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CHARACTERISTICS OF NUCLEONS EMITTED IN HADRON-NUCLEUS NUCLEAR COLLISIONS

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1. INTRODUCTION

In traversing atomic nuclei, hadronic projectiles are accompanied always by emission of nucleons from the target nuclei — in events without and with particle (hadron) production. The kinetic energies of the emitted protons are of ~ 20–500 MeV.

In some class of the hadron passages through layers of intranuclear matter, there occurs such interaction of the projectile which leads to hadron production. The production is realized via some intermediate objects, which are decaying into usually observed secondary hadrons — after having left the parent nucleus. In some other class of the hadron passages, the hadron production does not occur. In both the classes of events — with the particle production or without it — the fast nucleon emission proceeds in the same way.

The nucleon emission intensities (or the nucleon multiplicities) distributions are determined by nuclear sizes and the collision impact parameter if the projectile kinetic energy is over a few GeV (for the xenon nucleus this value is nearly 3.5 GeV).

The emitted protons in $p-Em$ collision reactions at 300–400 GeV exhibit a differential energy spectrum of the form: $N(E)dE \sim E^{-\gamma}\,dE$, where $N(E)$ is the number of protons per energy unit; γ has the value near to 1. The same energy spectrum is exhibited by the fast protons emitted in the pion-xenon nucleus collision reactions at energies from about 1 to about 10 GeV. The angular distribution of the fast protons is close to the form ~ exp (0.96 cos θ) and stays constant to the energy values range from about 2 to about 400 GeV.

After the passage of the incident hadron, the residual target nucleus is damaged locally, and it should transit itself into a new and stable stage. A long time after the passage ($10^{-16}\,s$) in emulsions the black track particles appear: (p, d, t) with kinetic energy $E \le 300$ MeV/nucleon; ^3He with energy $E \le 300$ MeV/nucleon. They are mainly the «evaporated» particles (the fragments of the target nuclei).

The mean emission intensity $\langle n_b \rangle$ of the black track leaving particles is determined by the intensity n_N (or n_p) of the emitted nucleons (protons). The $\langle n_b \rangle - n_p$ relation is independent of the number of produced hadrons in the hadron-nucleus collision reactions, which means that the hadrons produced by the projectile objects do not transfer any significant energy to the target nucleus.

The results on the nucleon emission characteristics are very important for various applications — in power energetics, in radioactive waste transmutation, in civil and environmental engineering.

From the above statement it follows that the emission of «fast» nucleons — with kinetic energies from about 20 up to about 500 MeV — is an observable phenomenon of the general nuclear process — *of the passage of the hadronic projectile through nuclei.*

The hadron passage through layers of intranuclear matter is a nuclear analogy of the well-known electromagnetic process — the passage of electrically charged particles through layers of materials. It is a general process in any of the hadron-nucleus inelastic collision.

It is desirable to have a special set of definitions and units for formulation of the laws of the hadron transition through layers of intranuclear matter, therefore.

2. SOME DEFINITIONS AND UNITS

The energy of a projectile hadron is called «high» when it is larger than the threshold for the pion production.

The collections of nucleons met in the nature as atomic nuclei will be called sometimes «intranuclear matter». It is convenient to express the thicknesses of intranuclear matter layers in units: nucleons per fm^2 or protons per fm^2. It will be natural to express the thicknesses of the intranuclear matter layers in nucleons or protons, or neutrons in their number (or intensity) per special area $S = \pi R_h^2 \approx \pi D_0^2$, where $D_0 \approx R_h \approx 1.81$ fm and $S = 10.3\ \text{fm}^2$; R_h is the strong interaction range which is approximately as large as nucleon diameter D_0.

3. THE LAWS OF NUCLEON EMISSION AND NUCLEAR FRAGMENT EVAPORATION FROM NUCLEI BOMBARDED BY HADRONS AT HIGH ENERGIES

It was mentioned earlier the importance of the results on the nucleon emission characteristics for various applications — in power energetics, in radioactive waste transmutations, in civil and environmental engineering. A presentation of the laws of the nucleon emission and nuclear fragment evaporation from the nuclei involved in the collisions will be to the point, therefore.

Law 1.

Any hadron of kinetic energy higher than the pion production threshold causes nucleon emission from the target nuclei in traversing them along a path λ [fm]. The number n_N of the emitted nucleons equals the number of nucleons contained within the cylindrical volume $V = \pi D_0^2 \lambda\ \text{fm}^3$ centred on λ in the target-nucleus:

$$n_N = \pi D_0 \lambda \langle \rho \rangle, \quad (1)$$

where D_0 [fm] is the diameter of the nucleon and $\langle \rho \rangle$ in nucleons/ fm^3 is the mean density of nucleons inside the volume V.

Law 2.

In passing through intranuclear matter, any hadron of kinetic energy larger than the pion production threshold loses monotonically its kinetic energy ΔE_h; the energy ΔE_h [MeV] of the hadron lost on the path length $\Delta\lambda$ [nucl/S] equals:

$$\Delta E_h \approx \varepsilon_h \Delta\lambda, \quad (2)$$

where ε_h [MeV/(nucl/S)] depends on the hadron identity. From experiments, for the pions $\varepsilon_h \approx 180$ MeV(nucl/S) and for the proton $\varepsilon_h \approx 360$ MeV(nucl/S).

Law 3.

Energy and momentum spectra, and angular distributions of nucleons appeared in the monotonic nucleon emission process are independent of the projectile energy and identity, in the target nucleus system of reference, and of the number n_N of emitted nucleons, and of the number n_π of produced pions in hadron-nucleus collisions.

Law 4.

The relation between the mean multiplicity $\langle n_b \rangle$ of evaporated charged fragment and the multiplicity n_p of emitted protons exists:

$$\langle n_b \rangle = 1.25(\lambda S + \{A - Z\} / Z) \quad (3)$$

and

$$\langle n_b \rangle / (\langle n_b \rangle + \langle n_p \rangle) = \langle n_b \rangle / \langle n_h \rangle = 0.4, \quad (4)$$

where $\lambda S = n_p$ and λ is the thickness of the nuclear matter layer involved in the hadron-nucleus collision, measured in [proton/S] units.

4. CONCLUSIONS

The hadron passage through layers of intranuclear matter is an experimental fact. The laws are tested experimentally with the incident hadron energy interval up to about 2000 GeV. The consistency of energy and momentum spectra, and angular distributions of the emitted nucleons was tested up to about 400 GeV.

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