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Disintegration of Nuclei by π^--Mesons*

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Investigations of nuclear disintegrations induced by π^--meson absorption in nuclear emulsions, exposed to the π^--meson beam of the 130-in. Rochester cyclotron, have been carried out. The energy spectrum of the protons emitted from the absorptions shows two distinct processes occurring: (a) evaporation of nucleons from an excited nucleus and (b) emission of knock-on protons, brought about by the interaction of a π^--meson with a multi-particle structure in the nucleus. Of the mesons ending in the emulsion, 10 ± 2 percent give rise to protons with energies $\geqslant 30$ Mev. Strong evidence is presented for the boson character of the π^--meson.

I. INTRODUCTION

THE disintegration of atomic nuclei by the absorption of π^--mesons can be investigated by the use of nuclear emulsions. Some work in this direction has been carried out by D. H. Perkins[1] using cosmic-ray mesons. Unfortunately, because of the small mass difference between μ- and π-mesons, it is difficult to distinguish between them unless the lengths of track in the emulsion are considerable. A more satisfactory source of slow π^--mesons is a large cyclotron. It is a simple procedure to screen out the π^+-mesons and to arrange the magnetic channel so that very few μ^--mesons (which are the disintegration products of the π^--mesons produced in the cyclotron target) will reach the emulsion.

Kodak NTB-3 emulsions were exposed to the π^--meson beam of the 130-in. Rochester cyclotron by Dr. S. W. Barnes. A systematic survey was made of 429 mesons ending in one particularly favorable pellicle of 250 microns thickness. A star-size distribution, a proton energy spectrum and information concerning the nuclear recoils associated with the meson absorption were obtained.

II. EXPERIMENTAL DETAILS

Nuclear emulsions can be calibrated by determining the relationship between grain densities of the tracks of singly charged particles and the specific energy loss of these particles. The latter quantity can be found from a knowledge of the residual ranges of the charged particles in the emulsion. The grain density as a function of residual range for 15 meson tracks of residual range greater than 1000 microns was obtained. This yielded a calibration for the emulsion for protons whose energy is less than 50 Mev. The calibration curve was then extrapolated to higher energies and was spot-checked in this region by the grain densities of several meson tracks of very large residual range. Several protons of known residual range were used to check the calibration in the 30–40 Mev region. The energy of the protons emitted as disintegration products of the nuclei was determined by their specific energy loss and/or residual range.

III. STAR-SIZE DISTRIBUTION

Table I shows the star-size distribution. The data are classified according to three interpretations as to the nature of tracks less than 6 microns in length: (a) All tracks between 0 and 6 microns in length classified as recoils (one star was found containing two tracks both less than 6 microns in length; in this case only one of these tracks was considered to be a recoil); (b) all tracks between 0 and 6 microns considered as prongs for all stars; (c) all tracks between 0 and 6 microns considered as prongs for all stars except those in which these tracks are the only ones (in these cases they are considered to be "recoils"). The authors consider the last interpretation to be closest to the truth; the reasons for this and its significance are presented below. Table I also contains a star-size distribution obtained by Adelman and Jones[2] at Berkeley, which is based on 512 meson events. Their data have been classified according to interpretation (c) listed above. (It should be noted that the Berkeley group uses 5 microns as the upper limit for recoil lengths; however, this should not affect the comparison between results.)

Table II shows the star-size distribution for those stars containing protons whose energy is greater than

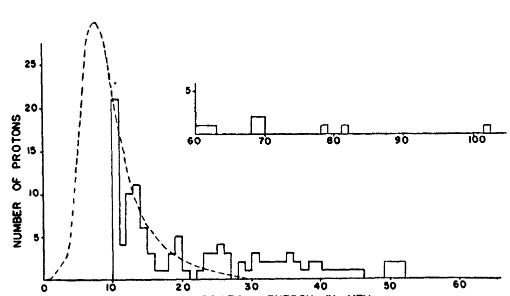

FIG. 1. Histogram representing energy distribution above 10 Mev of protons emitted as disintegration products of nuclei which have absorbed π^--mesons. The dashed curve represents energy distribution of protons evaporated from Ag nucleus of nuclear temperature between 2.5–3 Mev.

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[1] D. H. Perkins, Phil. Mag. 40, 601 (1949).

[2] Private communication.

TABLE I. Star-size distribution of π^--meson induced stars.

