Fast Protons from the Capture of π^- Mesons in Photographic Emulsions*†

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The spectrum of fast protons from 1631 π^- meson absorptions in Ilford G-5 and C-2 emulsions has been studied. It has been found that (16.1±1.8) percent of all π^- meson absorptions are accompanied by protons of energy greater than 20 Mev, and that (9.5±1.3) percent of all absorptions are accompanied by protons of energy greater than 30 Mev. The proton energies were estimated by grain counting in comparison with π^- mesons of known residual range. Allowance was made for the variation of grain density with position and depth in the emulsion. The energy spectrum is fairly flat from 30–70 Mev, but only three events were found above 70 Mev. Examination of stars from which the fast protons were emitted shows more prongs ejected opposite to the direction of the fast proton than are accounted for by evaporation from a recoiling nucleus. The energy spectrum favors the capture of the meson by a proton, with the recoil momentum taken by a small, variable number of nucleons. Furthermore, the evidence suggests that the low energy star prongs result from knock-on collisions of the primary nucleons with other nucleons inside the nucleus.

I. INTRODUCTION

THERE have been several attempts recently to discover the mechanism by which a π^- meson is captured by a complex nucleus. In the earliest models, the whole nucleus participated in the capture, and the entire rest of the mass of the π^- meson (about 140 Mev) was available for excitation of the nucleus. The evaporation models with an excitation energy of 140 Mev[1,2] fail to predict the observed energy spectrum[3,4] of the emitted charged particles. Furthermore, the observed average excitation energy of the meson stars was about 100 Mev,[3–5] considerably less than the total available energy. In 1949 Marshak[6] proposed a model in which the π^- meson interacts with a single proton of the nucleus, and the recoil momentum is taken up by a neighboring nucleon. The preliminary calculations indicated that more than 10 percent of the π^- absorptions should be accompanied by the emission of a proton of energy greater than 30 Mev. More detailed calculations by Fujimoto *et al.*[7] and by Tamor[8] supported this prediction. In order to check this prediction, the author,[9] Cheston and Goldfarb,[10] and Menon *et al.*[4] examined π^- meson endings in photographic emulsions capable of recording tracks of charged particles even at minimum ionization. They observed that fast protons[11] were indeed emitted from meson-induced stars, a result inconsistent with an evaporation process, but the data were too inconclusive to confirm or reject any of the specific hypotheses. The author's first study was essentially exploratory, with very few statistics and a crude method of energy estimation. Menon *et al.* and Cheston and Goldfarb had better statistics and more precise methods of energy determination. However, in each case the criterion of energy, the grain density, varied relatively slowly with proton energy in the neighborhood of 30 Mev. Furthermore, since the variation of observed grain density with position in the plate[12] and with depth in the emulsion was not taken into account, the number of protons of energy greater than 30 Mev could not be reliably determined.

II. EXPERIMENTAL ARRANGEMENT

The photographic plates were exposed in the 184-inch Berkeley cyclotron as shown in Fig. 1. They were put a relatively large distance from the target in order to reduce the background due to neutral particle from the target. At this distance most of the mesons which could reach the plates had enough energy (~30 Mev or more) to pass completely through the pack of plates. Therefore, a $\frac{3}{8}$-inch aluminum absorber was placed in front of the plates to slow down the mesons.

Ilford G-5 emulsions were chosen for this experiment

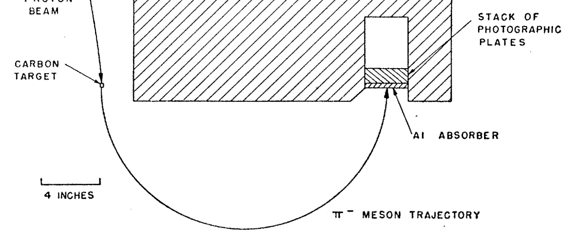

FIG. 1. Schematic diagram of apparatus for exposing plates.

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2 Y. Fujimoto and Y. Yamaguchi, Prog. Theor. Phys. **4**, 468 (1949).

