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ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ СО АН СССР

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HIGH EFFICIENCY NEUTRON SPECTROMETER WITH LOW BACKGROUND

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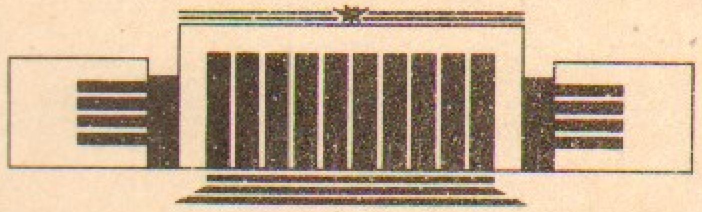

НОВОСИБИРСК

High Efficiency Neutron Spectrometer with Low Background

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ABSTRACT

A neutron energy spectrometer with a geometry close to 4π solid angle operated in the (1–5) MeV energy range at a suitable for a "cold fusion" experiment configuration and a very good n/γ discrimination, has been constructed. Tests of registration efficiency, energy resolution and radiation type identification have been made with a help of low intensity neutron and gamma sources. The spectrometer has shown the efficiency of about 10% at the $2\cdot10^{-3}s^{-1}$ background level and permits one to measure a neutron energy spectrum at a very low intensity of the source.

This paper describes physical principles, and design of the neutron detector system and results of its testing.

1. INTRODUCTION

At the first observations of a neutron emission in so called "cold fusion" reactions [1, 2] it was clear that for achievement of the reliable results in such experiments a neutron detector system should have a background level less than $10^{-2}s^{-1}$ at a registration efficiency of about 10%. The ^{3}He neutron counters SNM-18 with a polyethylene moderator and a good protection against neutrons and electromagnetic noises coming outside, permitted us in 1989 to construct a neutron detector with a suitable characteristics [3]. The neutron emission during chemical reactions in deuterised matter was observed by this detector [4]. In order to achieve more reliable results at a further step of the investigations it was necessary to decrease the background level and to measure an energy spectrum at a very low intensity of the neutron emission (10^{-2} n·s^{-1}·g^{-1}). According to these requirements a new detector system which is based on a determination of the correlations between the signals at the registration of the same neutron by a plastic scintillator detector at a few MeV energy region and then by ^{3}He neutron counters at a thermal energy of the neutron, has been constructed.

Because of the counter signal as soon as the scintillator detector one has the time duration of about 100 ns a random coincidence between the signals of these two type of the measurement systems should be a very small value. At the determination of the correlation between these signals one needs to take into account a significant time delay ($\sim$ 100 μs) between their generation. This time delay has been experimentally measured on the constructed spectrometer.

2. THE SPECTROMETER DESIGN

A schematic of the neutron energy spectrometer is shown in Fig. 1. The spectrometer consists of the scintillator detector (*9*) and six ^{3}He neutron counters SNM-18 (*4*). The scintillator detector is made of a cylindrical plastic (polystyrene) block with a 20 cm diameter. Two photomultipliers (Phillips 58 DVP) are connected to the both sides of this block. The cylindrical polystyrene block is placed inside a polyethylene cube (*5*) with 40 cm dimension. This cube is operated as a neutron moderator. An aluminum tube (*8*) with 4 cm inner diameter and 0.3 mm thickness of the wall crosses the cube and cylinder along the vertical axis. A test-tube (*6*) with an analysed matter has been placed inside this tube. The aluminum tube has a good electrical connect with a copper screen (*3*) of the spectrometer. The screen covers the scintillator detector with two photomultipliers and six ^{3}He neutron counters with theirs amplifiers. Such absolutely closing screen provides a good protection of the registration system against the electromagnetic noises. Moreover the neutron detector is placed in a room with metallic walls and roof. Outer surface of the copper screen is covered by a barium polyethylene shield (*2*) which reduces a flux of neutrons coming outside approximately in 30 times. In order to prevent the registration of cosmic particles by the scintillator detector all spectrometer is shielded by plate scintillator counters (*1*).

3. ELECTRONICS

Electronic scheme of the neutron spectrometer is shown in Fig. 2. Pulses of the photomultipliers PM pass through the discriminators D1 and come into a coincidence circuit CC1. The same configuration is realized for a CC2 coincidence circuit on which an antilogical pulse comes from the "veto" counters. "Veto" scintillator counters with an operated area 95×75 cm cover the spectrometer and are used as a trigger for the particles coming outside. The antilogical pulse from PT2 inhibit the coincidence circuit CC2 operation.

