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NEUTRON BEAMS FROM ION ACCELERATORS AND COLLIDERS

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1. INTRODUCTION

Results obtained in experimental studying of the nucleon emission from target nuclei induced by hadronic projectiles prompt how it is possible to produce monoenergetic high energy beams of neutrons at ion accelerators. It was discovered that a high energy hadron induces the emission of nucleons; the characteristics of the nucleon emission are the same for nuclear collisions in which hadrons are produced and for that collision reactions without production of hadrons. The number of the emitted nucleons equals the number of nucleons met by the hadron around its course in intranuclear matter within the nuclear forces range; the kinetic energy of the nucleons is from ~20 MeV to ~400 MeV; the energy spectra and angular distributions are practically independent of the incident hadron energy and identity, and stay constant for the incident hadron energy variations.

The neutron beams are produced naturally when heavy nuclei with energies larger than a few GeV/nucleon collide with nuclear targets. The energies of neutrons in the beams may be varied fluently from a few GeV to the maximum values of energy/nucleon of the accelerated ions; exactly, the neutron energy is as large as the energy per nucleon of the accelerated ions is.

The method of neutron beam construction at high energy nuclear accelerators was described in the author's former paper [1]. Here, a presentation of the properties of the neutron beams and their quantitative characteristics are presented, as predicted on the basis of experimental data on nucleon emission which occurs when a hadron strucks a nucleus at rest.

The expectations of the neutron beams properties have to be helpful for physicists and engineers in efforts to produce the beams and to investigate them.

2.CHARACTERISTICS OF THE NEUTRON BEAMS FROM HIGH ENERGY NUCLEAR ACCELERATORS

The relation between intranuclear matter density distribution and the multiplicity distribution of nucleons emitted from nuclei bombarded by high energy hadrons has been revealed experimentally [2]. On the other hand, many aspects about the intranuclear matter distribution are so firmly established that it is possible to use them in order to investigate other physical quantities [3—4]. The laws of the nucleon emission in hadron-nucleus collisions are known well enough experimentally, as well [5—20].

It is possible, therefore, to predict characteristics of the neutron beams obtained when a high energy nucleus is falling on a hadronic target at rest — on a nucleon, for example. The data below, in this section, will be related to the situation only when a high energy nucleus is collided with a nucleon at rest, for example — with a hydrogen target. Other types of nuclear collisions will be considered from the point of view under interest in the next sections, 3 and 4.

2.1. The Neutron Beam Intensities

In Table 1, the energies of the incident ions are accepted to be larger than about 10 GeV/nucleon; this way the effect of the nucleus energy loss in colliding with a nucleon is completely excluded from the consideration. At such conditions, any of the incident nuclei — from a light up to the heaviest one — will be pierced by a resting target nucleon in a head-on collision at 0 impact parameter [21—23]; at lower energies, the resting target nucleon cannot pierce the heaviest incoming nuclei [21]. In this case, the neutron emission intensity from the nucleus will depend on the incident nucleus energy — at least at the small impact parameters; but, the energy and angular spectra of the emitted nucleons will stay still constant.

It should be remembered that characteristics of the nucleon emission from a nucleus, when a hadron is passed through it, are the same for any hadron-nucleus collisions — when hadrons are produced or not, as it has been obtained experimentally [22].

At smaller energy of the incident nucleus, the emission of nucleons from it depends on the energy — because of the hadron stopping power in intranulear matter.

The neutron beam intensities are presented in Table 1.

Table 1. Mean numbers of neutrons per nucleus in the neutron bemas obtained in collisions of nuclei accelerated to energies over about 10 GeV/nucleon with a nucleon at rest [13,17]

The nucleus	Ne	S	Cu	Zn	Br	Ag	Xe	W	Au	Pb	U
$<n_n>$	1.8	2.2	3.3	3.4	3.8	4.3	5.1	5.9	6.1	6.2	6.6

2.2. Neutron Momenta in the Beams

The resulting momentum of each of the neutrons in a beam is determined by the sum of the incoming nucleus momentum $\mathbf{P}_A$ in GeV/nucleon and of the

momentum $\mathbf{P}_n$ in GeV of the neutron emitted from the nucleus at rest in hadron-nucleus collisions.