3 D. Perkins, Phil. Mag. **40**, 601 (1949).

4 Menon, Muirhead, and Rochat, Phil. Mag. **41**, 583 (1950).

5 J. Heidmann and L. LePrince-Ringuet, Compt. rend. **226**, 1716 (1948).

6 R. Marshak, Echo Lake Symposium on Cosmic Radiation (1949).

7 Fujimoto, Hayakawa, and Yamaguchi, Prog. Theor. Phys. **4**, 576 (1949).

8 S. Tamor, Phys. Rev. **77**, 412 (1950).

9 F. Adelman, Phys. Rev. **78**, 86(A) (1950).

10 W. Cheston and L. Goldfarb, Phys. Rev. **78**, 683 (1950).

11 In the rest of this paper, the term "fast proton" will refer to a proton of energy greater than 30 Mev.

12 K. Bowker, Phys. Rev. **78**, 87(A) (1950).

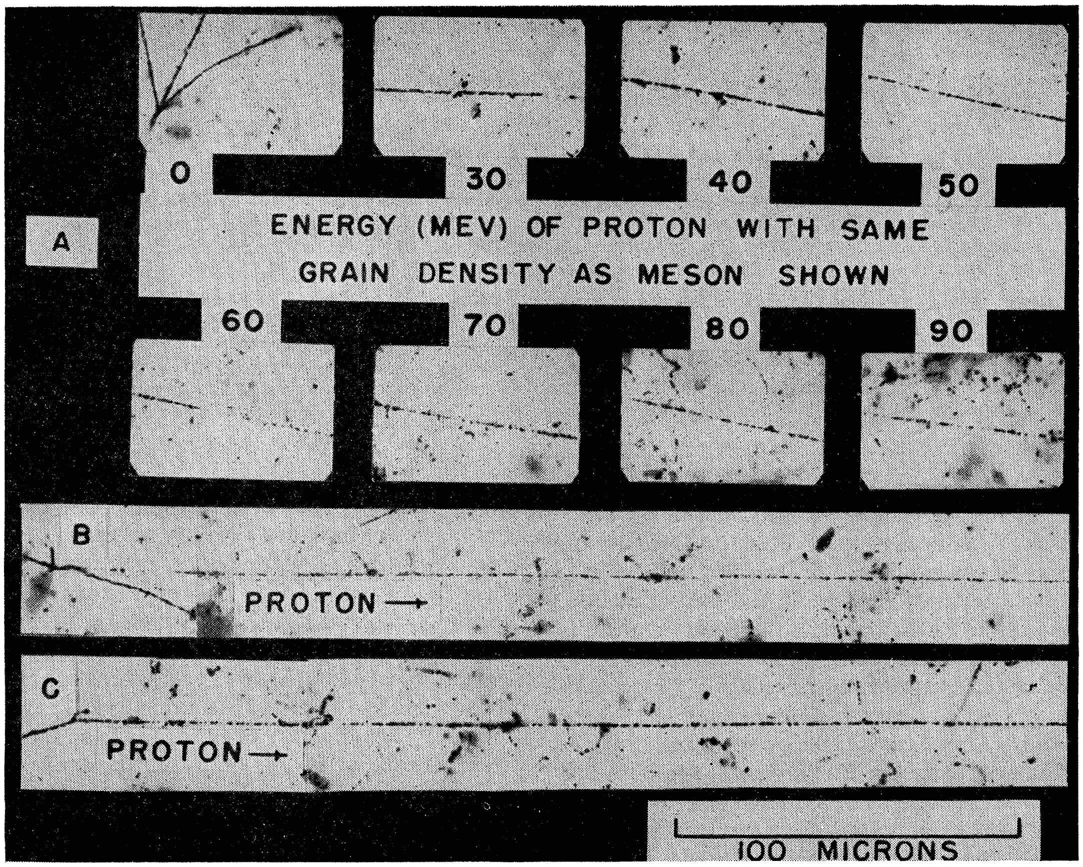

FIG. 2. (A) Photomicrograph of meson track taken at various velocities in G-5 plate. A proton at the same velocities would have the grain densities and energies shown. (B) 4-prong meson star, one of whose prongs is a 58-Mev proton. (C) Meson star with single prong, a 55-Mev proton. An electron is also associated with this event.