Signals from the ^{3}He neutron counters C after passing though amplifiers A and discriminators D3 are distributed between the neutron scaler S2 and Fan-In OR2. Identification of the neutron emitted from the center part of the spectrometer requires the following condition: two photomultipliers PM simultaneously must register a light flash in the scintillator; "veto" counters must not see a high energy particle at this time; during a waiting time interval (about one hundred of μs) any of the ^{3}He neutron counters C must register a neutron. The waiting time of the neutron counters corresponds to the time

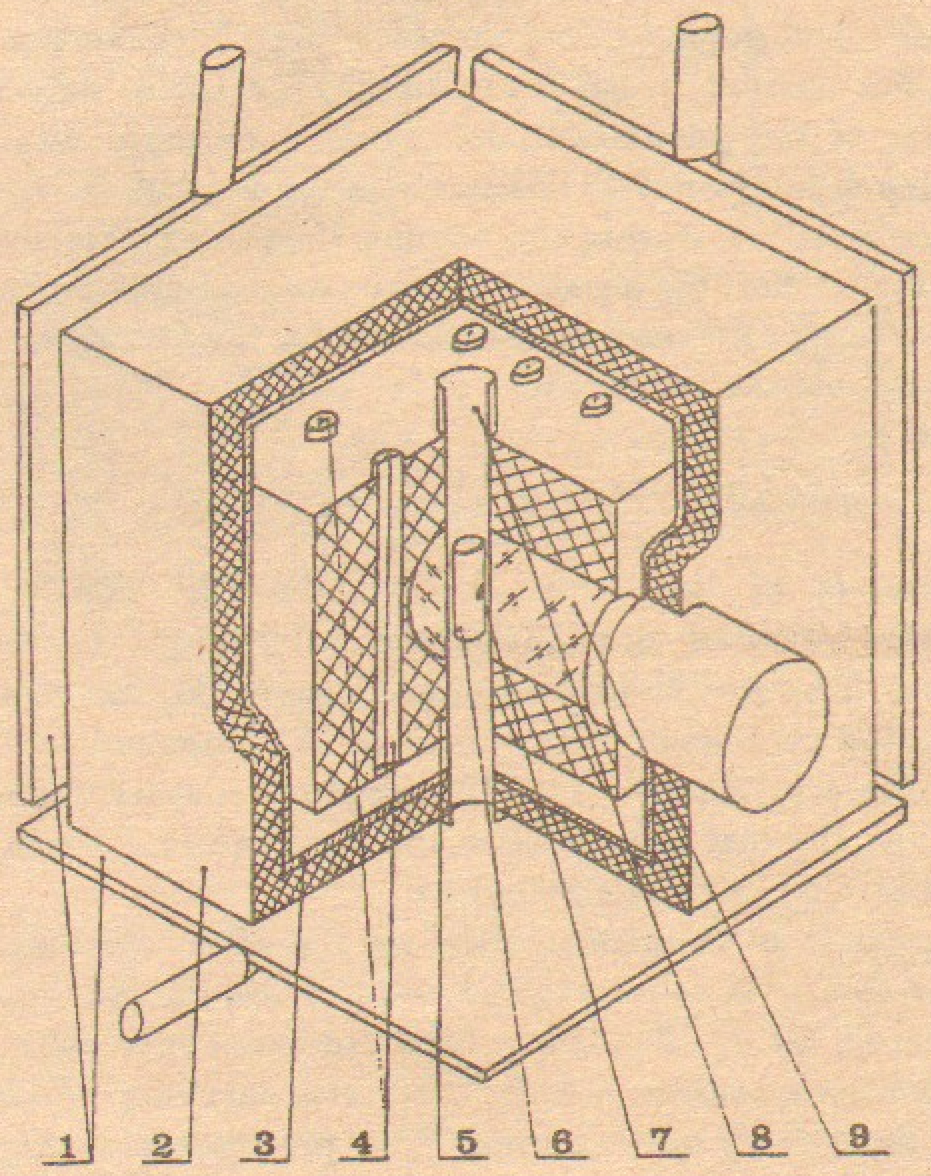


Fig. 1. The spectrometer schematic. *1* are scintillator "veto" counters; *2* is a shield against neutron; *3* is a copper screen; *4* are neutron counters; *5* is a polyethylene moderator; *6* is a test-tube; *7* is thermocouple; *8* is an aluminum tube; *9* is a scintillator detector.

interval between a coming of the fast neutron into the scintillator and its capture in the ^{3}He counter at the thermal energy.

Registration instruments: charge-to-digital converters (CDC), scalers (S), digital voltmeter (DV) are made in the CAMAC standard and controlled by "Odrenok" computer. The charge-to-digital converters measure the photomultiplier current pulses for obtaining an initial neutron energy. A digital analog of the photomultiplier signal is recorded into the computer memory independently of the ^{3}He neutron counter event. A number of the neutron counter events during the waiting time interval is also recorded. It gives possibility to find the number of neutrons produced by one reaction act.

