MODELLING MAIN CHARACTERISTICS OF FAST NEUTRON DETECTOR BASED ON RECOIL PROTONS WITH THE MONTE-CARLO METHOD

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The program for calculation of amplitude spectra and fast neutron detector efficiency has been developed with the Monte-Carlo method (MC). The detector operates on the basis of the method of recoil protons and consists of a hydrogenous radiator and a Si surface-barrier counter of protons. Testing of the MC-program was carried out. Energetic and angular dependence of amplitude spectra and detector efficiency at neutron energy of 1-15MeV were calculated.

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1. INTRODUCTION

The software and technique of restoring fast neutron spectra from the measured amplitude distributions are offered in papers [1-3]. The procedure of spectrum restoring is based on dependence of the amplitude distribution form on energy of neutrons. In turn this dependence is determined by properties of a certain detector.

Neutron detectors based on the method of recoil protons are widely used in nuclear-physical experiments [4,5]. To register scattered protons in such detectors the gas ionization cameras, scintillation and semiconductor counters are generally applied [4-7]. Each detector has its specific features connected with efficiency of fast neutron registration, sensitivity to accompanying γ-radiation, stability of working parameters etc. However, usage of surface-barrier Si (Au) counters with their simple construction and low sensitivity to γ-radiation has advantages over detectors of other types. At present, application of these detectors for spectrometry of fast neutrons remains an actual problem in experimental nuclear physics.

In the paper the model of calculating parameters of the fast neutron detector on the basis of the surface-barrier Si-counter is offered. To determine spectral and integrated characteristics of such a detector the FORTRAN program has been developed and realized. It allows simulating experimental amplitude spectra and neutron registration efficiency with the Monte-Carlo method. This program will be a base for developing an experimental sample of a spectrometer of fast neutrons. The basic elements of a code algorithm, its testing technique and calculation of results are indicated below.

2. CALCULATION TECHNIQUE

In the MC-program the process of interaction of fast neutrons with nucleuses of hydrogen and registration of recoil protons with the Si-counter is simulated. Design of the neutron detector is represented schematically in Fig. 1. The detector of a cylindrical form with a diameter d consists of a thin hydrogenous radiator with a thickness h_1 and a Si-counter of protons with a thickness of a sensitive layer h_2. The neutron with energy E_n drops under an angle θ_n on the radiator (in Fig. 1 $\theta_n=0°$) and interacts with a proton at depth z. The proton with energy $E_p=E_n\cos^2(\theta_p)$, scattered under the angle θ_p, in relation to an initial direction of neutron movement, loses a part of its energy ΔE_1 on the path length t_1 in the radiator and a part of its energy ΔE_2 in the sensitive layer of the Si-detector. The value ΔE_2 determines an amplitude of a "registered" signal from a neutron: $u=\Delta E_2$ in units of proton energies.

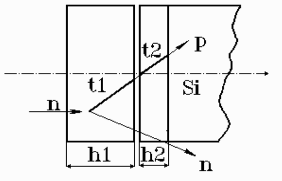

Fig. 1. *The scheme of detecting recoil protons*

The calculations are carried out not taking into account insignificant influence of the radiator on a neutron beam. For thin radiators h_1~1mm such assumption is quite justified.

The following values are given in the program at random:

- coordinates x, y on the radiator surface ($x,y \leq d/2$);
- coordinate z–depth (n,p)–interaction;
- angles φ and θ (φ–polar angle in the plane perpendicular to the direction of neutron movement, θ–azimuth angle relatively to this direction).

The trajectory of proton movement is set by direction cosines: $C_x=\cos(\varphi)\sin(\theta)$, $C_y=\sin(\varphi)\sin(\theta)$, $C_z=\cos(\theta)$. The appropriate coordinates are determined as follows: $x=tC_x$, $y=tC_y$, $z=tC_z$,, where t–length of a proton path in an appropriate material (radiator or silicon). The transition from angles φ and θ to C_x, C_y, C_z is carried out according to the algorithm offered in the program STANTON [8].

The energy losses of a proton are calculated analytically:

$$\Delta E_i = \int_0^{t_i} \left(\frac{dE}{dx}\right)_i dx\ , \tag{1}$$

where $(dE/dx)_i$ – stopping power of a proton in corresponding matter: i=1 – radiator, i=2 – silicon.

