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SILICON STRIP-DETECTOR WITH A POLYETHYLENE CONVERTER AS A POSITION SENSITIVE DETECTOR FOR A NARROW BEAM OF FAST NEUTRONS

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The possibility of using the silicon strip-detector coated with a polyethylene film for the coordinate determination of fast neutrons has been discussed. The accuracy of the fast neutron coordinate determination is dependent on peculiarities of the interaction of neutrons with polyethylene and the accuracy of the registration of the recoil protons produced by fast neutrons in a polyethylene film, i.e. energies and angular distributions of the recoil protons and characteristics of tracks produced in the detector. The average charge collected on strips as a function of coordinates of incident neutrons has been calculated. It is shown that the most important for the best charge collection and accuracy of the coordinate determination is the choice of the interstrip distance. The other factors influencing on the coordinate determination (the distribution of the electrical field in the detector, the ratio of the track length to the interstrip distance) have been discussed.

Keywords: position sensitive particle detectors, neutron detectors.

1. Introduction

Silicon strip-detectors with converters of neutrons into charge particles can be used as neutron position sensitive detectors. Semiconductor detectors with converters for detection of neutrons were investigated in a number of papers. They were used for the neutron spectroscopy [1], as the position sensitive neutron detectors [2], for investigations of thermal neutron fluxes [3, 4], for the neutron radiography [5, 6].

The neutron detection efficiency determines mainly by the efficiency of the conversion of the neutron radiation into charge particles or other ionization radiation. Relatively high efficiency ~3 - 4 % for the thermal neutrons detection can be obtain using for the neutron conversion the next nuclear reactions with high cross-section of the thermal neutrons absorption:

$$^{6}Li + n \rightarrow \alpha + {}^{3}H\ ,$$
$$^{10}B + n \rightarrow \alpha + {}^{7}Li\ ,$$
$$^{113}Cd + n \rightarrow {}^{114}Cd + \gamma + convertion\ electrons\ ,$$
$$^{155}Gd + n \rightarrow {}^{156}Gd + \gamma + convertion\ electrons\ ,$$
$$^{157}Gd + n \rightarrow {}^{158}Gd + \gamma + convertion\ electrons\ .$$

Such converters are well studied in a number of papers [2 - 7].

However, for fast neutrons (≥ 1 MeV) the efficiency of using such converters significantly decreases due to the decreasing neutron capture cross-section. For instance, in [5, 6] for pixel detectors with a ^{6}Li(n, α)^{3}H converter it was obtained the efficiency ~3 % for thermal neutrons and ~0.02 % for 4 MeV neutrons. At the same time with increasing of the neutron energies the detection of recoil protons becomes more efficient. For example, a polyethylene film can be used as a converter for generation of recoil protons. For polyethylene converters the efficiency can be estimated using the next expression

$$F \sim \sigma_n \cdot N_p \cdot d\ ,$$

where σ_n is the neutron elastic scattering cross-section, N_p is the proton concentration in polyethylene ($N_p = 0.8 \cdot 10^{23}$ cm^{-3} for polyethylene with the density $\rho = 0.93$ g/cm^3), d is the converter thickness ($d \leq R_{\max}$), where $R_{\max}$ is the maximum range of the recoil protons ($R_{\max} = 20$ μm for 1 MeV neutrons and $R_{\max} = 137$ μm for 3 MeV neutrons). The cross-section of the neutron elastic scattering in the polyethylene is from 4 to 1 barn in the range of the neutron energy from 1 to 3 MeV respectively. For polyethylene films with thicknesses equal to the maximum proton range one can obtain efficiencies 0.064 and 0.22 % for 1 MeV and 3 MeV neutrons respectively. Thus polyethylene converters suitable for using for fast neutron detections along with converters based on using nuclear reactions for producing secondary charged particles.

The objective of the present work is the consideration of the possibility of the coordinate determination of a narrow beam of fast neutrons using a polyethylene film as a convertor and a strip-detector for the registration of recoil protons. Thus there are two parts of the problem. The first part is the determination of characteristics of recoil protons penetrated into the strip-detector. It is well known problem considered in a number of papers [1 - 4, 6]. The second part is extracting the information about incident neutron coordinates from the data of responses of the strip-detector on penetrated recoil protons. The problem of registration of short range charge particles was studied in papers [8 - 11].