Digital voltmeter DV measures signals from the thermocouple (see Fig. 1 (7)) which controls the temperature of the test-tube during chemical process accompanied by its exchanges.

4. MEASUREMENTS OF THE CAPTURE DELAY TIME

Measurements of the delay time of the ^{3}He counter pulses after the scintillator detector one have been carried out in the constructed spectrometer. The scintillator detector registers the fast neutron due to a scattered proton producing a light flash at that moment when the neutron comes into the scintillator. The ^{3}He neutron counter registers the same neutron at the thermal energy after the time interval which takes for the neutron moderation in the polyethylene.

A logic pulse from the photomultipliers PM after coincidence circuit CC1 starts a time-to-digital converter and a stop pulse for the converter is taken from the Fan-In OR2. The delay time measurements have been done by using a radioactive neutron source ^{252}Cf with intensity of about 10 decays per second. Each decay of the nuclear ^{252}Cf produces in average 3.7 neutrons emitted with the most probable energy E_n close to 2 MeV (see [5]). On this purpose the scintillator detector event may be accompanied by a few ^{3}He counter events. This circumstance as it will be shown later, gives a possibility to obtain the registration efficiency of the spectrometer.

Results of the delay time measurements are shown as a histogram in Fig. 3. The histogram represents a number of the ^{3}He counter events coming in 10 μs intervals as a function of the delay time measured after the pulse from the scintillator detector. One can see that it takes a few tens of μs for the moderating of the neutrons, after this time interval their capture in the ^{3}He counters begins. Later the neutrons "live" in the moderator during $\sim$ 200 μs at a slowly decreasing of their quantity. Taking into account this result we have chosen the waiting time of the ^{3}He counters signals equal to 250 μs.

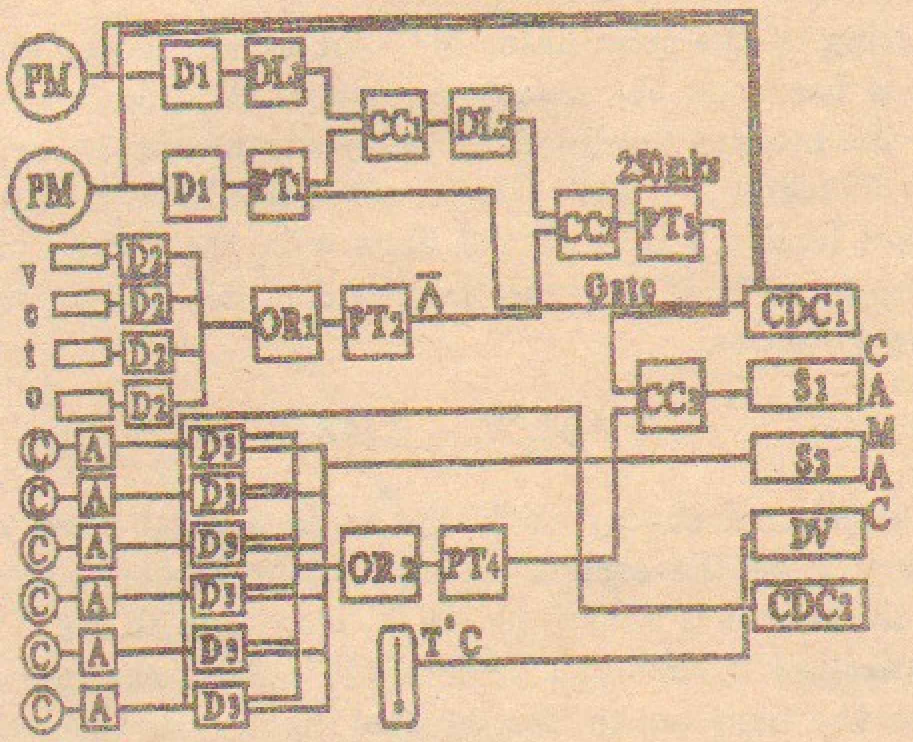


Fig. 2. Trigger logic and circuit scheme.

