SECONDARY STARS CREATED BY THE INTERACTION OF 8.7 Bev PROTONS WITH PHOTOEMULSION NUCLEI

G. B. ZHDANOV, P. K. MARKOV, V. N. STREL'TSOV, M. I. TRET'YAKOVA, CHENG P'U-YING, and M. G. SHAFRANOVA

Joint Institute for Nuclear Research

Submitted to JETP editor March 23, 1959

J. Exptl. Theoret. Phys. (U.S.S.R.) **37**, 611-615 (September, 1959)

The secondary interactions of fast neutrons, protons, and π mesons in a photoemulsion stack bombarded with 8.7-Bev protons were studied. It was found that, on an average, 0.68 ± 0.07 fast neutrons were created in a star. The fast nucleons carried away $(55 \pm 9)\%$ and the fast π mesons $(33 \pm 9)\%$ of the energy of the primary particle.

INTRODUCTION

FOR the study of high energy nucleons interacting with nucleons and nuclei, there is a definite interest in the distribution of energy among the secondary nucleons and π mesons. The data in Grigorov's work[1] leads to the result that the average transfer of energy to the fast nucleon after the collision of a 3 — 40 Bev nucleon with a light atom is 70% of the initial value. For the interaction of ~ 9 Bev protons with photoemulsion nuclei, the portion of energy transferred to the fast π's was 20 to 40% of the energy of the primary proton,[2] and the portion transferred to single fast secondary nucleons was equal to $(40 \pm 20)\%$.[3]

The goal of our work was to get an estimate of the energy of the fast nucleons and π's formed in the interaction of 8.7 Bev protons with nuclei of the photoemulsion atoms, on the basis of an analysis of the secondary stars.

EXPERIMENTAL ARRANGEMENT

The work was carried out on a stack (composed of 100 emulsion pellicles of the NIKFI-R type) which was bombarded by the inner beam of 8.7 Bev protons in the proton synchrotron of the Joint Institute for Nuclear Research, using an air-driven target introduced into the chamber at the end of each acceleration cycle. The stack was placed in a stainless-steel vacuum container with walls 3 mm thick. The scanning for stars was carried out by areas with a magnification of 300.

The angular half-width of the beam tracks was 0.2°. We counted as secondary stars* those which had no fast-particle track (with ionization J $\leq 1.4\,J_0$) forming in the plane of the emulsion an angle from 178° to 180° to the direction of the primary proton tracks.* To determine the stars created by fast secondary neutral and charged particles, we traced the fast particle tracks in 274 secondary stars up to their exit from the stack or until they took part in another star. On the basis of the analysis of these tracings, 677 secondary stars with one or more fast particles were classified in the following way.

1. If at least one of the fast-particle tracks in the star was in the interval 90° — 178° relative to the beam direction, we counted it as formed by a secondary charged particle. The error in estimating such stars was ~ 1%.

2. If the only fast-particle tracks in the star formed angles between 0° and 90°, we counted the star as created by fast neutrons (with energy > 500 Mev). Here the number of stars formed by neutrons, with $n_s = 1$, was overestimated by $(18 \pm 8)\%$, in the main on account of the fast secondary charged particles moving in the backward direction.

*The following terminology is used, for brevity: stars formed by protons of the primary beam are called primary; stars formed by particles created in the primary stars are called secondary, and so on.

*By J_0 we always mean the ionization of 8.7-Bev protons.