In the present paper the processes in polyethylene films are considered in Section 2 and the coordinate determination of recoil proton tracks and the accuracy of the neutron coordinate determination is consider in Section 3.

2. Neutron to recoil protons conversion in polyethylene film

The most of neutron detectors are based on conversion of the neutron flux into charge particles. We consider the neutron-proton elastic scattering as a mechanism of the energy transferring from a fast neutron to a proton. Polyethylene is used often as a hydrogen containing material.

The possibility of the neutron coordinate determination and the registration efficiency are determined by the processes of the recoil proton generation in polyethylene and the coordinate determination of the track of the recoil proton incident on the silicon strip-detector.

Fig. 1 shows the principle of the coordinate determination. Recoil protons entering into the strip-detector are generated in a polyethylene film in (n-p) collisions. These protons create electron-hole pairs. Analysis of the charge collected on strips allows to obtain information about the coordinate of the incident neutron.

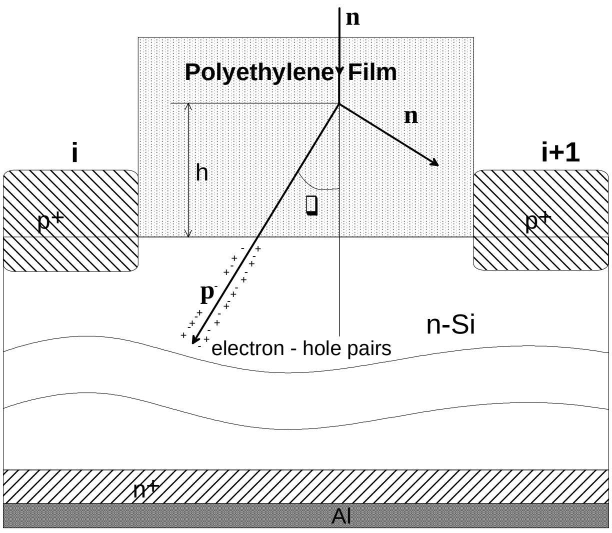

Fig. 1. Principle of the coordinate determination of fast neutrons using a polyethylene film for generation of the recoil protons.

The recoil proton energy in polyethylene is given by

$$E_p = E_n \cos^2 \theta , \qquad (1)$$

where E_n is the energy of the incident neutron and θ is the angle between pulses of the incident neutron and the recoil proton. For the maximum efficiency the film thickness should not exceed the maximum proton range in polyethylene $R_p(E_n)$. The energy of the proton penetrating into detector is given by

$$E_{p,s} = E_p - \Delta E_p \left(\frac{h}{\cos\theta} \right), \qquad (2)$$

where ΔE_p is the proton energy loss in polyethylene.

The proton range in polyethylene can be approximated by the empirical expression [1]

$$R_p = R_0 \cdot \left(\frac{E_p}{\text{MeV}} \right)^{\beta} , \qquad (3)$$

with parameters $R_0 = 20\,\mu\text{m}$, $\beta = 1.75$.

Consideration of the neutron conversion in a film assumes that a) the neutron beam incident on detector is monoenergetic; b) only single (n-p) collision take places in polyethylene; c) the film thickness is equal to the maximum recoil proton range $R_{\max}$.

The energy deposited into the strip-detector from a single event (recoil proton generated at the point h and the scattering angle θ) E_d is equal to the energy of recoil proton penetrated into detector. E_d is determined by the energy lost at the range $R_p - h/\cos(\theta)$ (see Fig. 1). Using (1) and (3) one can obtain

$$E_d = \left(\left(E_n \cos^2 \theta \right)^{\beta} - \left(\frac{h}{R_0 \cos\theta} \right) \right)^{\frac{1}{\beta}} \text{ MeV}. \qquad (4)$$

This energy determines the proton track length and orientation and hence the distribution of the charge in the strip-detector. The dependence of E_d versus h and θ is shown in the Fig. 2.