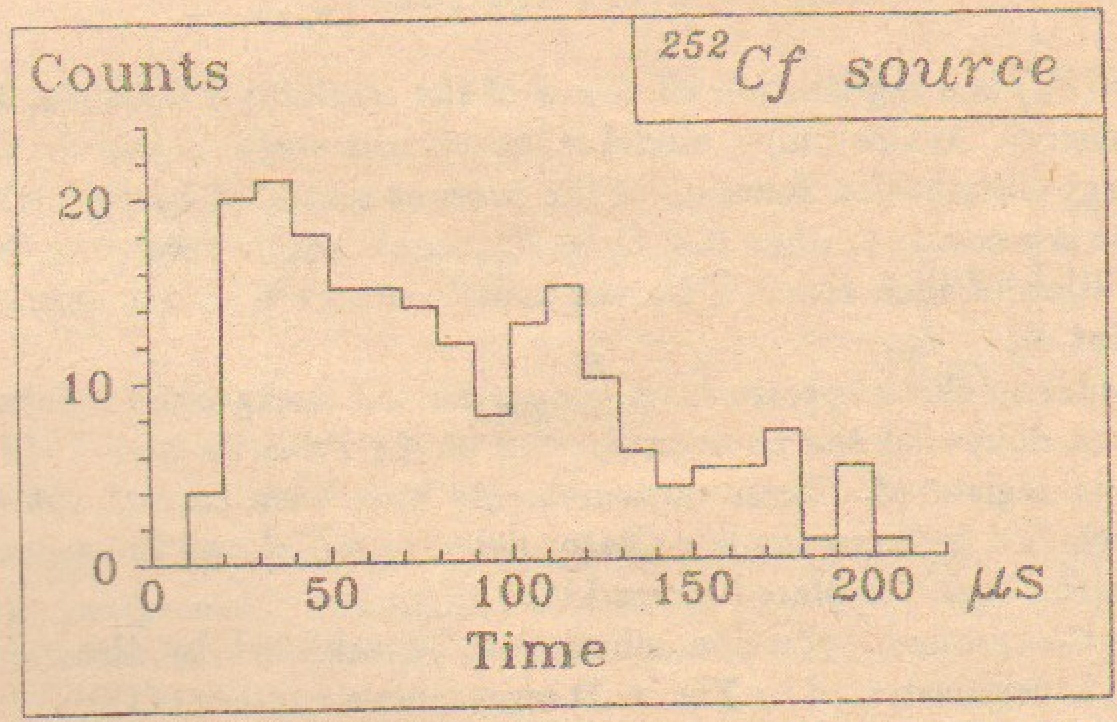


Fig. 3. Histogram characterizing the delay time of the neutrons.

5. PERFORMANCE OF THE DETECTOR

The operating of the scintillator detector as an energy spectrometer of the neutrons is based on the measurements of the photoemission which is generated by the protons scattered by the neutrons. In the 1–3 MeV energy interval the total scattering cross section of the fast neutrons on the hydrogen nuclei decreases from 4.3 Barn to 2.2 Barn with the energy increase. Then in the range up to 30 MeV the cross section decrease can be described by an approximation formulae:

$$\sigma_h = 4.83/E_n - 0.578 \text{ [Barn]}$$

where E_n is a neutron energy in MeV. As to a total cross section of the neutron scattering on the carbon nuclei σ_c (the second component of the scintillating material) it is unvariable at E_n from 2 to 10 MeV: σ_c=1.7 Barn. At this cross section σ_c one can neglect the carbon channel of the energy transmit from the neutron to the emitted light. In this case a neutron energy distribution function dN_n/dE_n can be described by using an energy distribution function of the scattered protons dN_p/dE_p in the following way (see, for example [6]):

$$\frac{dN_n}{dE_n} = -\frac{E_n}{S(E_n)}\frac{d}{dE_n}\left[\frac{dN_p}{dE_p}\right]_{E_p=E_n}$$

where $S(E_n)$ is a registration efficiency of the scintillator detector, E_p is the proton energy. At this simple model of the neutron scattering on the hydrogen the energy distribution function of the protons scattered by monochromatic neutrons is a constant when $0 \le E_p \le E_n$, and it equals sero when $E_p \ge E_n$. A derivation of such function on the proton energy E_p gives delta-function at a point $E_p = E_n$.

In order to check spectrometer properties the background measurements have been done and the neutron spectra of the Pu-α-Be and ^{252}Cf sources have been registered. These measurements have been carried out by using the correlation between the scintillator detector signal and the signals of the ^{3}He neutron counters placed around it.

The background reduction which can be achieved by this correlation method, is demonstrated by Fig. 4. It represents a number of the events vs an amplitude of their pulses. The upper diagram corresponds to the spectrum of the background pulses stored from one of the photomultipliers PM during 3205 s in the coincidence with another one signals. The down diagram shows the events selected from the upper spectrum on the correspond to the coinci-