so that the most energetic protons might be observed. Since these plates had acquired a heavy background of low energy electrons by the time they had reached Berkeley, it was desirable to eradicate the latent images by accelerated fading.[13] By storing the plates in an oven at about 33°C over a pan of water for about 50 hours and then drying, it has been found possible to eliminate 90 percent of the latent image electrons without any noticeable loss of sensitivity. The plates were exposed and developed as soon as possible after the background eradication.

Shortly after work was begun on this project, however, it was found from the variation of the grain density with meson residual range that the grain density in G-5 emulsions was a slowly varying function of proton energy below 40 Mev. Therefore, the proton spectrum below 60 Mev was examined in the less sensitive Ilford C-2 emulsions, which, incidentally, require no eradication.

III. PROCEDURE

To establish the variation of grain density with energy, mesons were grain-counted up to a distance of 3.7 mm from the end of their ranges, at which point the grain density was the same as that of a 90-Mev proton. It was found that the differential grain count could be treated as the product of two factors, one depending only upon energy and the other, only upon the depth in the emulsion.

The differential grain count was found to vary as $1/(E_{\text{proton}})^{\frac{1}{2}}$ in the G-5 plates in the range 45–90 Mev and in the C-2 plate in the range 20–60 Mev. Protons of energy greater than 60 Mev in the C-2 plates were not included, as the fluctuations of grain count due to the density of random grains are too large. Corrections were applied for the variation of grain count with depth in the emulsion.

IV. RESULTS

A total of 1631 meson absorptions were examined, 992 in G-5 emulsion and 639 in C-2 emulsion. Typical examples and grain densities of protons[14] of energy

[13] J. Spence, private communication.

[14] The grain density of a 20-Mev proton is equal to that of a 40-Mev deuteron or of a 60-Mev triton. Therefore the term "proton" includes deuterons of twice the energy and tritons of three times the energy in question. There are a few cases where positive identification can be made from the range of the particles, as will be discussed below.

greater than 20 Mev are given in Figs. 2 and 3. The energy spectrum of these protons, after the application of the geometrical corrections, is shown in Fig. 4; the standard deviation in the energy of a proton varies from $2\frac{1}{2}$ Mev at 20 Mev to about 6 Mev at 70 Mev. (16.1 ± 1.8) percent of all meson absorptions are accompanied by protons of energy greater than 20 Mev, and (9.5 ± 1.3) percent of all absorptions are accompanied by protons of energy greater than 30 Mev. In terms of ejected particles, (10.3 ± 1.2) percent of all star prongs are protons of energy greater than 20 Mev, and (6.0 ± 0.8) percent are protons of energy greater than 30 Mev. These numbers are in agreement with those of other workers.[4,10]

A precise prong spectrum[15] for meson induced stars may also be given by use of the data of this study. Since Adelman and Jones,[16] and Menon *et al.*[4] used the same conventions[17] for star prongs as the author, their data may be combined with that found here to give the prong spectrum of Table I, based upon 3366 meson stars.

V. DISCUSSION

When these results are compared with the theoretical predictions of π^- meson capture,[4,6,7,8,18] it may be seen that most of the models yield higher energy protons or larger numbers of protons (or both) than have been found here.