EXPERIMENTAL RESULTS

The distribution by number of fast particles n_s for stars formed by fast neutrons is given below. The number of stars with $n_s = 1$ was diminished by 18%, corresponding to the results given above. The data for $n_s = 0$ were got by calculation, as shown below.

n_s:	0	1	2	3	4	5	6	Total
Number of stars:	71	83	23	9	2	3	1	192

To estimate the average energy of the fast nucleons, one of the authors (Markov) suggested introducing the relative probability for the appearance of stars with fast-particle numbers $n_s \geq 3$ and $n_s \geq 1$:

$$\eta = N(n_s \geqslant 3) / N(n_s \geqslant 1).$$

An analysis of the experimental data on the interaction of protons with emulsion nuclei for various energies[3,4] shows that $\eta(E)$ is linearly dependent on the energy in the interval 3 to 9 Bev (Fig. 1),

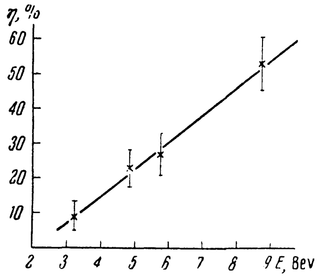


FIG. 1. Dependence of the relative probability η of the appearance of stars with fast-particle numbers $n_s \geqslant 3$ and $n_s \geqslant 1$ on the kinetic energy E of the protons according to references 3 and 4 (the line is drawn by method of least squares).

and this is significant for an estimate of the average energy of secondary particles in a nonmonochromatic spectrum. It is impossible to formulate a similar dependence for the stars formed by neutrons because there are no data corresponding to this in the literature. However, one can suppose that the $\eta(E)$ E dependence for stars formed by protons and neutrons in nuclei is unique, and then one can estimate the average energy by examining the stars formed by neutrons using the E dependence of $\eta(E)$ for stars formed by protons.

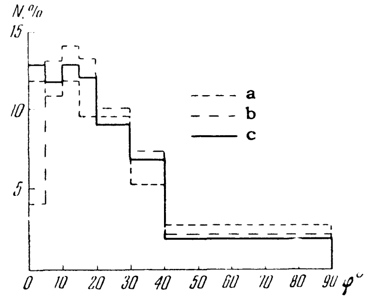
From the examined stars formed by neutrons, $\eta = 0.12 \pm 0.03$,* corresponding to (3.7 ± 0.5) Bev. The average energy of the stars formed by neutrons can be determined also by a different method, using the known E dependence of $\overline{n_s(E)}$ for stars formed by protons[5] and analogous to the method used in reference 3 to determine the energy of fast charged particles. It should be noted that this method is not fully independent of the first method. From the n_s distribution of stars created by protons of various energies,[4] one can estimate the portion of stars formed by neutrons with $n_s = 0$ corresponding to an average energy of 3.7 Bev. The answer should be 37%. It is essential here that the percentage of stars with $n_s = 0$ depend linearly on the energy in the 3 – 6 Bev region.[4] Thus the number of stars formed by neutrons should be 192, including stars with $n_s = 0$. The average number of fast particles in a neutron star is $n_s = 0.97 \pm 0.08$, and from this the average energy of neutron stars is obtained as (3.3 ± 0.5) Bev.

*Everywhere in this paper, only the statistical error is shown.

It is evident that both estimates agree within the limits of error. We take as the average energy of fast neutrons the average of the energies obtained by the two methods described above, or (3.5 ± 0.5) Bev. The average energy of fast protons will also be taken to be (3.5 ± 0.5) Bev.

By comparing the number of stars created by charged particles with ionization $J \leq 1.4\, J_0$, we can estimate the absolute number of fast neutrons belonging on an average to one star, taking the interaction cross sections of the charged particles and neutrons as equal and independent of the energy. Then for a given geometry the number of secondary stars is proportional to the number of particles created in the primary star. In Fig. 2, the angular

FIG. 2. Angular distribution of fast charged particles: a – originating in primary stars according to reference 3, b – generating observed secondary stars, c – generating secondary stars taking into account corrections for the gap 0°–5°.



distribution of fast charged particles which produced secondary stars is given with and without corrections for ineffective counting of stars in the interval 0° – 5°. The angular distribution of fast charged secondary particles in the range 0° to 90° is also given, from the data in reference 3. To make the two coincide, one must introduce a correction for the geometry for stars formed by fast charged particles coming out at an angle > 20° to the beam direction. After this is done, it turns out that 857 stars from fast charged particles correspond to 192 stars formed by neutrons. Their distribution according to multiplicity is given in the table.