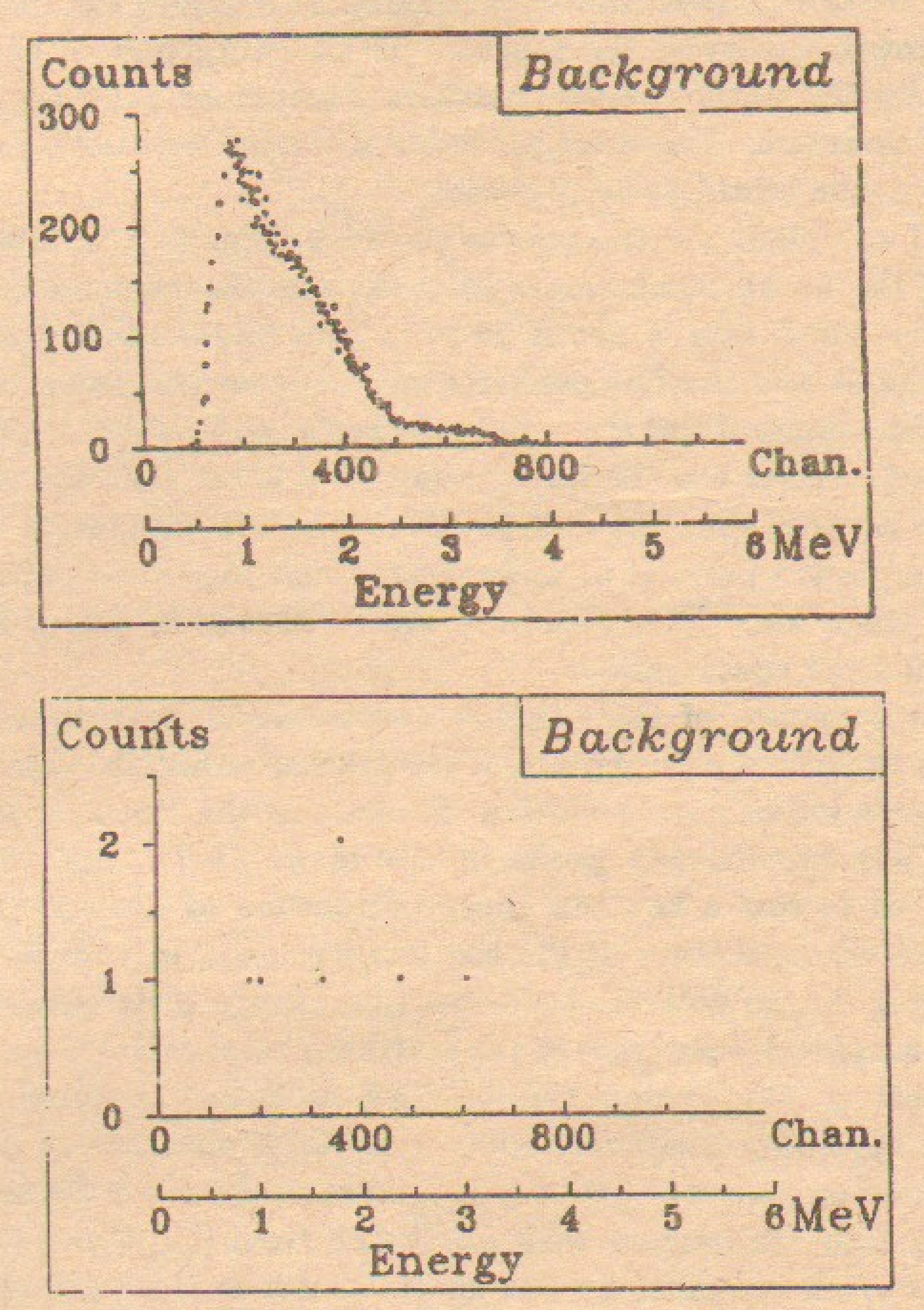


Fig. 4. Results of the background measurements. Upper diagram is the background of the scintillator detector only. Down diagram shows the events chosen by using the correlation technique.

dence between the scintillator detector signals and ^{3}He neutron counter ones. One can see that the background noise given by the light coming to these photomultipliers from the scintillating material, are reduced due to this technique at least in two orders. It permits to measure the neutron energies at a very low intensity of the sources. These background events can not be produced by the outer coming particles because of a strong inhibition by the "veto" counters. The most probably it should be a result of radioactive pollutions in the scintillating material.

Table 1 complements the results shown in Fig. 4. One can see that the number of the background events from the scintillator detector is 34701 per 3205 s. The count rate is about 10 s^{-1}. The coincidence of the scintillator detector signals and the ^{3}He counters ones reduces this value to 7 events per the same time interval and the count rate becomes $2 \cdot 10^{-3} s^{-1}$. So, the neutron energy spectrometer has the background level lower than the detector based on the ^{3}He neutron counters only [4]. Moreover the correlation method of the n/γ discrimination permits us to have the count rate close to the background one, even when the ^{137}Cs gamma source with the intensity $1.5 \cdot 10^4 s^{-1}$ is placed inside the spectrometer.