The model of Menon *et al.*,[4] however, does not seem inconsistent with the present data. They assumed that the primary interaction takes place among 3 or 4 nucleons, and that the energy of those nucleons which do not escape is used in heating the nucleus. For their preliminary calculations, they assumed an α-particle model, for which calculations had been made by Ruddlesden and Clark.[19] The predictions of this preliminary computation are an excitation energy of 120 Mev, which is somewhat high, and a peak in the number of protons between 30 and 40 Mev, for which there is no evidence in Fig. 4. However, when the interactions of the smaller numbers of nucleons are taken into account, the mean excitation energy should decrease and the peak should be smoothed out. Thus,

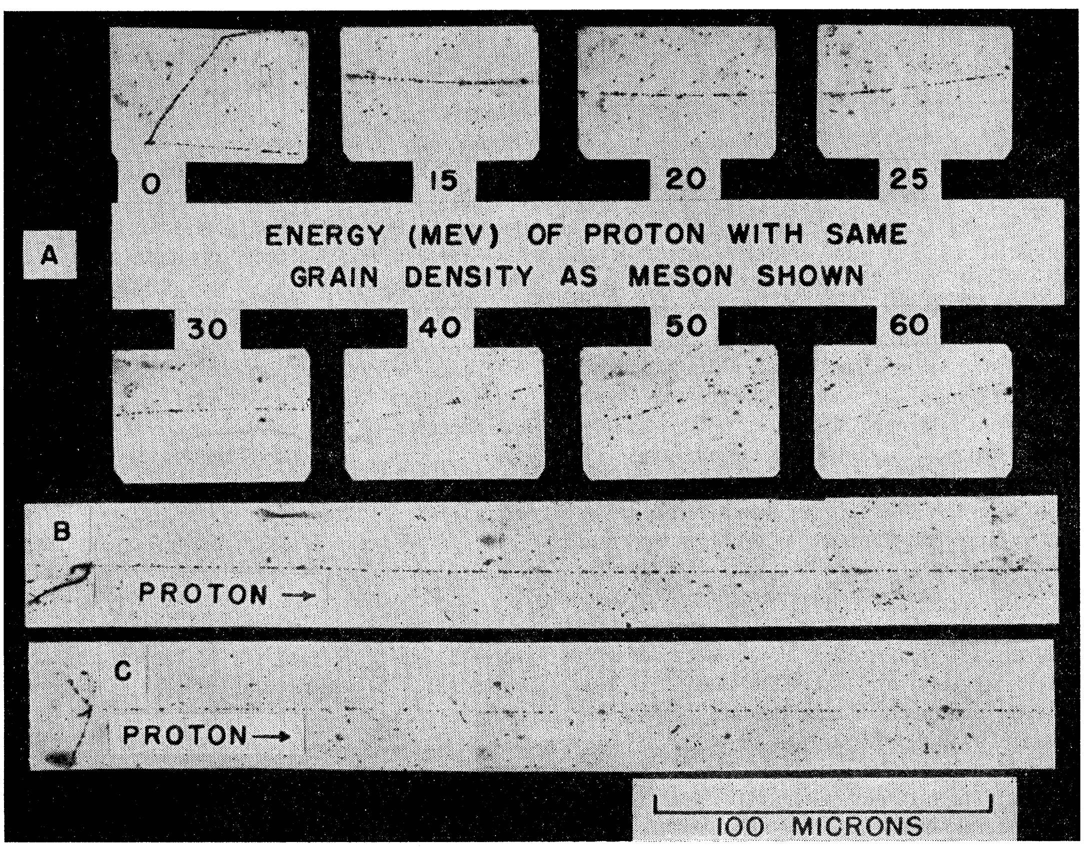

FIG. 3. (A) Photomicrograph of meson track taken at various velocities in a C-2 plate. A proton at the same velocities would have the grain densities and energies shown. (B) 2-prong meson star, one of whose prongs is a $20\frac{1}{2}$-Mev proton. (C) 3-prong meson star, one of whose prongs is a $56\frac{1}{2}$-Mev proton.

[15] I.e., the frequency distribution of stars of a given number of prongs.
[16] F. Adelman and S. Jones, Science **111**, 226 (1950).
[17] Any group of grains (except an electron track) leaving the terminus of a meson with a well-defined direction is a star prong.
[18] Fujimoto, Takayanagi, and Yamaguchi, Prog. Theor. Phys. **5**, 498 (1950).
[19] S. Ruddlesden and A. Clark, Nature **164**, 487 (1949).