From the condition $E_d = 0$ one can obtain the dependence of the maximum angle of scattering when recoil proton can reach the detector on the neutron energy and the point of the (n-p) scattering

$$\cos(\theta_{\max}) = \left(\frac{h}{R_0 E_n^{\beta}} \right)^{\frac{1}{2\beta+1}} . \qquad (5)$$

Points of entering recoil protons into the strip-detector create “spot” on the strip-detector surface with the radius $x_m = h\sin(\theta_{\max})$. Taking the thickness of the polyethylene film equal to the maximum proton range $R_{\max} = R_0 E_n^{\beta}$ one can obtain

$$\cos(\theta_{\max}) = \left(\frac{h}{R_0 E_n^{\beta}}\right)^{\frac{1}{2\beta+1}} . \qquad (6)$$

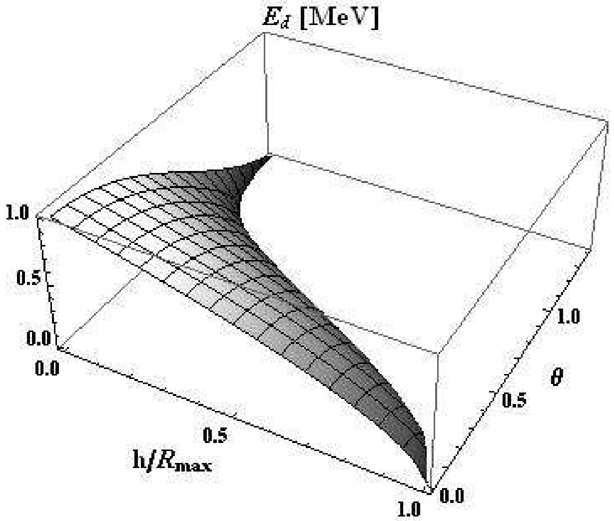

Fig. 2. Deposited energy as a function of the point of the neutron-proton scattering h and the angle of the scattering θ.

Fig. 3 shows the dependence of the spot radius x_m on the neutron energy E_n and the point h of (n-p) scattering.

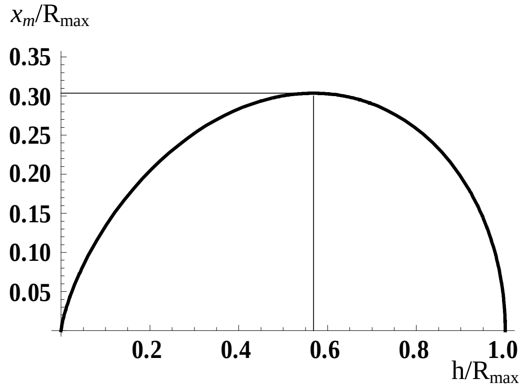

Fig. 3. The spot radius versus the point of (n-p) scattering.

The maximum radius of spot is $R_{spot} = x_m^{\max} = 0.3037\,R_{\max}$ at $h\big|_{x_m^{\max}} = 0.5681 R_{\max}$.

3. Neutron coordinate determination

Coordinates of incident neutrons can be determined from measurements of charges collected on adjacent strips from recoil proton tracks.

A. Proton tracks in strip-detector

A recoil proton creates a track of ionization in silicon. There are the following stages in the evolution of a track [12, 13]:

a) generation of the primary excitation region with the radius r~100 Å and the characteristic time t~10^{-12} s;

b) thermalisation and creation of the plasma track with r~1 μm, t~10^{-11} s;

c) drift and diffusion (the dividing and collecting charges on strips) r~6 μm, t~10^{-8} s.

The peculiarities of collection of short-range particles in strip-detectors were discussed in [10, 11].

The track length in silicon can be approximated by the same form as for the polyethylene

$$_p(\theta,h) = l_p(E_d) = R_1 \cdot \left(\frac{E_d}{\text{MeV}}\right)^{\beta_1} , \qquad (7)$$

where R_1, β_1 are the empirical parameters for silicon. Approximation of proton range data from PSTAR Databases [14] gives $R_1 = 15.5\,\mu\text{m}$ and $\beta_1 = 1.63$ for proton energy from 0.1 MeV to 4 MeV.