Further reducing of the neutron spectrometer background level as we hope, may be achieved to replace of the central scintillator block by another one without a radioactive pollution. Because of the Pu-α-Be source neutron spectrum has two distinct peaks in the range (3–7) MeV this source has permitted us to test a neutron energy resolution of our spectrometer. The pulse amplitude spectrum of the scattered protons in case of this source is shown in Fig. 5. To determine the neutron energy distribution function the measured amplitude spectrum of the scattered protons has been differentiated with respect to the proton energy. An analytical approximation of the amplitude spectrum has been done to perform the correct differentiation. The obtained on this way neutron spectrum of the Pu-α-Be source is shown in the Fig. 5 in comparison with one taken from [6]. One can see that the energy spectrum obtained by our spectrometer is close enough to it. As a result of it we may say, that neutron energy resolution is about 1 MeV.

Fig. 6 represents the amplitude spectrum of the pulses from the scintillator detector when a radioactive neutron source ^{252}Cf has been placed inside the spectrometer. This spectrum has been obtained by using the correlation procedure. For the ^{252}Cf source the correlation technique gives the opportunity to obtain good results in the neutron measurements. This technique measures about 4 events per second at the source with the strength of about 10 decays per second Fig. 6. In the case when the correlation technique is switched off, the radioactive pollution gives the background count

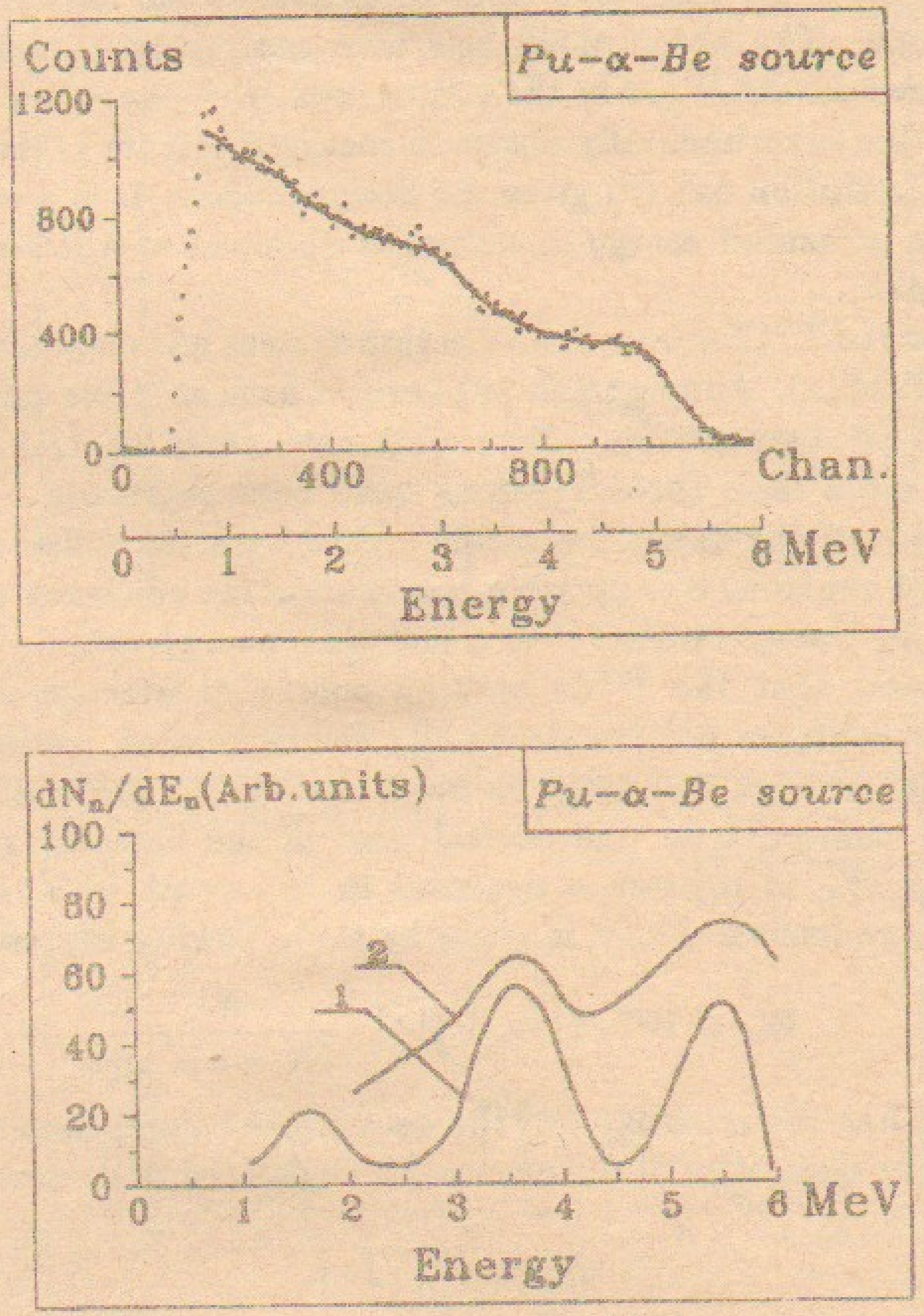


Fig. 5. Energy spectrum of the neutrons emitted by the Pu-α-Be source. Upper diagram is the amplitude spectrum of the scattered protons. Down diagram is the neutron energy spectrum: curve *1* is obtained by the derivation of the analytical approximation of the amplitude spectrum represented on the upper diagram; curve *2* is graphic taken from [6].