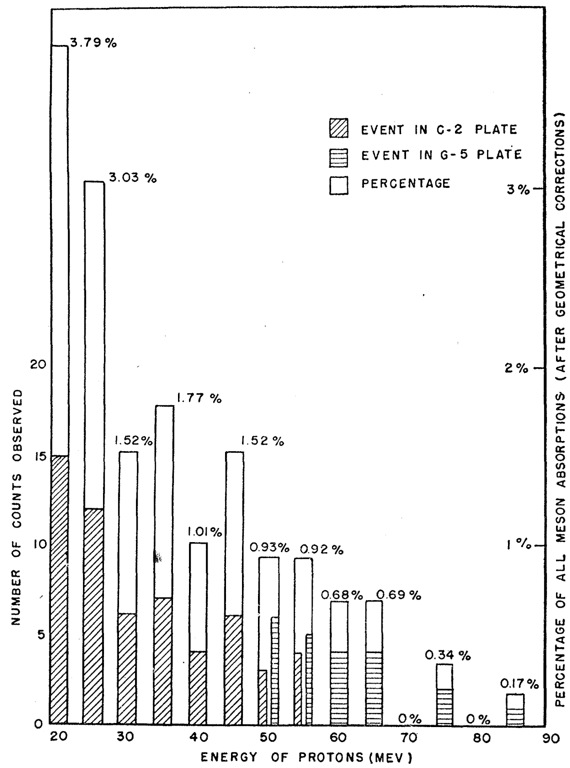

FIG. 4. Energy spectrum of emitted protons of energy greater than 20 Mev, before and after geometrical corrections.

their proposed model is not inconsistent with the spectrum of Fig. 4.

In Fig. 4 the number of protons in the range 20–30 Mev is twice the number in the range 30–40 Mev. Since a 20-Mev proton could reasonably have come from a nuclear evaporation with excitation energy of 100 Mev, while a proton of 30 Mev is much less likely to have come from such a process, the energy spectra of the protons from the primary and secondary processes overlap considerably. This implies either that relatively low energy primary nucleons occur often or that some of the lower energy protons are knock-on particles from collisions with high energy primary nucleons.

Another characteristic of the energy spectrum is that the number of protons decreases slowly with energy in the range 30–70 Mev, and drops off above 70 Mev; there are fewer protons of energy greater than 70 Mev than there are in any 5-Mev interval below 70 Mev. Thus relatively few of the π^- absorptions take place with the creation of a primary nucleon of energy greater than 70 Mev, while nucleons occur often with energies lower than this figure. Therefore, the primary act must take place often among two or more nucleons, with a deuteron or triton seldom acting alone as the recoil particle. On the other hand, three of the emitted particles ended in the emulsion. Two of these were actually protons by range and grain density, and the third was a 54-Mev deuteron. In addition, one particle was found which was probably a triton of 30 Mev, and another was either a 23-Mev proton with abnormally high grain density or a 31-Mev deuteron with abnormally low grain density. Neither of these is included in the data. Thus it appears that deuterons and tritons actually take part in the primary process; if they were knock-on particles, the energetic primaries required would lead to a larger number of protons of energy greater than 50 Mev than in the range 30–50 Mev,[20] in contradiction to Fig. 4. This conclusion does not contradict the earlier conclusion of this paragraph, since there is not enough data to observe the relative numbers of protons, deuterons, and tritons.

The prong spectrum of the stars in which a fast proton appears is quite similar to the normal prong spectrum of π^- mesons absorbed in photographic emulsions (Table I). If one takes into account the limitations of the comparison of prong spectra with poor statistics and the lack of detailed knowledge of the process, one may still state reasonably that most of the π^- absorptions which are not accompanied by protons of energy greater than 20 Mev are accompanied by neutrons of similar energies. This would seem to indicate that the number of neutrons available as the recoil particle is twice the number of available protons (since one neutron is always involved), as in the α-particle model of nuclei.

