сообщения
объединенного
института
ядерных
исследований
дубна

E1-93-30

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MONOENERGETIC, COLLIMATED BEAMS OF HIGH ENERGY NEUTRONS FROM HEAVY ION ACCELERATORS

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1993

1. INTRODUCTION

The subject matter in this paper is a presentation of a new method of neutron beam construction at high energy heavy nuclei accelerators; here "high" is used for nuclei energies when larger than about 1 GeV/nucleon. The method bases on experimental information about the properties of the nucleon emission from target nuclei in traversing them by hadronic projectiles [1—4].

2. THE PHYSICAL FOUNDATION OF NEUTRON BEAMS PRODUCTION WITH HEAVY ION ACCELERATORS

Let us observe hadron-nucleus collisions at high energies in the laboratory system — when the target nucleus rests in it. Atomic nuclei emit nucleons when bombarded by high energy hadronic projectiles; among these nucleons the protons are known well as the grey-track, or g-track leaving particles, if registered in photonuclear emulsions [5]. The emission intensity, energy and angular characteristics of the nucleons do not depend on whether hadrons are produced in the hadron-nucleus collision reactions or not [6]. They are independent of the incident hadron energy and identity at energies higher than a few GeV, as well [6—9].

On the average, the neutron-proton ratio n_n/n_p in the series of the emitted nucleons equals [10,11] $n_n/n_p = (A - Z)/Z$.

It is known, from experiments [10,11], that the number n_N of the nucleons emitted from a target nucleus when a hadron pierced it through corresponds to the thickness λ of the intranuclear matter layer covered. On the average, the neutron-proton ratio in the sample of the emitted nucleons equals $n_n/n_p = (A - Z)/Z$, but in any case the relative numbers $n_n + n_p = N_N$; the numbers n_p of the protons in any colllision case fluctuate according to the binomial distribution

$$P(n_p) = C_S^{n_p} \left(\frac{Z}{A}\right)^{n_p} \left(1 - \frac{Z}{A}\right)^{\lambda \cdot S - n_p}, \qquad (1)$$

where λ in nucleons/S; $C_{\lambda S}^{n_p} = \frac{n_N!}{n_p!(n_N - n_p)!}$; $\lambda S = n_N$; $S = \pi R^2$, where R is the nuclear interaction range $R \approx D_0$ — the diameter of the nucleon; the numbers of neutrons may be from $n_n = 0$ up to $n_n = n_N = \lambda S$, but the number of the protons will be then $n_p = n_N - n_n$, correspondingly.

Energy and momentum spectra, and angular distributions of the nucleons emitted from the nuclei traversed by hadronic projectiles are independent of the projectile identity and energy, in the target nucleus system of reference, and of the number n_N of the emitted nucleons [7,8]. The particle production process initiated by the hadronic projectile does not influence the nucleon emission process [6].

On the basis of the results obtained from our experiments, we are in a position to conclude that: 1. On its passage through a nucleus a high energy hadron induces the emission of nucleons with kinetic energy between about 20 and 400 MeV; the passages of a hadron through nuclei can be observed some times in its pure kind in track detectors. 2. On the background of the hadronic projectile passage through atomic nuclei particle producing reactions in them may occur; such reactions do not disturb the nucleon emission process.

The nucleons exhibit a differential energy spectrum of the form

$$N(E)dE = E^{\gamma}dE, \tag{2}$$

where $N(E)$ is the number of protons per event and energy unit MeV, γ is of the value [6,12,13] 1.09 ± 0.02.

The angular distribution of the protons is close to the form

$$\frac{1}{\sigma}\frac{d\sigma}{d(\cos \nu)} \sim e^{0.96 \cos \nu} \tag{3}$$

and stays constant independently of the incident hadron energy and identity; the energy independence was proved [12] in the energy range 2—400 GeV. The angular distribution of the emitted neutrons is, according to the estimations, similar.

The nucleon emission from target nuclei induced by hadronic projectiles is the physical phenomenon which the method of neutron beam production with heavy-ion accelerators is proposed to be based on.

3. PRODUCTION OF HIGH ENERGY NEUTRON BEAMS WITH HEAVY-ION ACCELERATORS

The method of high-energy neutron beams production with heavy ion accelerators is a simple consequence of the physical phenomenon consisting in the emission of nucleons from target nuclei induced by hadronic projectiles; the description of the phenomenon is presented in section 2 and in the papers cited above [1—4, 6—11]. When an accelerated ion is thrown on a hadron, on a proton or a neutron — for example, resting in the laboratory system, a narrow beam of free accelerated neutrons should appear collinearly around the incident nucleus initial course. We used here the working hypothesis that the induced nucleon emission preceeds in the same way both in the laboratory and in the antilaboratory reference systems.