rate of about 10 s^{-1} which is higher than the ^{252}Cf source gives. The amplitude spectrum of the scattered protons measured in case of the ^{252}Cf source has been differentiated with respect to the proton energy. For the correct derivation an analytical approximation of the amplitude spectrum has been done. The obtained on this way neutron spectrum of the ^{252}Cf source is shown in the Fig. 6 in the comparison with one taken from [5]. One can see that the experimentally obtained energy spectrum (*1*) is similar to the analytical description one (*2*) given for decay process. It is a very important fact that the measured energy spectrum is obtained at a low number of the neutron events.

In case of the ^{252}Cf source the detection system has measured 4578 events per 1401 s (Table 1). Among them 3914 events have only one emitted neutron, 597 events have two neutrons, 60 events have three neutrons and, finally, in 7 events more than three neutrons have been registered. By using the relations between the quantities of the events with the different numbers of the registered neutrons it is possible to calculate the efficiency of the neutron registration by the spectrometer in a few MeV energy range.

It is known that the ^{252}Cf neutron source in average on the decays produces 3.7 neutrons per one decay [5]. For estimation one can accept the number of neutron per one decay as N=4. Let W is a probability to register one neutron emitted from the central part of the detector system. Then a probability W_n to register n neutrons in the event with the N emitted neutrons in one nuclear decay, is given by the following expression:

$$W_n = W^n \cdot (1-W)^{n-1} \cdot \frac{N!}{(N-n)! \cdot n!}.$$

If the source has the intensity I of the decays per second then during a time interval (t) the quantities of the events M_n registered with the n neutrons, is following:

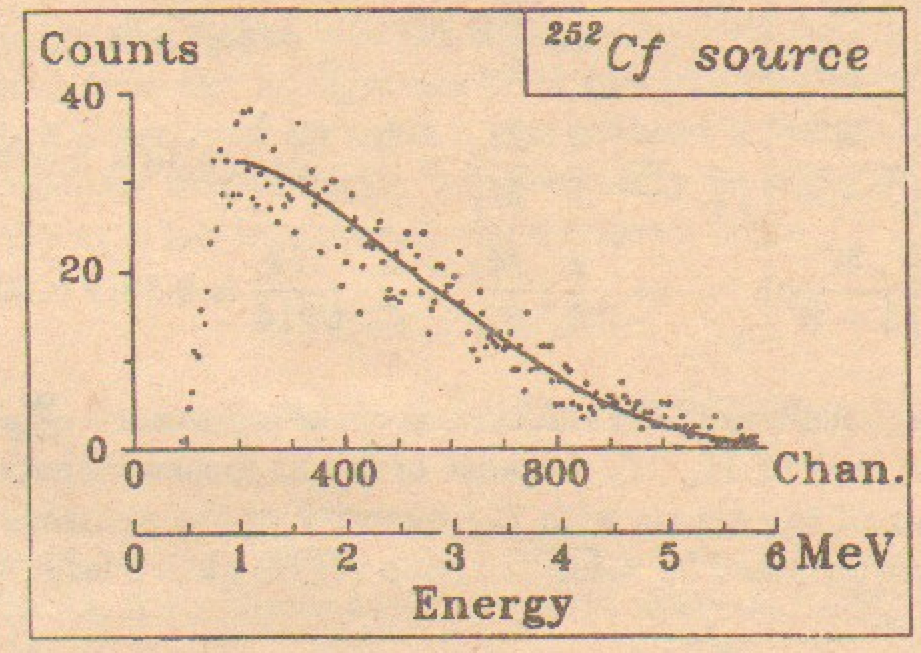
$$M_n = W_n \cdot I \cdot t.$$

In the case N=4 the ratio between the quantities of the events with the different numbers of the neutrons are following:

$$\frac{M_4}{M_3} = \frac{W^4}{4W^3 \cdot (1-W)} = \frac{1}{4} \cdot \frac{W}{(1-W)},$$

$$\frac{M_3}{M_2} = \frac{4W^3 \cdot (1-W)}{6W^2 \cdot (1-W)^2} = \frac{2}{3} \cdot \frac{W}{(1-W)},$$

$$\frac{M_2}{M_1} = \frac{6W^2 \cdot (1-W)^2}{4W \cdot (1-W)^3} = \frac{3}{2} \cdot \frac{W}{(1-W)}.$$



