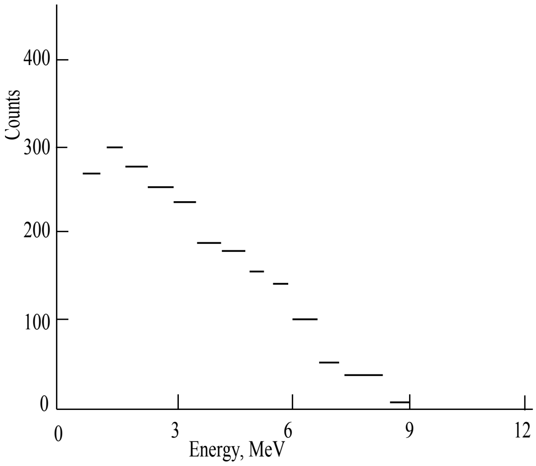

Fig.2. Neutron energy spectrum measured by the NS-2 at point 5 at a proton energy of 10 MeV during the on period (prompt neutrons)

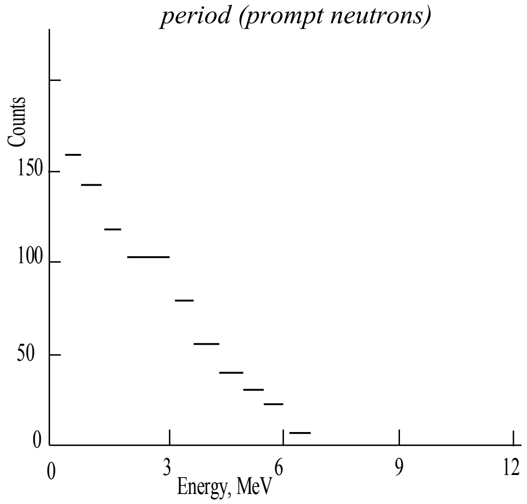

Fig.3. Neutron energy spectrum measured by the NS-2 at point 5 at a proton energy of 10 MeV at the off period (latent neutrons)

2. MEASUREMENT OF NEUTRON RADIATION SPECTRAL CHARACTERISTICS BY MEANS OF ACTIVATION TECHNIQUE

Aside from the neutron spectrometer NS-2, the activation technique was also used to measure the neutron spectra. For the purpose, threshold detectors made from magnesium, iron, zinc, cobalt, etc., arranged along the axis of the accelerated beam, were used. The total proton fluence on the target was $3.64 \cdot 10^{16}$, the exposure time was 7.9 h. The rate of activation was determined from the intensity of gamma-radiation accompanying the β-decay of radioactive nuclides produced.

The spectrum of neutrons was restored on a method of effective threshold cross sections [2]. Cross sections of activation of threshold detectors for energy neutrons E_n<10MэВ varies rather slowly, therefore it can be approximated step function, having put cross section of i-st threshold reaction of below threshold energy E^i_{ef} equal 0, and higher- is constant and equal to σ^i_{ef}. Values of effective thresholds E^i_{ef} for the used reactions are resulted in table 2.5 in work [2]. Then speed of activation of the i-st threshold detector A_i, is connected to cross section of activation and with spectrum of neutrons φ(E) in the following expression:

$$A_i = \int_{E_{th}}^{\infty} \sigma_i(E) \cdot \varphi(E) \cdot dE = \sigma^i_{ef} \cdot \int_{E_{th}}^{\infty} \varphi(E) \cdot dE.$$

The effective threshold cross section will be equal to

$$\sigma^i_{ef} = \frac{\int_{E^i_{th}}^{\infty} \sigma_i^2(E) \cdot \varphi(E) \cdot dE}{\int_0^{\infty} \sigma_i(E) \cdot \varphi(E) \cdot dE},$$

where E_{th} is the threshold of reaction. As a neutron spectrum φ(E), we took the calculated spectrum of neutrons generated on the copper target under the action of 10 MeV protons. The calculations were carried out by the statistical model of the compound nucleus with due account for the pre-equilibrium decay [3]. With knowledge of effective threshold and the reaction cross section, one can determine the integral spectrum value through the use of the measured activation integrals:

$$\Phi(E^i_{ef}) = \frac{A_i}{\sigma^i_{ef}} = \int_{E^i_{ef}}^{\infty} \varphi(E) \cdot dE .$$

With a set of threshold detectors the neutron spectrum is obtained in the form of histograms

$$\varphi_i(E) = \frac{\Phi(E^{i-1}_{ef}) - \Phi(E^i_{ef})}{E^i_{ef} - E^{i-1}_{ef}}, i = 1,2,...n .$$

The measured data are presented in Fig.4. The measured neutron spectrum is identical to the spectrum obtained by neutron spectrometer measurements (Fig.2). Therefore, the measurements of neutron spectra in continuous and discrete regimes give identical results.