The momenta of the nucleons emitted from the target nucleus at rest in a hadron-nucleus collisions do not depend on the momentum of the incident hadron and on its identity [10,15]. Then, the neutron momenta in GeV $\mathbf{P}_{bn}$ in the neutron beams are:

$$\mathbf{P}_{bn} = \mathbf{P}_A + \mathbf{P}_n; \qquad (1)$$

$|\mathbf{P}_n|$ varies from about 0.19 GeV/c up to about 0.95 GeV/c, in average $<|\mathbf{P}_n|> \doteq \text{const} \doteq 0.4$ GeV/c. When $|\mathbf{P}_A| >> |\mathbf{P}_n|$, the approximated relation may be used:

$$\mathbf{P}_{bn} \doteq \mathbf{P}_A . \qquad (2)$$

At energies of the nuclear projectiles high enough, at tens GeV/nucl for example, the neutron beams will be almost monoenergetic practically.

2.3. Angular Distributions of Neutrons in Beams

The angle ϑ between the neutron beam axis — along $\mathbf{P}_{bA}$ the direction of ion beam — and the nucleon emission direction — along $\mathbf{P}_n$ relatively to the hadron-nucleus collision axis — can be determined by:

$$\vartheta = \measuredangle\left(\mathbf{P}_{bA}, \mathbf{P}_n\right). \qquad (3)$$

At momenta of the incident nucleus $\mathbf{P}_{bA}$ large enough, the angle between the neutron trajectory and the neutron beam axis will be near to 0. Maximum value of the angle ϑ is when the nucleon emission directions $\mathbf{P}_n$ are perpendicular to the beam axis — when $\mathbf{P}_n$ is normal to $\mathbf{P}_{bA}$.

At incident nucleus momentum $\mathbf{P}_{bA}$ high enough, when $|\mathbf{P}_{bA}| >> |\mathbf{P}_n|$, the approximate relation may be used:

$$\vartheta \doteq 0, \qquad (4)$$

and the momentum $\mathbf{P}_{bn}$ of the neutron in the neutron beam will be:

$$\mathbf{P}_{bn} \doteq \mathbf{P}_{bA} . \qquad (5)$$

2.4. The Neutron Energy and Intensity Regulation in Produced Beams

The intensity of neutrons in the produced neutron beams is adjustable — by regulation of the incident nuclei beam intensity; the energy of the neutrons in the produced beams is adjustable as well — by regulation of the incident nuclei energy in the beam from ion accelerator.

In average, the intensity of the neutron beam of energies high enough — higher than about 10 GeV — can be adjusted by regulation of the intensity of the incident ions from the nuclear accelerator. When the intensity of the incident nuclei is I_{0i} nucl/cm^2/s the mean intensity of the neutrons I_{0n} in the produced neutron beam will be

$$I_{0n} = I_{0i} <n_n>, \qquad (6)$$

where $<n_n>$ is the average number of neutrons emitted when nucleons are striking the resting nuclei [17].

3. NEUTRON BEAMS AT NUCLEAR ACCELERATORS AND COLLIDERS

Any of beams of nuclei accelerated to energies high enough, thrown on any target, produces the beam of nucleons of corresponding energies and intensities collimated around the accelerated beam axis. Such beams are visible well enough on photographs of the nucleus-hadron and nucleus-nucleus collision events at GeV energies — on the photographs the beam of sharply collimated protons is visible clearly among the electrically charged products of the collision reaction. In such a beam the neutrons are presented, and the neutron intensity is, in average, as $(A - Z)/A$ portion of the nucleon intensity; usually, for heavier nuclei the ratio A/Z is larger than 1, up to about a little more than 2, for Ne, S, Cu, Zn, Mo, Ag, Xe, Au, Pb, U — for example. Then, the neutron beams are about two times more intensive than the proton beams.

After experimental investigations of the nucleon emission from nuclei, in hadron-nucleus collision reactions, I am in a position to state that:

In operating the high energy ion accelerators and ion colliders, the intensive beams of neutrons are produced always when the nuclear beams come into collision with targets or other nuclear beams. The neutron beams directed along the accelerated ion beam axis are collimated in a definite manner. The neutrons from the beams may cover relatively long distances from the place where the beams were produced.

I am afraid that these beams could be not discovered by physicists and by dosimetrists in them up to now. The beams are existing naturally when the nuclear accelerators and colliders are operating. The beams should be separated and prepared for practical use.

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