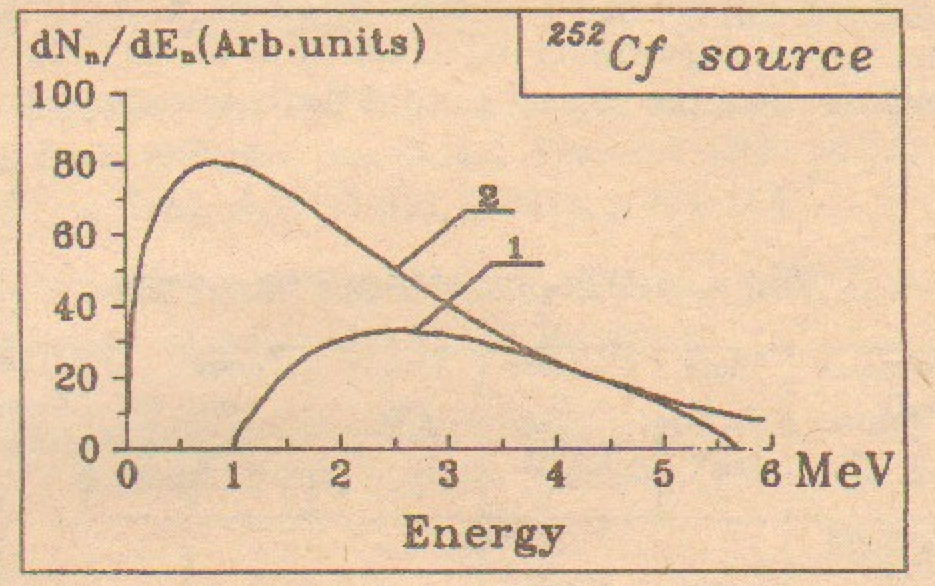


Fig. 6. Energy spectrum of the neutrons emitted by the ^{252}Cf source. Upper diagram is the amplitude spectrum of the scattered protons. Down diagram is the neutron energy spectrum: curve *1* is obtained by the derivation of the analytical approximation of the amplitude spectrum represented on the upper diagram; curve *2* is graphic of the analytical function taken from [5].

One can see that the parameter $\frac{W}{1-W}$ does not depend on the source intensity and it is determined by the ratios between different M_n only. So, one can write:

$$\left[\frac{W}{1-W}\right]_{4,3} = 4\cdot\frac{M_4}{M_3} = 4\cdot\frac{7}{60} \approx 0.47 \pm 0.24,$$

$$\left[\frac{W}{1-W}\right]_{3,2} = \frac{3}{2}\cdot\frac{M_3}{M_2} = \frac{3}{2}\cdot\frac{60}{579} \approx 0.16 \pm 0.027,$$

$$\left[\frac{W}{1-W}\right]_{2,1} = \frac{2}{3}\cdot\frac{M_2}{M_1} = \frac{2}{3}\cdot\frac{579}{3914} \approx 0.10 \pm 0.004,$$

It is clear that such way of the calculation of the parameter $\frac{W}{1-W}$ is not enough correct in the case of M_4/M_3, because of in our measurements the value M_4 is the number of the events with the quantity of the neutrons more than 3. And the result obtained by using the ratio M_4/M_3 has a large difference with the other ones.

The parameter $\frac{W}{1-W}$ characterizing the registration efficiency can be accepted of about 0.1 and as a result of it the efficiency of the detector system at the registration of a few MeV neutrons is estimated on a level of about 10%. So the registration efficiency is of about 10% for a few MeV neutrons emitted from the central part of the spectrometer.

Table 1

The neutron spectrometer operation

N	Measurement mode	Time (s)	Number of events	Count rate (s^{-1})	Quantity of the events with the different number of neutrons				Total number of neutrons
					1	2	3	>3	
1	Background scintill. detector	3205	34701	10.8	–	–	–	–	34701
2	Background scintill. detector with ^{3}He-counters	3205	7	$2\cdot10^{-3}$	7	0	0	0	7
3	^{252}Cf source scintill. detector with ^{3}He-counters	1401	4578	3.3	3914	597	60	7	5316

CONCLUSION

So, we have constructed the scintillator energy spectrometer operated in the range (1–6) MeV at the neutron registration efficiency of about 10%, very good n/γ discrimination and the background level near $2\cdot10^{-3}s^{-1}$. It may be expected that the background level can be done much lower if the scintillator block is replaced by another one without a radioactive pollution.

The spectrometer demonstrates the possibility to measure the neutron energy spectrum at a low intensity of the neutron source.

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