Fig. 4 shows the track distribution in silicon from (n-p) collisions at different h in the plane $y = 0$. Length of a track is given by

$$l(h,\theta) = \frac{h}{\cos(\theta)} + R_1\left[\left(E_n \cos^2(\theta)\right)^{\beta} - \frac{h}{R_0\cos(\theta)}\right]^{\beta_1/\beta} . \qquad (8)$$

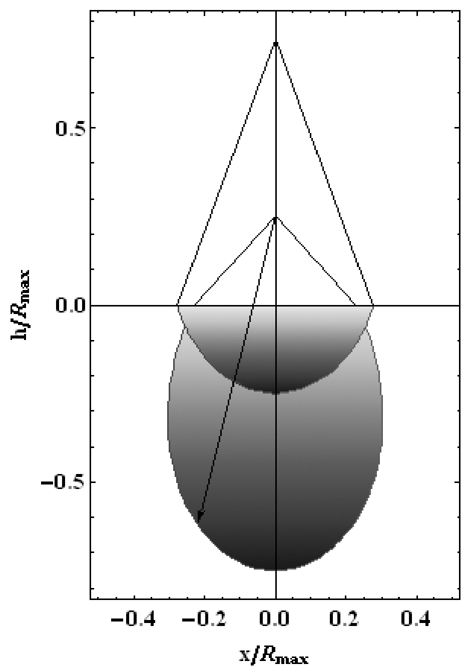

Fig. 4. The track distribution in silicon from (n-p) collisions at different points h.

Fig. 5 presents a 3D picture of the tracks in silicon.

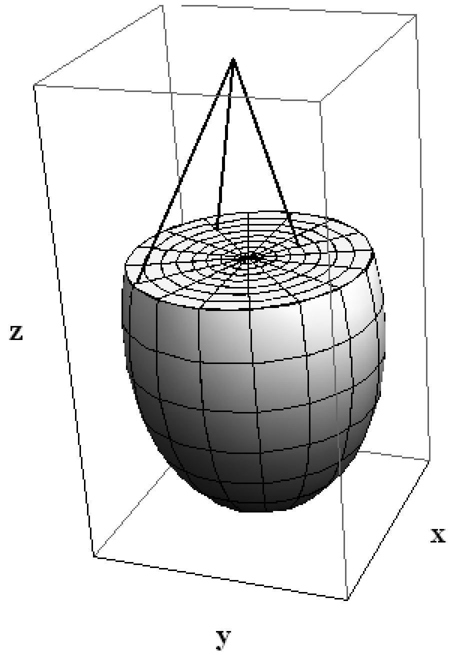

Fig. 5. 3D region of proton tracks in silicon strip-detector.

Geometry of the single track registration is illustrated in Fig. 6.

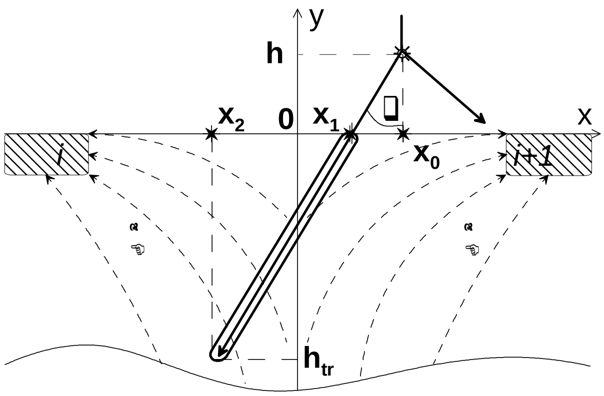

Fig. 6. Geometry of the coordinate determination of the recoil proton.

Charge generated by the proton with energy E_d in silicon is $q = E_d / E_i$, where E_i is the average energy of the e-h pair creation ~3.6 ± 0.3 eV.

