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Abstract

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INTERACTION OF 9-BeV PROTONS WITH FREE AND BOUND NUCLEONS IN PHOTOGRAPHIC EMULSION*

(Presented by Academician L. A. Artsimovich, 5 VI 1958)

An emulsion chamber consisting of 100 layers of NIKFI-R type emulsion, of thickness $\sim 450\,\mu$ and area 10×10 cm^2, was irradiated at the synchrophasotron with protons of energy 9 BeV. The emulsion layers were scanned along the tracks of the primary protons. Over a length of 485 m, 1308 cases of proton interactions with nuclei were found (scatterings through an angle less than 5° are not included in this number), of which 178 events were assigned to cases of proton interaction with nucleons in photographic emulsion. Cases of interaction of primary protons with free protons and with protons bound in nuclei were selected on the basis of the following criteria: a) an even number of prongs; b) absence of an electron emerging from the center of the star; c) the range of a secondary particle, except for protons from elastic $(p{-}p)$ scattering, mesons, and hyperons, had to exceed 4 mm, which makes it possible to exclude interaction cases in which evaporation particles are present; d) the emission angles and energies of the secondary particles must not contradict the kinematics of the collision of a proton with a proton at rest. A case was considered to be a collision of a proton with a quasifree neutron if the star had an odd number of prongs and satisfied criteria c) and d) for selecting $(p-p)$ events.

In this way 115 cases similar to $(p-p)$ interactions and 63 cases similar to $(p-n)$ interactions were selected, hereafter called $(p-p)$ and $(p-n)$ events. Taking the number of collisions of protons with quasifree protons in the nucleus to be equal to the number of collisions with quasifree neutrons, and excluding cases of elastic $(p-p)$ scattering, one can obtain, as an approximate estimate of the cross section for inelastic $(p-p)$ interaction at 9 BeV, the value ~ 30 mb. In this estimate the hydrogen content in the emulsion was calculated from the data of M. F. Rodicheva and from work ([1]). From works ([2–11]) and from the estimate given here it follows that the cross section for inelastic $(p-p)$ interaction remains practically unchanged in the range from 1 to 9 BeV. The results of works ([11–14]), relating to cosmic rays, also indicate that the cross section for inelastic $(p-p)$ interaction apparently remains constant also in the region of higher energies.

Of the 115 $(p-p)$ events, 11 cases were assigned to elastic $(p-p)$ scattering on hydrogen in the emulsion. To identify these cases, the following quantities were determined: a) the angle between the direction of motion of the primary proton and the scattering plane (the noncoplanarity angle); b) for the smaller scattering angle—the difference between the measured angle and the angle which, according to the kinematics, corresponds to the larger scattering angle; c) for the larger scattering angle—the difference between the measured angle and the angle which, according to the kinematics, corresponds to the observed energy of the recoil proton. If these quantities did not exceed the errors of measurement of the corresponding—

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of angles (in the present case $\leqslant 1^\circ$), the event was regarded as elastic $(p-p)$ scattering.

The differential cross sections of elastic $(p-p)$ scattering cannot be estimated from the data obtained because of insufficient statistics; it should be noted, however, that the scattering angles in the center-of-mass system for all cases of $(p-p)$ scattering do not exceed 22°, i.e., they are smaller than the angle corresponding, for example, to the first diffraction minimum for the black-sphere model with radius $1 \cdot 10^{-13}$ cm.

To determine the total cross section of elastic $(p-p)$ scattering, the efficiency of registering elastic-scattering events was found as a function of the angle between the scattering plane and the emulsion plane.

Table 1

Distribution of $(p-p)$ and $(p-n)$ events by the number of all tracks and the number of fast tracks

n or n_s	$(p-p)$ $N(n)$	$(p-p)$ $N(n_s)$	$(p-n)$ $N(n)$	$(p-n)$ $N(n_s)$
0	–	0	–	7
1	–	23	24	18
2	52	33	–	8
3	–	17	29	22
4	44	23	–	3
5	–	3	8	4
6	8	5	–	1
7	–	–	2	0
Mean number of tracks per star	3.15 ± 0.12	2.7 ± 0.1	2.6 ± 0.2	2.2 ± 0.2

The corresponding correction was calculated from 39 cases which, in terms of registration efficiency, are similar to the cases of elastic $(p-p)$ scattering, and was found to be 1.5 ± 0.2. The total cross section of elastic $(p-p)$ scattering at an energy of 9 Bev, taking account of this correction and of the background from quasielastic $(p-p)$ scattering ($\sim 10\%$), is

$$\sigma_{pp}^{\text{el}} = (10 \pm 4) \text{ mb}.$$

Comparison of this value with experimental data ([9]) shows that the total cross section of elastic $(p-p)$ scattering, when the energy changes from 6 to 9 Bev, does not change within the experimental errors. An estimate of the total cross section of $(p-p)$ interaction at an energy of 9 Bev, obtained as the sum of the elastic and inelastic cross sections, gives a value of ~ 40 mb.