In the present program version the isotropic (n,p)-scattering is supposed to be given in c.i.s.. This approximation is executed with a good accuracy up to En ~ 20 MeV [5]. For transition into l.s. the cinematic correction is entered into the differential cross-section (n,p)–scattering [9]:

$$\frac{\sigma(\theta)}{\sigma(\theta^{/})} = \sqrt{8\,(1+\cos(\theta^{/}))}\ , \tag{2}$$

where θ – angle in l.s., $\theta^{/}$ – angle in c.i.s.

The efficiency of neutron registration with the detector is determined as follows:

$$\varepsilon = n\sigma(E_\mathrm{n})\frac{N_\mathrm{det}}{N_\mathrm{total}}\ , \tag{3}$$

where n–density of hydrogen atoms in the radiator, σ–total cross-section (n,p)–scattering, N_det–the number of the registered protons with energy higher than threshold E_th, N_tot–total number of random events.

The empirical dependence of a total cross-section (n,p)–scattering from neutron energy E_n is approximated accurately by expression [5]:

$$\sigma(E_\mathrm{n}) = 1{,}3\left(\frac{3}{(1{,}22-0{,}06E_\mathrm{n})^2+\frac{E_\mathrm{n}}{2}}+\frac{1}{(0{,}27+0{,}06E_\mathrm{n})^2+\frac{E_\mathrm{n}}{2}}\right), \tag{4}$$

where $\sigma(E_\mathrm{n})$ is given in barn, E_n – in MeV.

The brief contents of the program algorithm is the following:

1. Reading input dates (parameters and characteristics of the detector and neutron beam).
2. Generating a number of random events N_tot:

2.1 choosing coordinates x, y, z of interaction of a neutron with a proton;

2.2 choosing angles φ and θ of proton output;

2.3 controlling a proton trajectory crossing with a sensitive layer of the Si-detector (if it is not present, return to item 2.1);

2.4 determining energy losses of a proton in the radiator (if $\Delta E_1 \geq E_\mathrm{p}$, return to item 2.1);

2.5 determining energy losses in silicon ΔE_2 and forming an amplitude spectrum.

3. Calculation of neutron registration efficiency for given registration thresholds.
4. Writing down an amplitude spectrum and efficiency.

3. TESTING OF THE MC–PROGRAM

For examination of the MC-program an analytical test variant of calculating amplitude distributions has been developed. It assumes the following:

- normal falling of neutrons into the center of the radiator surface ($\theta_\mathrm{n}=0°$, $x=y=z=0$);
- stopping power of a proton do not depend on its energy ($(dE/dx)_i=\mathrm{const}=c_i$, i=1, 2);
- the range of a proton in silicon $R \geq t_2$, where t_2–effective thickness of sensitive layer of the Si–detector: $t_2=h_2/\cos(\theta_\mathrm{p})$, where θ_p–outlet angle of proton.

The later condition determines dependence of the amplitude of a "registered" signal:

$$u = \Delta E_2 = \frac{c_2 h_2}{\cos(\theta_\mathrm{p})}\ . \tag{5}$$

The value of residual energy of a proton after passing layers t_1 and t_2 is:

$$E_2 = E_\mathrm{p}(\theta) - \Delta E_1 - \Delta E_2 = E_\mathrm{n}\cos^2(\theta_\mathrm{p}) - \frac{c_1 h_1}{\cos(\theta_\mathrm{p})} - \frac{c_2 h_2}{\cos(\theta_\mathrm{p})}\ . \tag{6}$$

The expression (6) determines an interval of angles, in which the ratio (5) is executed:

$$0 \leq \theta_\mathrm{p} \leq \theta_\mathrm{max}\ , \tag{7}$$

where the value θ_max can be taken from (6) for E_2=0:

$$\cos(\theta_\mathrm{max}) = \sqrt[3]{c_1 h_1 + c_2 h_2}\ . \tag{8}$$

The range of "registered" amplitudes corresponded to an interval of angles (7), is determined from (6) and (8):

$$E_\mathrm{min} \leq E_p \leq E_\mathrm{max}\ , \tag{9}$$

where $E_\mathrm{min}=h_1c_1$, $E_\mathrm{max}=E_\mathrm{min}/\cos(\theta_\mathrm{max})$.