Track characteristics are the following:

$\vec{p} = \{x_0 + h \cdot \tan(\theta)\cos(\varphi), h \cdot \tan(\theta)\sin(\varphi), 0\}$ is the entrance proton point, where φ is the azimuth angle;

$\vec{l_p} = \{l_p(\theta, h), \theta, h\}$ determines the length and the orientation of the proton track in silicon. Therefore $\vec{l_p}$ determines the track charge distribution in the detector and thus charge dividing and collecting on strips.

Charge collected from a single track on i-*th* strip is

$$q_i(\vec{p}, \vec{l_p}) = f_i(\vec{p}, \vec{l_p})\, q(l_p), \tag{9}$$

where $f_i(\vec{p}, \vec{l_p})$ is the response (charge collection) function of the strip-detector. This response function depends on the detector design (the strip width, the interstrip distance, the electrical field distribution etc.).

It's impossible to determine the neutron coordinate by the registration of single tracks because in each collision different tracks can be generated with the probability $w\left(\theta, l_p(h, \theta)\right)$.

To obtain from the experiment the information about the point of the neutron incidence x_0 the average charge collected on i-*th* strip from many tracks should be measured.

B. Charge collection on strips

The average charge collected on i-*th* strip can be written in the form

$$\overline{Q_i}(x_0) = \frac{1}{2\pi}\int_0^{R_{\max}} dh \int_0^{\theta_{\max}(h)} w(\theta, l_p(h, \theta)) \times \tag{10}$$

$$\times \int_0^{2\pi} q(l_p(h, \theta))\, f_i(\vec{p}, \vec{l_p}(h, \theta, \varphi)) \sin(\theta)\, d\theta\, d\varphi.$$

This integral depends on the coordinate of an incident neutron x_0 because $\vec{p} = \vec{p}(x_0, h, \theta, \varphi)$. The total average charge deposited in detector is given by

$$\overline{Q} = \int_0^{R_{\max}} dh \int_0^{\theta_{\max}(E_d)} w(\theta, l_p(h, \theta))\, q(l_p(h, \theta)) \sin(\theta)\, d\theta\,. \tag{11}$$

The integral response function of the detector is $\overline{Q_i}(x_0)/\overline{Q} = F(x_0)$ which depends on the detector design, the interstrip distance, the strip width, the electrical field distribution.

To illustrate behavior of the response function we assume that the collection of charges on adjacent strips depends on the position of tracks relatively the plane $x = 0$ (Fig. 7).

Let $\rho(x_0, \vec{l_p})$ be the charge density in a proton track in silicon. Then the total charge in the track is

$$q(\vec{l_p}) = \int_{\vec{l_p}} \rho(x_0, \vec{l_p})\, d\vec{r}. \tag{12}$$

The charge collected on i-*th* strip from a track is given by

$$q_i(\vec{l}_p) = \int_{\vec{l}_p} \sigma(x)\rho(x_0,\vec{l}_p)d\vec{r} = \int_{x>0} \rho(x_0,\vec{l}_p)dx\,, \quad (13)$$

where $\sigma(x) = \begin{cases} 0 & x < 0 \\ 1 & x \geq 0 \end{cases}$ is the step function.

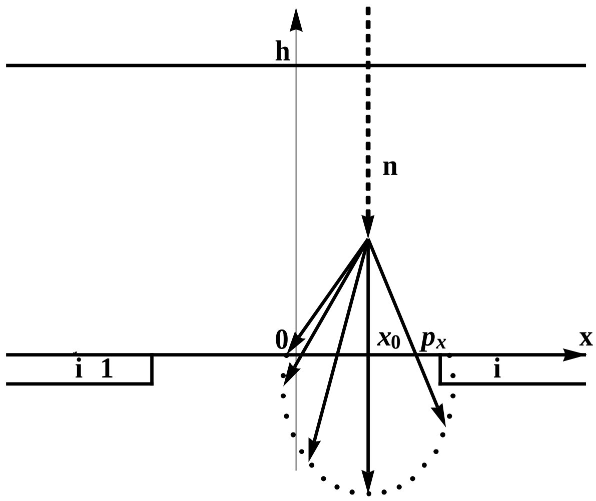

Fig. 7. Schematic view of tracks division between strips.