The distributions $N(n)$ and $N(n_s)$ of inelastic $(p-p)$ events and $(p-n)$ events by the number of all tracks n and the number of fast particles n_s in a star are presented in Table 1 (n_s is the number of particles with ionization $\leqslant 1.4\, I_{\text{plateau}}$). Comparison of these data with the results of Refs. ([10,11]) shows that the mean number of charged particles emitted in a $(p-p)$ interaction increases rather slowly as the energy of the incident proton changes from 3 to 9 Bev. The mean number of fast charged particles emitted in $(p-p)$ events at an energy of 9 Bev is appreciably smaller than the corresponding value $\overline{n}_s = 3.4 \pm 0.1$ for proton-nucleus interaction ([15]).

The angular distributions of all charged particles and of fast charged particles in the laboratory system are shown in Fig. 1, where the abscissa gives the cosine of the angle formed by the direction of motion of the particle with the direction of motion of the primary proton, and the ordinate gives the relative number $f(\cos\theta)$ of particles emitted in the given interval of $\cos\theta$. The angular distributions of charged particles from $(p-p)$ and $(p-n)$ events agree within statistical errors (Fig. 1A). Half of the secondary particles are emitted within a cone angle of $18.5 \pm 1.4^\circ$ for $(p-p)$ events and $18.5 \pm 1.8^\circ$ for $(p-n)$ events. The angular distributions of tracks in inelastic $(p-p)$ events for different n (Fig. 1B) also do not differ within the errors.

The angular distributions of fast charged particles in $(p-p)$ and $(p-n)$ events are identical. In Fig. 1C these distributions are compared with the angular distribution of fast particles from the interaction of a proton with a complex nucleus ([15]). From this comparison it is seen that, in proton-nucleon collisions, the secondary fast particles are concentrated in a narrower interval of angles than in the collision of a proton with a complex nucleus. In the first case the forward-backward ratio of the numbers of fast charged particles is

51 ± 8; in the second case, 19 ± 3. Such a difference in the angular distributions (and in the mean numbers of fast charged particles) may be connected with the development of a cascade inside the nucleus.

The tracks of all secondary particles from $(p—p)$ and $(p—n)$ events were followed until stopping, leaving the chamber, decay, or secondary interaction. In $(p—p)$

Fig. 1. Angular distributions

Figure 1: Fig. 1. Angular distributions

events, of 21 tracks of particles that stopped in the chamber, 15 proved to be proton tracks and 6 tracks of π mesons. In $(p$—$n)$ events, 4 protons and 4 π mesons stopped in the chamber. One case was found of the production, in a $(p$—$p)$ event, of a Σ^+ hyperon decaying according to the scheme $\Sigma^+ \to n + \pi^+$.

Fig. 1. A –angular distributions of charged particles from $(p$—$p)$ and $(p$—$n)$ events: **a** –$(p$—$p)$ (328 particles), **b** –$(p$—$n)$ (165 particles). **B** –angular distributions of charged particles from $(p$—$p)$ events: **a** –$n = 2$ (52 events), **b** –$n = 4$ (44 events), **c** –$n = 6$ (8 events). **C** –angular distributions of fast charged particles: **a** –$(p$—$p)$ (277 particles), **b** –$(p$—$n)$ (138 particles), **c** –p-nucleus (15) (845 particles).

The mean free path for nuclear interaction of fast secondary particles from $(p$—$p)$ events is (34 ± 6) cm and from $(p$—$n)$ events (28 ± 7) cm. These values do not differ from the free paths for the interaction of protons and π mesons with energies from 1 to 6 Bev, and also from the expected

···path length for protons with an energy of 9 BeV, reported in Ref. (15). According to the data of the present work, the mean free path for the interaction of protons with an energy of 9 BeV with nuclei in photographic emulsion is (37.1 ± 1.0) cm.

Using the dependence of n_s on the energy of the primary protons (see (15)) and analogous data for π-mesons (16–18), one can estimate the mean kinetic energy of the fast particles that produce secondary interactions. For particles emitted at angles less than 10° (lab. system) to the direction of motion of the primary proton (one half of the secondary stars are produced by such particles), the secondary stars have $\overline{n_s} = 2.1 \pm 0.3$. The mean kinetic energy of these particles is 6–7 BeV if they are protons, and about 5 BeV if they are π-mesons. Particles emitted at angles greater than 10° produce stars with $n_s = 0.3 \pm 0.1$.

It is of interest to compare the results described above with calculations based on the statistical theory of multiple particle production (19, 20). Such a comparison will be carried out in another paper.

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Note: Figure translations are in progress. See original paper for figures.