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## Abstract

## Full Text

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# EMISSION OF HELIUM PARTICLES IN INTERACTIONS OF HIGH-ENERGY PIONS AND NUCLEONS WITH COMPLEX NUCLEI

The phenomenon of the formation of energetic aggregates of nucleons is a complex reaction involving the interaction of many high-energy particles. The physical mechanism of the emission of such particles remains unclear at the present time. The appearance of energetic heavy particles in nuclear disintegrations is often associated with the development of a cascade of nucleon collisions in the nucleus (<sup>1-4</sup>), although the mode of transfer of large kinetic energy to groupings of nucleons, without causing their destruction in such a process, remains unclear. In this connection, much attention is being given to the study of the process of formation of groupings of nucleons in the form of deuterons, tritons, and helium particles with kinetic energy considerably greater than the energy of Coulomb repulsion (<sup>5-8</sup>). However, the available experimental facts characterizing the features of the emission of energetic heavy particles are still very scanty.

In the present work we describe the results of investigations of the emission of doubly charged particles with kinetic energy  $E_{\text{kin}} > 100$  MeV, formed in interactions of high-energy pions and protons with nuclei of photographic emulsion. The lower limit of the energy of helium particles adopted in our investigations makes it possible to exclude any mechanism of emission based on the process of nuclear evaporation.

Fig. 1. Angular distributions of helium particles with allowance for geometrical corrections (histograms normalized to 100). 1— $E_p = 10$  GeV, 2— $E_p = 19.5$  GeV, 3— $E_\pi = 7.5$  GeV, 4— $E_\pi = 17.5$  GeV

**Fig. 1.** Angular distributions of helium particles with allowance for geometrical corrections (histograms normalized to 100).

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For the investigation, Ilford G-5 photographic emulsion stacks were used, irradiated in Geneva with protons of energy 19.5 GeV and  $\pi$ -mesons of 17.5 GeV. By scanning over the area, 12,222 proton-nucleus interactions and 14,828 pion-nucleus interactions with a number of gray-black tracks  $N_h \geq 2$  were registered. For analysis, only cases of doubly charged particles with an angle of dip into the emulsion of not more than  $10^\circ$  were selected.

As a result of detailed identification of each track by various methods (dependences  $g^*—p\beta$ ,  $N^*—p\beta$ ,  $g/g_0—R$ , the constant-sagitta method, etc.), helium particles were found in 119 proton and 240  $\pi$ -meson stars.

particles with  $E_{\text{kin}} > 100$  MeV. Of this number of interactions, in 31 proton-nucleus disintegrations and 74 pion-nucleus disintegrations helium isotopes with kinetic energy  $E_{\text{kin}} > 200$  MeV were emitted. Moreover, the disintegrations from which doubly charged particles are emitted occur mainly in the heavy nuclei of the photographic emulsion (Ag, Br).

Fig. 2. Dependence of the kinetic energy of helium particles on their emission angle. Crosses denote data for 19.5 GeV protons; dots, for 17.5 GeV  $\pi$ -mesons.

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The kinetic energy of doubly charged particles was determined from multiple Coulomb scattering for particles passing through and interacting in the emulsion, and from the  $E—R$  dependence in the case of their stopping.

The angular distributions of helium particles with  $E_{\text{kin}} > 100$  MeV, shown in Fig. 1 with geometric corrections taken into account, are sharply anisotropic, and the degree of anisotropy increases with increasing energy of these particles. It is seen from the figure that the angular distributions of doubly charged particles from disintegrations caused by primary  $\pi$ -mesons of 7.5 and 17.5 GeV are completely identical, but differ from the distributions of such particles at primary-proton energies of 9 and 19 GeV by a somewhat smaller forward collimation. However, this difference is covered by the large statistical errors in these studies.

The dependence shown of the mean energy of helium isotopes on their emission angle in the laboratory coordinate system (Fig. 2) indicates that the particles are emitted mainly into the forward hemisphere, and that in the energy interval 100–200 MeV no appreciable dependence on angle is observed. Particles with  $E_{\text{kin}} > 200$  MeV are emitted at considerably smaller angles ( $\theta_{1/2} = 21^\circ$ ) to the direction of the primary particles, and only particles with  $E_{\text{kin}} > 1$  GeV are sharply collimated along the direction of the primary beam ( $\theta_{1/2} \sim 10^\circ$ ).

The energy spectrum of helium particles (Fig. 3), both in the case of primary protons of 9 (7) and 19.5 GeV and of pions of 7.5 (9) and 17.5 GeV, can be represented by the analytic dependence

$$N(E) dE = \text{const} \cdot E^{-2.6 \pm 0.4} dE. \quad (1)$$

In this case the exponents of  $E$ , within the errors, coincide with one another for all four values of the primary-particle energy. Analysis of the distributions presented indicates the absence of any appreciable dependence of the energy spectrum of doubly charged particles on the energy of the bombarding particles in the range 10–20 GeV.