The most interesting feature of the data appeared upon an examination of the stars associated with the energetic protons. In these stars the observed ratio between the numbers of star prongs emitted in the backward and forward hemispheres (with respect to the energetic proton) is very significantly higher than that calculated with generous assumptions, ascribing the asymmetry to the motion of the recoiling nucleus. The asymmetry is calculated assuming that the residual nucleus has a mass twelve times that of a proton, and the outgoing particles are assumed to have the lowest velocity which is used in measuring the asymmetry. All particles are assumed to be either protons or α-particles.

The disagreement between the observed and calculated ratios is, in fact, striking, and leads immediately to an alternative model. The secondary star prongs are assumed to be due mainly to impacts with primary nucleons traveling through the nucleus. Seldom would a particle be expected to be emitted in the direction of an emitted fast proton. However, one can no longer assume that there are two 70-Mev nucleons traveling in opposite directions, for then the observed energy spectrum would have more high energy protons.[20, ‡]

[20] M. Goldberger, Phys. Rev. 74, 1269 (1948).

‡ *Note added in proof:* It has been pointed out by Dr. H. York that the calculations of Goldberger (see reference 20) are not consistent with experiment, so that the conclusions based upon this computation are weakened considerably. (See J. Hadley and H. York, Phys. Rev. 80, 345 (1950). (The experimental data are, unfortunately, not strictly applicable to the problem of meson absorption.) Nevertheless, since the energy spectrum of the primary nucleons in the two-nucleon model will extend well above 70 Mev when the initial momentum distribution is taken into account, it is puzzling that so few protons of energy greater than 70 Mev are seen.

Therefore it is proposed that the primary interaction takes place among a small, but variable, number of nucleons (most often 2, 3, or 4), as in Menon *et al.*[4] This permits the emission of protons up to 70 Mev with reasonable probability, and protons up to 95 Mev occasionally. These nucleons have a spread of energies which favors the emission of low energy knock-on particles. Since the mean free path of such a nucleon is of the order of the nuclear radius for an element like Ag,[20] each nucleon will collide, on the average, one time inside the nucleus. But most of the knock-on particles will not be able to escape from the nucleus. Qualitatively, therefore, about one extra prong is expected, on the average, to accompany an energetic prong. This figure is consistent with the observed number of star prongs.

A test of this hypothesis would be to calculate the energy and angular distribution of the knock-on particles. The Monte Carlo method of calculation appears to be most suitable, but it will not be attempted in this paper.

TABLE I. Prong spectrum of π^- meson stars.

Number of prongs	1	2	3	4	5	6
Percent of stars	32.4±1.0	32.7±1.0	22.3±0.8	10.5±0.6	2.0±0.2	0.1±0.1

VI. ACKNOWLEDGMENTS

I should like to thank Dr. W. Barkas, Dr. H. Bradner, Dr. C. Richman, and Dr. R. L. Thornton for their guidance and encouragement, and to express my gratitude to the other members of the Film Program at the Radiation Laboratory for their cooperation and for many fruitful discussions. I am also indebted to Mr. A. Oliver for the preparation of Figs. 2 and 3, and to Miss Betty Summers for the other figures.

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Limits of Stability of the Heavy Elements and the Effects of Nuclear Shell Structure*

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The systematics of beta-decay, alpha-emission, and spontaneous fission will be investigated in order: first, to determine the theoretical limits to the periodic table, and secondly, to examine the effects of nuclear shell structure on the end of the periodic table. Curves of beta-stability and lifetimes against alpha-emission and spontaneous fission will be drawn for the heaviest elements and will be extrapolated in order to yield information about the stability or form of instability of the transuranic elements. Nuclear shell structure will be seen to be responsible for the stability of Th^{232} and U^{238} as well as the instability of the group of highly radioactive elements beginning with polonium.

I. INTRODUCTION

URANIUM is the heaviest known naturally occurring element on a macroscopic scale. Presumably, when the earth was formed ($\sim 3\times 10^9$ years ago), several isotopes, now unknown, were present. The only nuclei still occurring naturally are those whose half-lives are appreciable compared to 10^{8-9} years.