The momenta $\vec{P}_N$ of the accelerated nucleons will be $\vec{P}_N = \vec{P}_i + \vec{p}_N$, where $\vec{P}_i$ in MeV/c is the momentum of any nucleon in the accelerated to the momentum $\vec{P}_N$ in MeV/c/nucleon ion, $\vec{p}_N$ in MeV/c is the momentum of this nucleon obtained in the nucleon emission process. When the momenta of the nucleons in the accelerated projectile ion $\vec{P}_N$ are larger by much than the momenta of the nucleons $\vec{p}_N$ obtained in the nucleon emission process then simple formula may be used

$$P_N \doteq P_i \, \mathrm{MeV/c}, \tag{4}$$

independently, whether the particle production process accompanies the nucleus-hadron collision or not.

In fact, any nucleus accelerated in the laboratory system may be considered as a narrow beam of monoenergetic nucleons bound by nuclear forces. In colliding with a hadron at rest, the moving nucleus is pierced through and the nucleons are emitted from it — in the emission process induced by the hadron passed through the moving target nucleus — and a namber of nucleons corresponding to the intranuclear matter layer involved become to be free and continue the moving with additional momentum $\vec{p}_N$ obtained in the emission process described in other our works [1—4]. This way a new beam of nucleons is formed in which some definite part of nucleons are free and moving with the momenta $\vec{P}_i + \vec{p}_N$, where $\vec{P}_i$ is the momentum of any of nucleons inside the accelerated nucleus and $\vec{p}_N$ is the momentum of the nucleon emitted from the nucleus in the emission process [1—4], in the laboratory system. The mean value of the momentum $\langle|\vec{p}_N|\rangle \doteq 90$ MeV, independently of the high energy hadronic projectile momentum. Usually, $|\vec{p}_N| \ll |\vec{P}_i|$, then $\vec{P}_N = \vec{P}_i + \vec{p}_N \doteq \vec{P}_i$.

The mean number $\langle n_N \rangle$ of the emitted nucleons is [1,4,6,9]

$$\langle n_N \rangle = \langle \lambda \rangle \cdot S \cdot \left(1 - e^{-\frac{\langle \lambda \rangle}{\lambda_t}}\right), \tag{5}$$

where $\lambda_t = 1/\sigma_t$ is the hadron mean free path in nucleons/S in intranuclear matter; $<\lambda>$ in nucleons/S is the mean thickness of the intranuclear matter layer for a given ion [14]; σ_t is the total hadron-nucleon cross-section in S/nucleon; $S = \pi D_0^2 \doteq 10\ \mathrm{fm}^2$, $D_0 \doteq R$ is the nuclear forces range. The mean number of the emitted protons is

$$<n_p> = \frac{Z}{A} <\lambda> \cdot S \cdot \left(1 - e^{-\frac{<\lambda>}{\lambda_t}}\right), \tag{6}$$

where A and Z are the mass and charge numbers. The mean number of the emitted neutrons is

$$<n_n> = \frac{A-Z}{A} <\lambda> \cdot S \cdot \left(1 - e^{-\frac{<\lambda>}{\lambda_t}}\right). \tag{7}$$

The values of the numbers of the neutrons and protons fluctuate according to formula (1).

After separation of the charged component from the free-nucleon beam the produced neutron beam will be strongly collimated, and the neutrons in it will be monoenergetic, practically; the neutron energy may be regulated fluently by means of energy regulation of the accelerated initial ions.

The sparseness of the energy values of the beam neutrons decreases with increase of the energy of the accelerated ions, it may be estimated by the formula

$$\frac{\Delta\vec{P}_N}{\vec{P}_N} = \frac{\vec{P}_i + \vec{p}_N - \vec{P}_i}{\vec{P}_N} = \frac{\vec{p}_N}{\vec{P}_N}. \tag{8}$$

For $|\vec{p}_N| \doteq 90$ MeV and $\vec{P}_N \doteq 10^6$ MeV the value of p_N/P_N will be about 10^{-3}.

4. CONCLUSION AND REMARKS

The newly recognized physical phenomenon — the passage of a hadron through layers of intranuclear matter — was used as the physical basis of the method for high energy neutron beam production with accelerators of nuclei. This nuclear phenomenon, recognized well enough in our works [1—4] may be treated as an analogue of the known well electromagnetic phenomenon — the passage of an electrically charged particle through layers of materials.

The method allows one to produce collimated beams of monoenergetic high energy neutrons; the neutron energy may be varied fluently by means of the variation of the ion beam energy. This way the beams of neutron energies which are as high as the energies of the accelerated ions may be obtained.

The dispersion of the neutron energy values in the produced beams depends on the neutron energy; the higher is the energy, the lower is the dispersion. The angular dispersion of the neutrons in a beam depends mainly on the angular dispersion of the nucleus beam in an accelerator; the angular distribution of the emitted nucleons should be taken into account only at low energies of the accelerated neutrons, lower than about 10 GeV.

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Received by Publishing Department
on February 3, 1993.