Number of prongs	0	1	2	3	4	5
Number of stars[a]	151	100	71	69	30	8
Percent of total	35.2	23.3	16.5	16.1	7.0	1.9
Number of recoils	70±10	43	20	8	—	—
Number of stars[b]	81±10	127±10	94	81	38	8
Percent of total	18.9±2.3	29.6±2.3	21.9	18.9	8.8	1.9
Number of stars[c]	151	57	94	81	38	8
Percent of total	35.2	13.3	21.9	18.9	8.8	1.9
Percent of total[d]	30.5	17.8	26.9	15.2	7.8	1.8

[a] Tracks with lengths between 0 and 6 microns are considered as recoils.
[b] Tracks with lengths between 0 and 6 microns are considered as prongs.
[c] Tracks with lengths between 0 and 6 microns and which are the only visible tracks emanating from the absorption are considered as recoils; all others are considered as prongs.
[d] Berkeley data based on 512 stars; interpretation (c) applied, but with 5 microns as upper limit to recoil length.

30 Mev. These high energy protons are listed as prongs while, as above, the tracks less than 6 microns in length are considered first as recoils and then as prongs. (In this case, criterion (b) coincides with (c).)

IV. HIGH ENERGY PROTONS

Figure 1 is the energy spectrum of the protons of energy $\geqslant 10$ Mev emitted as disintegration products of the nuclei. This, together with the spectrum below 10 Mev, indicates two qualitative features: a spectrum which corresponds to the evaporation of particles from a nucleus of a given nuclear temperature and, in addition, a high energy ($\geqslant 30$ Mev) "tail." This "tail" gives an indication of the mechanism of interaction of the π^--meson with the nucleons in the nucleus. The dotted curve in Fig. 1 is the energy spectrum of protons evaporated from a silver nucleus of nuclear temperatuer between 2.5 and 3 Mev.[3] The theoretical curve is fitted to the experimental curve at 10 Mev. It should be noted that the evaporation spectrum predicts essentially no protons with energies above 30 Mev; it is for this reason that we have assumed that most protons above 30 Mev are high energy knock-on protons. The evaporation spectrum should not be expected to hold for the light nuclei of the emulsion. However, since most of the mesons are presumably absorbed by the heavy nuclei, the energy spectrum for all the nuclear evaporations should not essentially differ from that shown in Fig. 1.

Of the absorptions observed, 10.0±2.0 percent give rise to protons with energies $\geqslant 30$ Mev. Counting as prongs only those tracks greater than 6 microns in length, 7.9±2.0 percent of the star prongs are protons with energies $\geqslant 30$ Mev, while counting all tracks as prongs, 6.1±2.0 percent of the star prongs are protons of such energies. (The errors quoted are statistical errors.)

The absorption process has been considered by Tamor[4] as an interaction of the π^--meson with an alpha-particle-like structure and a two nucleon (proton-plus-proton or neutron-plus-proton) structure in the nucleus. The π^--absorptions in the light and heavy nuclei in the emulsion as typified by nitrogen and silver, respectively, were separately examined. According to the alpha-particle model, 12 percent of the absorptions in nitrogen and 13 percent of those in silver yield protons with energies $\geqslant 30$ Mev, while the two nucleon structure predicts that 48 and 24 percent of the absorptions in nitrogen and silver, respectively, yield high energy protons. Assuming that $\frac{2}{3}$ of the absorptions occur in the heavy elements and $\frac{1}{3}$ in the light, the two nucleon model would predict that 32 percent of the meson absorptions should give rise to protons with energies $\geqslant 30$ Mev. (It is assumed that this relative number of absorptions in light and heavy nuclei also holds for π^--mesons, although the number quoted was found for μ^--mesons; this assumption must be quite accurate.[5]) The experimental evidence favors the former hypothesis. It should be noted that Perkins observes 7±2 percent of the π^--stars (based on 120 meson events) yield fast protons (above 30 Mev). Adelman[6] has found similar results on the basis of 120 meson events.

Five of the 429 meson events observed were stars showing a visible excitation energy of approximately 100 Mev, assuming 7 Mev binding energy per particle in the nucleus. One proton track exhibited a grain density corresponding to an energy greater than 100 Mev and represents the largest visible excitation observed. In addition, three deuterons of energy between 20 and 30 Mev were observed as disintegration products. Nuclear disintegration products with such high total energy are strong evidence for the boson character of the π^--meson.[7,8]

V. RECOIL OF THE ABSORBING NUCLEUS

In an attempt to obtain information concerning the recoil of the nucleus absorbing the π^--meson, stars with one visible track emanating from the collision were examined. Figure 2 is a histogram showing the fre-

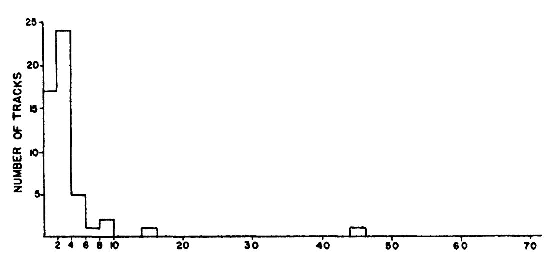

FIG. 2. Range distribution below 75 microns of tracks associated with stars showing only one visible track.