It should be noted that no appreciable change has been found in the maximum energy of helium particles in proton-nucleus interactions with increasing energy of the primary protons. In the case of  $\pi$ -meson interactions, a slight increase (of the order of 30%) is observed in the maximum energy of the emitted doubly charged particles as the energy of the primary pions increases.

In Table 1 the fraction of doubly charged particles per star is given for different intervals of their energy at primary-proton energies of 9 and 19.5 GeV. For the same energy intervals, Table 2 gives cross sections for emission of helium particles caused by  $\pi$ -mesons of energy 7.5 and 17.5 GeV. Analysis shows that, with increasing energy of the primary proton, the production cross section of helium particles with kinetic energy greater than 100 MeV does not change within the errors—

Fig. 3. Energy distributions of helium particles of 100 MeV with allowance for the geometric correction (normalized). 1— $E_p = 9.5$  GeV, 2— $E_p = 19.5$  GeV, 3— $E_\pi = 7.5$  GeV, 4— $E_\pi = 17.5$  GeV

**Fig. 3.** Energy distributions of helium particles of 100 MeV with allowance for the geometric correction (normalized).  
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**Table 1**

Frequency of appearance of helium particles (in %)

$E_p,$ GeV	$E_{\text{kin}} >$ 100 MeV, with- out geo- met- ric cor- rec- tion	$E_{\text{kin}} >$ 100 MeV, with geo- met- ric cor- rec- tion	$E_{\text{kin}} >$ 200 MeV, with- out geo- met- ric cor- rec- tion	$E_{\text{kin}} >$ 200 MeV, with geo- met- ric cor- rec- tion	$E_{\text{kin}} >$ 400 MeV, with- out geo- met- ric cor- rec- tion	$E_{\text{kin}} >$ 400 MeV, with geo- met- ric cor- rec- tion	$E_{\text{kin}} >$ 500 MeV, with- out geo- met- ric cor- rec- tion	$E_{\text{kin}} >$ 500 MeV, with geo- met- ric cor- rec- tion
	9.0	$1.24 \pm 0.14$	$5.04 \pm 0.6$	$0.58 \pm 0.1$	$1.79 \pm 0.3$	$0.14 \pm 0.05$	$0.41 \pm 0.14$	$0.05 \pm 0.02$
19.5	$1.07 \pm 1.12$	$4.8 \pm 0.5$	$0.44 \pm 0.08$	$1.67 \pm 0.3$	$0.08 \pm 0.03$	$0.22 \pm 0.09$	$0.04 \pm 0.02$	$0.1 \pm 0.06$

—whereas in the case of  $\pi$ -mesons the interaction cross section for the formation of doubly charged particles increases. These circumstances, as is seen from Tables 1 and 2, do not depend on the energy of the emitted helium particles.

Our conclusions about the constancy of the formation cross section of doubly charged

**Table 2**  
**Emission cross section  $\sigma$  (in mb)**

$E_\pi$ , BeV	$E_{\text{kin}} >$ 100 MeV	$E_{\text{kin}} >$ 100 MeV	$E_{\text{kin}} >$ 200 MeV	$E_{\text{kin}} >$ 200 MeV	$E_{\text{kin}} >$ 400 MeV	$E_{\text{kin}} >$ 400 MeV	$E_{\text{kin}} >$ 500 MeV	$E_{\text{kin}} >$ 500 MeV
$E_\pi$ , BeV	without geo- metri- cal cor- rec- tion	with geo- metri- cal cor- rec- tion	without geo- metri- cal cor- rec- tion	with geo- metri- cal cor- rec- tion	without geo- metri- cal cor- rec- tion	with geo- metri- cal cor- rec- tion	without geo- metri- cal cor- rec- tion	with geo- metri- cal cor- rec- tion
7.5	$3.43 \pm$ 0.41	$15.75 \pm$ 1.89	$1.08 \pm$ 0.23	$3.76 \pm$ 0.8	$0.20 \pm$ 0.10	$0.98 \pm$ 0.48	—	—
17.5	$5.93 \pm$ 0.5	$29.1 \pm$ 2.2	$1.54 \pm$ 0.18	$5.4 \pm$ 0.62	$0.45 \pm$ 0.10	$1.20 \pm$ 1.25	$0.33 \pm$ 0.08	$0.92 \pm$ 0.23

particles in proton-nucleus interactions agree with the results of works <sup>(9,10)</sup> on the investigation of the yield of fragments of low energies.

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