In view of the fact that the average energy of the neutrons producing the observed stars is large, one must suppose that only an insignificant percentage of these neutrons can come out at angles > 20° to the primary proton beam direction. Therefore no geometrical corrections were made for stars formed by neutrons. For angles between 0° and 90° an average of 3.03 fast charged particles[3] were emitted for each primary star. So the average number of fast neutrons per star was equal to

$$192 \cdot 3.03 / 857 = 0.68 \pm 0.07.$$

Assuming that the proton-nucleus interaction creates an equal number of fast protons and neu-

Distribution by n_S of stars formed by charged particles with ionization $J \leq 1.4 J_0$ at angles of flight $0° - 90°$ to the beam direction

n_s	0	1	2	3	4	5	Total
Number of stars (after introducing corrections)	499*	240	85	24	5	4	857
Experimentally observed number of stars	266	201	64	18	5	2	556

*Stars with $n_s = 0$ were not counted on the entire area. After introducing corrections, their number was 499.

trons* (whose average energy was estimated above) we find that the average energy taken away from a star by the fast particles is (4.8 ± 0.8) Bev, that is, $(55 \pm 9)\%$ of the energy of the primary proton.

It should be noted that if $\overline{n}_S(E)$ has a smaller value for stars formed by neutrons than for those formed by protons, this circumstance leads to an underestimate of the nucleon energy, as determined by the two methods given above. However, in this same case an additional number of neutron-created stars with $n_S = 0$ involves overestimates, so that the average energy taken away by the nucleons is not essentially changed. Thus, for example, if the energy of the neutrons were underestimated by 1 Bev, the energy carried away by the fast nucleons makes up on the average $(63 \pm 9)\%$ of the energy of the primary proton.

Knowing the average energy taken away by the fast nucleons and also the average nuclear dissociation energy, equal to (1.0 ± 0.1) Bev per star in agreement with reference 3, it is possible to estimate the average total energy of fast π mesons. It turns out to be (2.9 ± 0.8) Bev per star or $(33 \pm 9)\%$ of the primary proton energy. Within the limits of statistical error, this value coincides with the results obtained in reference 2.

From reference 3 it is known that the average number of fast charged particles per star is 3.2. If there are 0.68 fast protons to a star, then we get 3.8 ± 0.3 fast π mesons. From this it follows that the average total energy of the pions is (0.8 ± 0.2) Bev.

The methods described so far, of estimating the energy of secondary particles were founded on the determination of the number of particles in the stars they created. Along with this, we measured the angles of flight of the fast particles for stars having $n_S \geq 2$, both relative to the direction of the primary proton beam and to the direction of the generating particle, if the latter was charged. The basic problem in these measurements was in separating the stars created by high energy nucleons and mesons, since in this last case the angular distributions were significantly wider.*

To perform the indicated task it is expedient to assign to each star one angular characteristic, for example, the average flight angle $\overline{\theta}$ of fast particles relative to the primary protons. We could verify here that in the case of the stars from charged particles these average characteristics as a rule changed little in changing over to reading all angles with the direction of the generating particle. In Fig. 3 the distributions by angular characteristics are shown for secondary stars created by neutrons (a) and by fast charged particles making angles $\leqq 10°$ (b) and $> 10°$ (c) to the primary beam.

Even in a cursory comparison of Figs 3a, 3b, and 3c it is evident that stars with average emission angles $\overline{\theta} > 60°$ for fast particles are very rare in group a, somewhat more common in group b, and even more common in group c. Approximate calculations show that the bounding value of the angle $\overline{\theta}$, 60°, roughly corresponds to the transition from stars formed by nucleons to stars formed by π mesons.