At conversion from c.i.s. into l.s. an anisotropy (2) of proton yield arises. Taking into consideration (5) and (8), it results in energetic dependence of proton yield distribution:

$$\frac{dN}{dE} = 2N_{\text{tot}} \frac{c_2^2 \cdot x_2^2}{E_{\text{p}}^3} . \qquad (10)$$

Yield of protons in an energetic interval $\Delta E = E_2 - E_1$ is follows:

$$\Delta N = \int_{E_1}^{E_2} \left(\frac{dN}{dE} \right) dE = N_{\text{tot}} c_2^2 h_2^2 \left(\frac{1}{E_1^2} - \frac{1}{E_2^2} \right) . \qquad (11)$$

The result of the calculations according to the analytical dependence (11) are compared to those based on the MC–program, in which the choosing of angles is carried out in a range $0 \le \theta_p \le \theta_{max}$. As an illustration the example of such comparison executed is given in Fig. 2 for the following parameters: E_n=14 MeV, h_1=0.1 mm, h_2=0.2 mm, c_1=8.8 MeV/mm, c_2=10 MeV/mm, cos(θ_{max})=0.5905, $N_{tot}=10^5$. As it is seen from Fig. 2, the results obtained from the analytical dependence (11) and those received with the help of MC–program, coincide, that testifies to a right choice of the calculation algorithm.

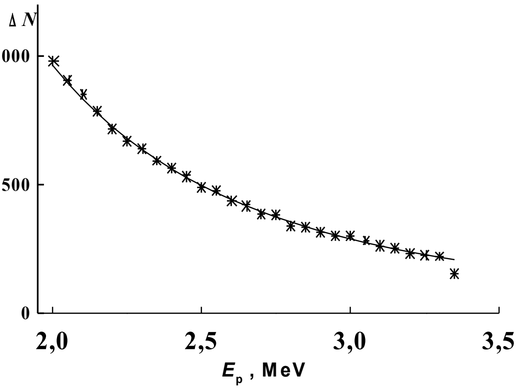

Fig. 2. *Test calculation. A solid line - analytical dependence, asterisk— MC-program*

4. RESULTS OF CALCULATIONS DONE WITH THE MC-PROGRAM

The amplitude spectra and efficiency of the neutron detector operated on the basis of recoil protons depend on parameters of the detector, characteristics of a neutron beam and conditions of a neutron registration: thickness of the radiator; sensitive layer of the Si-detector; element composition of the radiator; energy of neutrons and their angle of incidence onto the detector; a threshold of registration etc.

The examples of calculations done with the MC–program, which reflects these dependences, are indicated below. The calculations are executed for the detector of a diameter d=22 mm, h_2=0.2 mm, matter of radiator is mylar (density 1.4 g/cm3, contents of hydrogen 36 %). The values of energy losses and proton regions are calculated with the program TRIM [10].

Fig. 3 presents the amplitude spectra calculated for monoenergetic neutrons with energies E_n=1, 10 and 15 MeV, dropping normally onto the surface of the detector with h_1=0.018, 0.92 and 1.89 mm, accordingly. The number of random events is equal to $N_{tot}=2.5 \cdot 10^4$ for E_n=1 MeV and $N_{tot}=10^5$ for E_n=10 and 15 MeV. It is necessary to mark that the amplitude distributions are not normalized for the total efficiency of the detector.

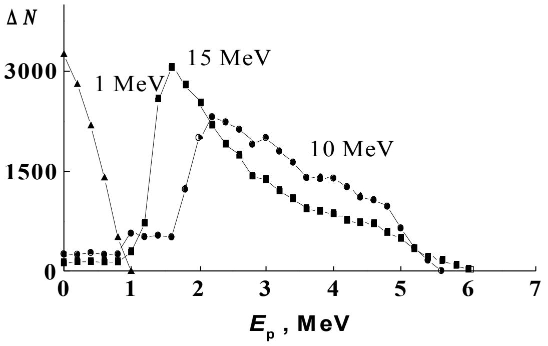

Fig. 3. *Amplitude spectra for E_n=1, 10 and 15 MeV*

Integration of the amplitude spectra (see Fig. 3) for various values of initial proton energy gives the dependence of fast neutrons registration efficiency ε on neutron energy E_n and threshold of registration E_{th}: ε (E_n,E_{th}). The dependence of efficiency ε in ranges of energy E_n=1–15 MeV and of registration threshold E_{th}=0 –5 MeV is indicated in Fig. 4. The calculations are executed for neutrons dropping perpendicularly to the surfaces of the detector for radiator thickness h_1=0.5 mm and $N_{tot}=10^4$.