The beta-stable isotopes occur in a relatively narrow band; those nuclei lying outside this band are unstable with respect to positron emission or K-capture on the one side, and negative beta-emission on the other. This band would theoretically continue without limit onward towards higher and higher atomic number. However, the beta-stable transuranic elements do not occur in nature because of instability against alpha-decay or fission.

The manner in which an unstable nucleus is most likely to have decayed is governed by the lifetimes against the three forms of decomposition. At present there is no isotope known which has had fission as its main mode of decay.

Existing data will here be used to draw curves of beta-stability and lifetimes against alpha-decay and fission. These curves will yield information on the effects of nuclear shell structure on the end of the periodic table. To obtain information about the stability or form of instability of the transuranic elements, these curves will be extrapolated. In performing the extrapolations, it is assumed that nuclear shell structure alone is responsible for all major irregularities in the nuclear masses.

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II. BETA-STABILITY

As a result of the dependence on the even and odd character of the proton and neutron numbers, all nuclides may be divided into three general classes, those of odd A, those of even A and even Z, and those of even A and odd Z. For each class, the nuclear mass as a function of A and Z lies on a surface having the general shape of a valley. A curve connecting the values of Z_A, the coordinate of the bottom of the "odd A" valley, as a function of A is often called the line of beta-stability. All beta-stable odd-A nuclei lie within $\frac{1}{2}Z$ units of this curve. The region of stability of the even-even nuclides is bounded by limits approximately symmetrical with respect to Z_A. The curves representing Z_A and the region of beta-stability are here indicated on