In this case the charge collection function for a track is given by

$$f_i(\vec{p},\vec{l}_p) = f_i(x_0,\vec{l}_p) = \begin{cases} 0 & p_x < 0, \theta < 0 \\ 1 & p_x > 0, \theta > 0 \\ 0 < f_i < 1 & |\, p_x \,| < x_{\max} \end{cases}$$

The response function in the interval $|\, p_x \,| < x_{\max}$ can be calculated only numerically in each concrete case for the specific strip-detector design.

The total average charge collected from all tracks on i-*th* strip is the sum of collected charges from all individual tracks

$$\overline{Q_i}(x_0) = \sum_{l_p} q_i(x_0,\vec{l}_p) =$$

$$= \sum_{l_p} \int w(\theta,l_p)\,\sigma(x)\,\rho(x_0,\vec{l}_p)\,d\,\vec{r} = \quad (14)$$

$$= \int \rho_{tot}(x_0,\vec{r})\sigma(x)\;d\,\vec{r} = \int_{x>0} \rho_{tot}(x_0,\vec{r})\,d\,\vec{r},$$

where $\rho_{tot} = \sum_{l_p} w(\theta,l_p)\rho(x_0,\vec{l}_p)$ is the sum of the charge densities of individual tracks.

Thus $\overline{Q_i}$ is the part of the total deposited charge on the right hand side from the plane $x = 0$. The $\overline{Q_i}$ is a complicated function of the film thickness, the neutron energy E_n and characteristics of the strip-detector. The most important for the best charge collection is the choice of the interstrip distance. Analysis of (14) as a function of the neutron coordinate x_0 allows to estimate the accuracy (uncertainty in the determination of the coordinate of the incident neutron with respect to the center of the interstrip distance) and limitation of the coordinate determination and can be carried out only numerically in each concrete case.

C. Accuracy of the neutron coordinate determination

From above some conclusions about choice of the optimal detector geometry can be made. Our consideration supposes that neutron beam is incident between strips and all tracks from the spot are collected on adjacent strips. The position resolution in this case is mainly determined by spot size. Hence the interstrip distance d should be of the order of the spot size $d \geq R_{spot}$. At $|\, x_0 \,| \geq R_{spot}$ all tracks are collected on one strip. The strip width w must be of the order of the spot radius as well as interstrip distance d. So the pitch width $d + w$ must be of the order of the maximum diameter of the spot $2R_{spot}$.

Because of difficulties of the calculation of the response function the information about x_0 in the interval $|\, x_0 \,| < R_{spot}$ are indefinite. Thus in the case when the radius of a neutron beam is smaller than the spot size the neutron coordinate can be determined with the accuracy of order of the spot radius $R_{spot} = 0.3037 R_{\max}$. For example, for 1 MeV neutrons $R_{\max} = 20$ μm and the accuracy is 6 μm, for 2 MeV neutrons $R_{\max} = 67$ μm and the accuracy is 20 μm.

Calculations of the total charge deposited into the strip-detector using (11) show that the tracks with angles θ less than 36° give 80 % of the contribution into the charge distribution. The entrance points of recoil proton tracks are distributed inhomogeneous along the spot radius. The central region of the spot gives the main contribution into the total charge $\overline{Q}$. For more realistic estimation of the accuracy of the neutron coordinate the diffusion broadening of the tracks should be considered.