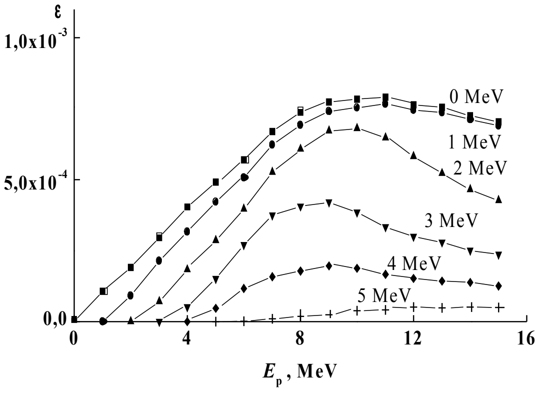

Fig. 4. *Energetic dependence of efficiency*

The important characteristic of the fast neutron detector is the dependence of registration efficiency on the angle θ_n of neutron incidence onto the detector. Change of efficiency, in turn, is determined by respective change of amplitude distribution. Fig. 5 illustrates the amplitude distribution alteration caused by changing the angle θ_n. The calculations have been executed for monoenergetic neutrons with E_n=10 MeV, angles θ_n=0°, 40° and 90° and appropriate values h_1=0.5, 0.5 and 0.1 mm; $N_{tot}=10^5$. It is seen, that with increase of the angle θ_n the range of registered amplitudes increases up to the maximum energy of a proton equal to E_n.

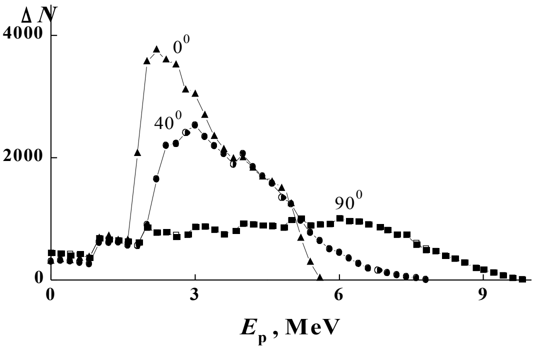

Fig. 5. Amplitude spectra for θ_n=0°, 40° and 90°

The angular dependence of neutron registration efficiency with E_n=10 MeV is represented in Fig. 6. Because of the peculiarities of spectral amplitude distribution (initial part of a spectrum, see Fig. 5) the efficiency weakly depends on a threshold of registration in an interval E_{th}=0–2 MeV and it depends highly on an angle of neutron incidence. With increase of a registration threshold the efficiency becomes less sensitive to the angle of neutron incidence for the front angles and it depends more on a value of the threshold.

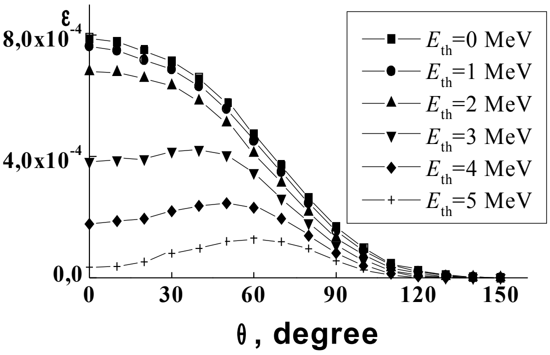

Fig. 6. Angular dependence of efficiency

5. CONCLUSIONS

The program for calculation of amplitude distributions and efficiency of fast neutron registration with the detector based on recoil protons has been developed with the Monte-Carlo method. The test–program calculating amplitude spectra with the analytical method was created. The conducted comparisons of calculations made with the analytical and Monte-Carlo methods showed a satisfactory agreement.

On the basis of the calculated amplitude spectra it is possible to carry out the restoring of neutron spectra, measured with the detector, in a range of neutron energies E_n~0,5–8 MeV. For restoring spectra of neutrons with E_n>8–10 MeV it is necessary to take into account the contribution into amplitude distributions of charged particles from (n,p) and (n,α)–reactions on nucleuses of carbon and oxygen contained in the radiator, and on nucleuses of silicon which compose the base of the surface–barrier detector of charged particles.

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