[3] Harding, Lattimore, and Perkins, Proc. Roy. Soc. **A196**, 325 (1949).

[4] S. Tamor, Phys. Rev. **77**, 412 (1950).
[5] Cosyns *et al.*, Proc. Phys. Soc. London **62**, 360A, 801 (1949).
[6] Adelman, private communication.
[7] R. E. Marshak, Phys. Rev. **75**, 700 (1949).
[8] Tiomno and Wheeler, Rev. Mod. Phys. **21**, 153 (1949).

quency of these track lengths up to 75 microns. This histogram exhibits one very striking feature: 90 percent of all tracks from one-track stars with lengths less than 75 microns are grouped in the region below 6 microns. The peak in the histogram between 2 and 4 microns may not be an actual one as the efficiency for observing tracks less than 3 microns long is low. These short tracks could be: (a) slow charged particles (e.g., protons or alpha-particles) emitted from the nucleus; (b) Rutherford scattering near the end of meson tracks; (c) recoils of the absorbing nuclei which have emitted one fast neutron as envisaged in Tamor's alpha-particle model interaction. If these tracks are slow protons or alpha-particles, it is difficult to see why there is such an abundance of track lengths below 6 microns and such a paucity between 6 and 75 microns since the energies of protons and alpha-particles whose ranges are about 6 microns in the emulsion are well below the Coulomb barriers for these particles even in a carbon nucleus. Some of these "tracks" may arise from Rutherford scattering of the meson in its last few microns. The probability for such scattering was calculated using 20 degrees as the cut-off angle for the integration since mesons which scatter through angles less than this value could not be seen in the photographic emulsion. Of those mesons which produce no disintegrations, 6 percent should show tracks between 2 and 6 microns in

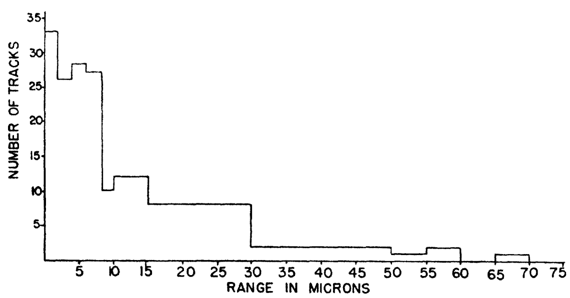

FIG. 3. Range distribution below 75 microns of tracks associated with stars showing more than one visible track.

length if these tracks are due to Rutherford scattering of the meson. The calculation was made with a power-law dependence of range on energy in this energy region ($r=AE^x$). This probability accounts for an inappreciable fraction of the short "tracks" observed. The short "tracks" were also observed to be roughly isotropic in angular distribution, which further rules out the Rutherford scattering hypothesis with its strong angular dependence. It is therefore concluded that most of these "tracks" are in all probability recoils of the absorbing

TABLE II. Star-size distribution for stars with protons of energy $\geqslant 30$ Mev.

Number of prongs	1	2	3	4	5
Number of stars[a]	16	9	13	4	1
Percent of total	37.2	21.0	30.2	9.3	2.3
Number of stars[b]	12	11	13	6	1
Percent of total	27.9	25.6	30.2	14.0	2.3

[a] All tracks with lengths between 0 and 6 microns are considered as recoils.
[b] All tracks with lengths between 0 and 6 microns are considered as prongs.

nuclei associated with the emission of high energy neutrons as is predicted by the alpha-particle model interaction.

In contrast to the data of Fig. 2, Fig. 3 gives a histogram of the lengths of tracks from stars which have more than one track. There is some evidence in the 0 to 6 micron interval of a maximum; however, it is difficult to decide what fraction of the tracks below 6 microns represents recoiling nuclei, because of the large number of tracks in the region above 6 microns.

Finally, it is worth noting that we have examined the last few microns of tracks of iron nuclei appearing in similar emulsions exposed to cosmic radiation by Drs. Bradt and Peters of this laboratory; we found that the ends of iron tracks exhibited the same visible properties as those tracks which we have interpreted as recoiling nuclei.

VI. CONCLUSIONS

The experimental evidence shows that in the process of slow π^--meson absorption by nuclei, two processes are to be considered: (1) the evaporation of nucleons from an excited nucleus; (2) the emission of energetic nucleons brought about by the interaction of the meson with some sub-structure in the nucleus. The number of events observed with high energy protons indicates that the nuclear substructure is a multi-particle one, as typified by the alpha-particle model. It is to be hoped that further work on the very short prongs, which are presumed to be nuclear recoils, will yield further evidence as to the nature of the interaction. The high visible excitation energies observed for the excited nucleus lends strong evidence for the boson character of the π^--meson.

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