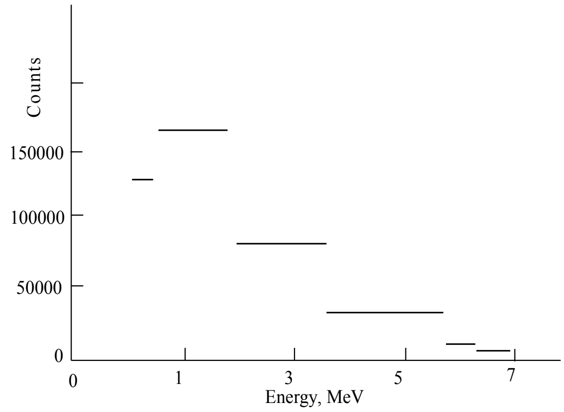

Fig.4. Neutron energy spectrum measured by means of activation detectors

3. DETERMINATION OF NEUTRON YIELDS FROM THE COPPER TARGET

The spectra of gamma-radiation that resulted from induced activity were measured after the accelerator being operated for 6 hours was switched off. The operation parameters of the accelerator were as follows: average pulse current 1.2 mA, beam energy 10 MeV, frequency 1 Hz. The beam was absorbed in the copper target presenting a set of copper foils with a total thickness of 340 g/cm^2, ensuring the total beam absorption. The target frame was made from aluminum. In the experiment, we used a Ge(Li) spectrometer situated at 4 m from the target. A series of 6 measurements was performed during 24 hours following the stop of the accelerator. As an additional criterion in the identification of elements of the corresponding gamma-lines present in the spectrum, their half-lives were used. The last ones were determined from the intensity ratios for different time periods after accelerator stop. Table 2 gives the main gamma-lines of induced activity.

Table 2

Energy, keV	Reaction	Half-life
511, 669, 962	$^{63}Cu(p,n)^{63}Zn$	38.4 m
511, 1115	$^{63}Cu(p,n)^{63}Zn$	245 d
1368, 2754	$^{27}Al(p,\alpha)^{24}Na$	15.02 h
1095, 1292	$^{58}Fe(n,\gamma)^{59}Fe$	45,6 d

As it follows from the table, the induced activity is the result of interaction between the primary accelerated proton beam and the target material, and also between the secondary neutrons and the structure element materials. The gross activity at the moment of accelerator stop was calculated to be $(4.2\pm0.4)\cdot10^{10}$ Bq and was mainly contributed by zinc isotopes, i.e., by the copper activity target. The gross activity of zinc isotopes was used to estimate the yield of neutrons from the (p,n)-type reaction on the copper target, since the activity of radioactive nuclide is determined by the total number of its nuclei. Taking into account the attenuation of gamma-radiation in the vacuum enclosure of the accelerator and the decay of zinc nuclide during irradiation, the total number of neutrons produced was estimated to be $(1.4\pm0.2)\cdot10^{14}$. The total proton fluence on the target was $4\cdot10^{16}$. Therefore, the neutron yield per accelerated proton of 10 MeV energy makes $(3.5\pm1.0)\cdot10^{-3}$ for the copper target, this being in good agreement with the earlier data [4].

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ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ СПЕКТРА НЕЙТРОНОВ, ГЕНЕРИРУЕМЫХ В МЕДНОЙ МИШЕНИ ПРОТОНАМИ С ЭНЕРГИЕЙ 10 МэВ

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Проведено измерение энергетических спектров и интенсивности нейтронного излучения, генерируемого в медной мишени пучком протонов с энергией 10 МэВ. Спектры нейтронов измерены с помощью двух различных методик: с дискриминацией гамма-фона по форме импульса, а также с применением активационных детекторов. Определен выход нейтронов из медной мишени – $(3.5\pm1.0)\cdot10^{-3}$ на один ускоренный протон с энергией 10 МэВ.

ЕКСПЕРИМЕНТАЛЬНЕ ДОСЛІДЖЕННЯ СПЕКТРУ НЕЙТРОНІВ, ЩО ГЕНЕРУЮТЬСЯ В МІДНІЙ МІШЕНІ ПРОТОНАМИ З ЕНЕРГІЄЮ 10 МеВ

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Проведено вимір енергетичних спектрів і інтенсивності нейтронного випромінювання, генеруемого в мідній мішені пучком протонів з енергією 10 МеВ. Спектри нейтронів вимірювалися за допомогою двох різних методик: з дискримінацією гамма-фону за формою імпульсу, а також із застосуванням активаційних детекторів. Визначено вихід нейтронів з мідної мішені - $(3.5\pm1.0)\cdot10^{-3}$ на один прискорений протон з енергією 10 МеВ.