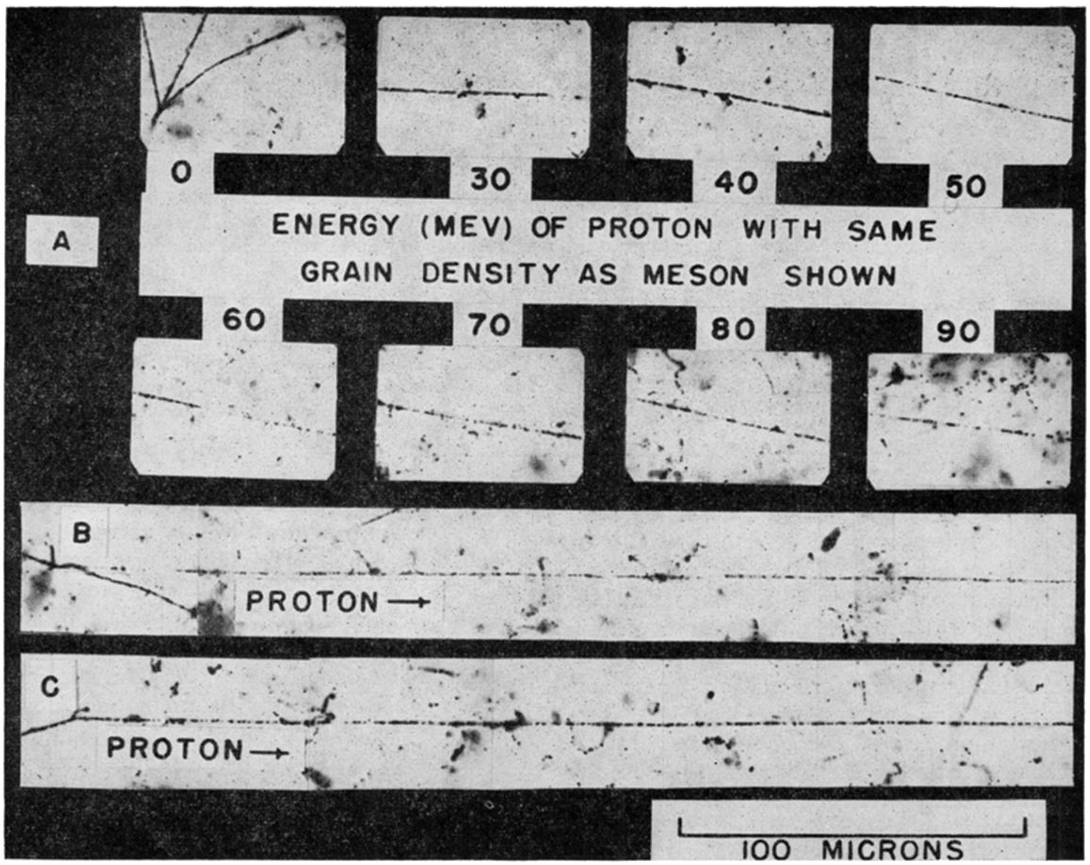

FIG. 2. (A) Photomicrograph of meson track taken at various velocities in G-5 plate. A proton at the same velocities would have the grain densities and energies shown. (B) 4-prong meson star, one of whose prongs is a 58-Mev proton. (C) Meson star with single prong, a 55-Mev proton. An electron is also associated with this event.

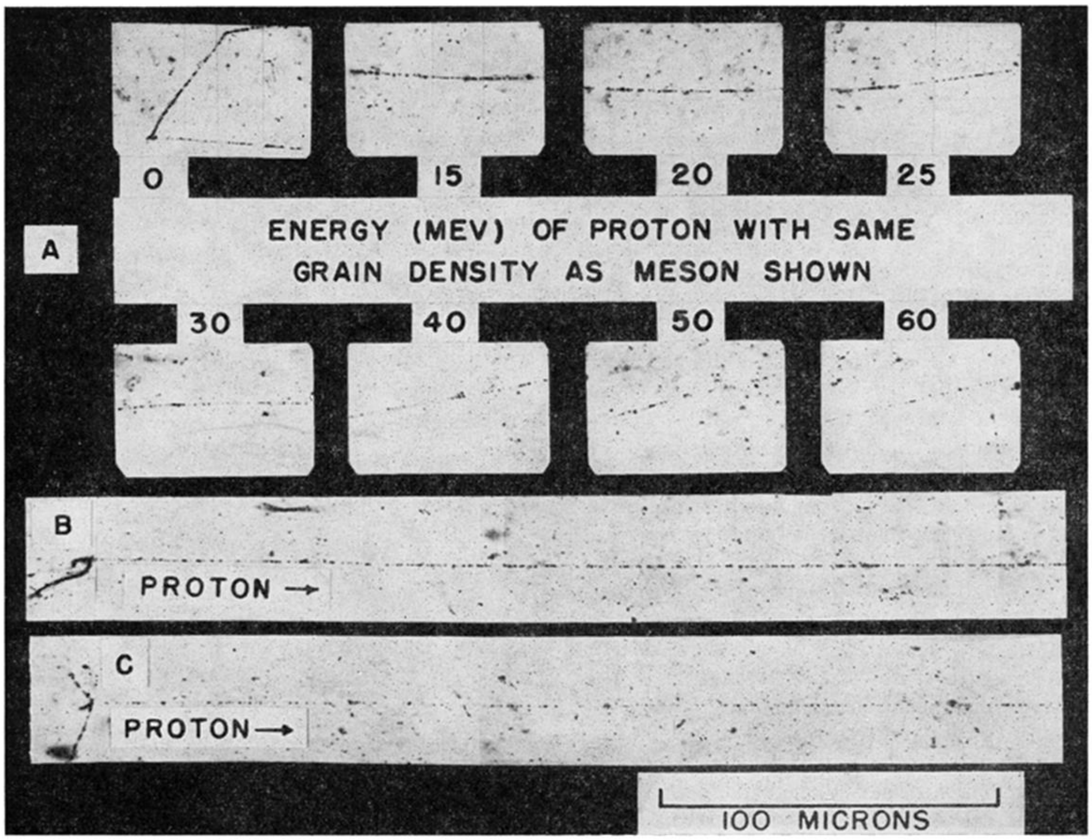

FIG. 3. (A) Photomicrograph of meson track taken at various velocities in a C-2 plate. A proton at the same velocities would have the grain densities and energies shown. (B) 2-prong meson star, one of whose prongs is a 20½-Mev proton. (C) 3-prong meson star, one of whose prongs is a 56½-Mev proton.