The diffusion broadening of a track b_{diff} can be neglected when its value is less than the maximum spot radius $b_{diff} << R_{spot}$. The diffusion broadening can be estimated as

$$b_{diff} \sim \sqrt{D_p \tau_{drift}} \sim \left(D_p \frac{l_p}{\mu_p \bar{E}} \right)^{1/2} \sim \left(\frac{kT}{e} \frac{l_p \cdot d}{V_{depl}} \right)^{1/2}, \quad (15)$$

where D_p is the hole diffusion coefficient; τ_{drift} is the charge collection time (the drift time); μ_p is the hole mobility; $\bar{E}$ is the average electric field in the detector; k is the Boltzmann constant; T is temperature; e is the electron charge; V_{depl} is the applied voltage (we suppose it equal to the full depletion voltage). The full depletion voltage is given by [12] $V_{depl} \cong d^2/(2\varepsilon \cdot \mu \cdot \rho)$. For a typical strip-detector with $d = 300\,\mu\text{m}$ and $\rho = 1$ kOhm·cm one can obtain $V_{depl} \sim 300$ V. Thus we have $b_{diff} \sim 1\,\mu\text{m}$ for the 1 MeV proton. As we can see the condition $b_{diff} << R_{spot}$ is fulfilled in this case.

In the case when $d << R_{spot}$ the charges of the track will be shared between many strips. The neutron coordinate is determined by the center of weight of collected charges on different strips.

4. Conclusions

The possibility of the coordinate determination of a narrow beam of fast neutrons using a polyethylene film as a neutron converter and the silicon strip-detector has been shown.

Measurements of average collected charges on the detector strips allow obtaining information about the incidence point of neutrons between strips.

The accuracy of the coordinate determination depends on the distribution of the proton tracks in the volume of the silicon strip-detector and the relation between ranges of recoil protons and the interstrip distance. Estimations give the accuracy of the order of $\sim 0.3R_{\max}$, where $R_{\max}$ is the maximum recoil proton range in polyethylene when interstrip distance is order of the spot radius.

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КРЕМНІЄВИЙ СТРІП-ДЕТЕКТОР З ПОЛІЕТИЛЕНОВИМ КОНВЕРТОРОМ ЯК ПОЗИЦІЙНО ЧУТЛИВИЙ ДЕТЕКТОР ДЛЯ ВУЗЬКОГО ПУЧКА ШВИДКИХ НЕЙТРОНІВ

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Розглянуто можливість використання кремнієвого стріп-детектора з поліетиленовою плівкою для визначення координат швидких нейтронів. Точність визначення координат швидких нейтронів залежить від особливостей взаємодії нейтронів з поліетиленом, а також від точності реєстрації в стріп-детекторі протонів віддачі, що утворюються внаслідок пружного розсіяння нейтронів у поліетилені. Таким чином, точність визначається енергіями та кутовим розподілом протонів віддачі та характеристиками треків, що утворюються в детекторі. Розраховано залежність середнього заряду, зібраного на смужці, від координати нейтрона. Показано, що найбільш важливим для точності визначення координат є вибір віддалі між смужками. Розглянуто вплив на точність визначення координат інших факторів, таких як розподіл електричного поля в детекторі та відношення довжини треку до відстані між смужками.

Ключові слова: позиційно чутливий детектор, детектор нейтронів.

КРЕМНИЕВЫЙ СТРИП-ДЕТЕКТОР С ПОЛИЭТИЛЕНОВЫМ КОНВЕРТОРОМ КАК ПОЗИЦИОННО ЧУВСТВИТЕЛЬНЫЙ ДЕТЕКТОР ДЛЯ УЗКОГО ПУЧКА БЫСТРЫХ НЕЙТРОНОВ

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Рассмотрена возможность использования кремниевого стрип-детектора с полиэтиленовой пленкой для определения координат быстрых нейтронов. Точность определения координат быстрых нейтронов зависит от особенностей взаимодействия нейтронов с полиэтиленом, а также от точности регистрации в стрип-детекторе протонов отдачи, которые образовались вследствие упругого рассеяния нейтронов в полиэтилене. Таким образом, точность определяется энергиями и угловым распределением протонов отдачи и характеристиками треков, которые образуются в детекторе. Рассчитана зависимость среднего заряда, собранного на полоске, от координаты падающего нейтрона. Показано, что наиболее важным для точности определения координат есть выбор расстояния между полосками. Рассмотрено влияние на точность определения координат других факторов, таких как распределение электрического поля в детекторе и отношение длины трека к расстоянию между полосками.

Ключевые слова: позиционно чувствительный детектор, детектор нейтронов.

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