A more detailed analysis of Fig. 3 gives the following results:

1. The ratio of the number of fast protons to the number of fast neutrons does not significantly exceed unity.

*Thus, for example, there are grounds for supposing that asymmetry between protons and neutrons would show up at the very first in the secondary particles emitted at small angles to the direction of the primary. A subsequent analysis of the angular distributions in the stars we studied showed that the ratio of the numbers of such particles, created by neutral and charged nucleons, could differ from unity by no more than 30%. We got an analogous result on the small deviation from proton-neutron symmetry in the analysis of Fig. 3 below.

*This was due, first, to the lower (average) energies of the mesons in comparison with nucleons and, second, to the velocity being smaller in the center of mass system (of the stationary and incident systems) for equal energies of mesons and nucleons.

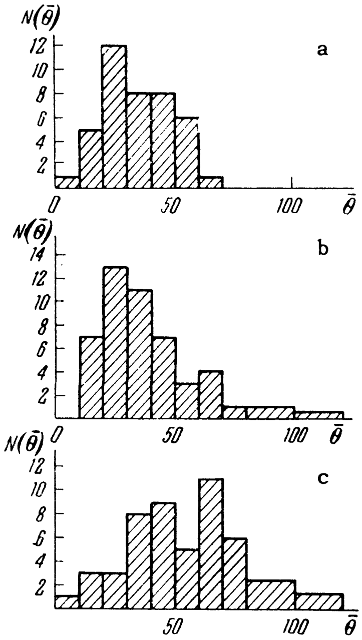


FIG. 3. Distribution of particles by average angle of flight $\bar{\theta}$ for secondary stars: a – formed by neutrons, b – formed by fast charged particles moving at angles $\phi \lesssim 10°$, and c – at $\phi > 10°$, relative to the primary beam.

2. The ratio of the number of protons and mesons among the particles forming stars with $n_s \geq 2$ is 1.5 to 2, which is evidenced by the significantly higher average energy of protons in comparison with mesons.

3. Among the secondary particles, moving away at angles $\leq 10°$ to the direction of the primary protons, $\sim 80\%$ are nucleons.

CONCLUSIONS

The following results were obtained in the work:

1. For the interaction of an 8.7 Bev proton with nuclei of the emulsion atoms, there is an average of (0.68 ± 0.07) fast (with energy > 500 Mev) neutron per star, with average energy (3.5 ± 0.5) Bev.

2. Under the assumption that the number of fast protons and neutrons (calculated for one star) and their average energy are equal, fast nucleons carry away $(55 \pm 9)\%$ of the energy of the primary particle.

3. The average number of fast (with energy > 80 Mev) π mesons, neutrals included, emitted in one interaction is 3.8 ± 0.3. Their average total energy is (0.8 ± 0.2) Bev.

4. An analysis of the angular distributions of fast tertiary charged particles in secondary stars testifies that $\sim 80\%$ of the secondary particles moving at an angle $\leq 10°$ to the direction of the primary protons are nucleons.

The authors thank M. Ya. Danysh, M. I. Podgoretskiĭ, and I. L. Rozental' for their discussion of a number of questions, and also to the group of workers taking part in the measurements and photoemulsion scanning.

[1] N. L. Grigorov, Usp. Fiz. Nauk **58**, 499 (1956).

[2] Bayatyan, Gramenitskiĭ, Nomofilov, Podgoretskiĭ, and Skrzypczak, JETP **36**, 690 (1959), Soviet Phys. JETP **9**, 483 (1959).

[3] Belyakov, Shu-fan, Glagolev, Alkhazhov, Kirillova, Markov, Lebedev, Tolstov, Tzyganov, Shafranova, and Tsyng-se, Proceedings, Annual International Conference on High Energy Physics at CERN, Geneva (1958), pp 309-318.

[4] W. R. Johnson, Phys. Rev. **99**, 1049 (1955).

[5] Bogachev, Shu-fan, Gramenitskiĭ, Kirillova, Lebedev, Lyubimov, Markov, Merekov, Podgoretskiĭ, Sidorov, Tolstov, and Shafranova, Атомная энергия (Atomic Energy) **4**, 281 (1958).

Translated by W. Ramsay
122