Scattering and Absorption of Pi-Mesons in Carbon*

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The interactions of positive and negative pi-mesons of 62 Mev with carbon nuclei were studied in a magnet cloud chamber, using the external beams of the Nevis cyclotron. A Coulomb-nuclear interference is observed in the elastic scattering. This establishes that the nuclear potential is attractive for mesons. Nuclear cross sections obtained are $\sigma_{abs}=181\pm22$ mb, $\sigma_{el\ sc}=148\pm30$ mb. A complex square well model for the nucleus is considered.

I. EXPERIMENTAL PROCEDURE

A DETAILED investigation has been made of the scattering and absorption of positive and negative pi-mesons in carbon nuclei. To accomplish this, a 16-inch cloud chamber, working in a magnetic field of 5000 gauss, was exposed to the 70-Mev meson beams of the Nevis cyclotron. The chamber was expanded once per minute, and at optimum supersaturation the cyclotron was pulsed. Figure 1 represents a typical photograph of the meson beam, in which, however, two interactions are observed. The scattering plate has a thickness of 2.14 g/cm^2. Momenta of incident and emerging particles are determined with an average precision of 10 percent, which includes measurement errors as well as multiple scattering and turbulence effects. The latter contributions are determined from zero field photographs which are taken every tenth expansion. The momentum measurements are performed on stereoscopic reprojections by comparing the tracks with curves drawn on Lucite templates. The templates are also used to extrapolate the tracks to the origin of the event in the carbon plate. All energies are then corrected for the ionization loss in the carbon.

About 4000 photographs were scanned in reprojection for interactions, flux tracks, and π-μ decays in the gas. A total of 500 carbon events was recorded with approximately equal numbers of positive and negative mesons in the interval 62 ± 10 Mev (interaction energy). These included stars, inelastic scatterings and elastic scatterings greater than 9°. Corrections to the data include the following: (1) Beam contaminations were determined for cloud-chamber geometry as in previous experiments[1] to be 12 ± 3 percent electrons in the π^- beam, less than 2 percent positrons in the π^+ beam; 8 ± 3 percent mu-mesons in both beams.[2] A correction was made for the number of electrons which stop in the plate because of radiative collisions. (2) The finite thickness of the plate leads to the necessity of recognizing "stoppings" as an important part of the interaction. These may be due to stars with low energy and fast neutron prongs, or prongs emitted at $\sim90°$. Also, inelastically scattered mesons or elastic scatters through $\sim90°$ or out of the illumination would appear as stops. The latter is by far the most serious source of error and is avoided by restricting the region of acceptance for these events to a central fraction of the illuminated depth. A correction is then made to the elastic scattering, using the observed angular distribution and the total solid angle lost to the scattered meson. The thickness of the plate also obscures the distinction between strongly inelastic scatterings and stars. Thus, the inelastic cross section quoted is actually a lower limit.

II. EXPERIMENTAL RESULTS

The results are presented in Table I and in Figs. 2 and 3.[3] The errors quoted in the table include statistics, beam uncertainties and, where necessary, estimates of the errors in corrections. The elastic scattering results are integrated from 20° because, as is seen from Figs. 2 and 3, the rise is so rapid below 20° that small uncertainties in the lower limit would severely affect the cross sections. The inelastic scatterings that have been observed were defined by an energy change of at least 15 Mev. This definition was imposed by the energy resolution, and hence it is recognized that a part of the "elastic" cross section may actually be due to incoherent scattering. The average energy of the inelastically scattered π^- mesons is 22 Mev; of the π^+ mesons, 30 Mev.

The absorption of the π^+ mesons exhibit an interesting feature which is illustrated by the star in Fig. 1.[4] The two emergent fast protons bear an angular relation to the incident meson and to one another, which is consistent with the reaction $\pi^++d\rightarrow p+p$. If we consider angular agreement within 10° as establishing a correlation, the fraction of observed stars which exhibit this correlation is 12 ± 4 percent. This corresponds to a cross section of 19 mb, and within the poor statistics available the proton angular distribution is isotropic.

* This program was jointly sponsored by the ONR and AEC.
1 Lederman, Booth, Byfield, and Kessler, Phys. Rev. 83, 685 (1951).
2 The μ^+ contamination of the π^+ beam is assumed equal to the μ^- contamination of the π^- beam.
3 The total cross sections are to be compared with the results of a similar experiment by A. Shapiro [Phys. Rev. 84, 1063 (1951)], in which the mean interaction energy was 45 Mev.
4 Similar events in emulsions were discussed by G. Bernardini, International Conference, Chicago, September, 1951. See also, Bernardini and Levy, Phys. Rev. 84, 610 (1951).

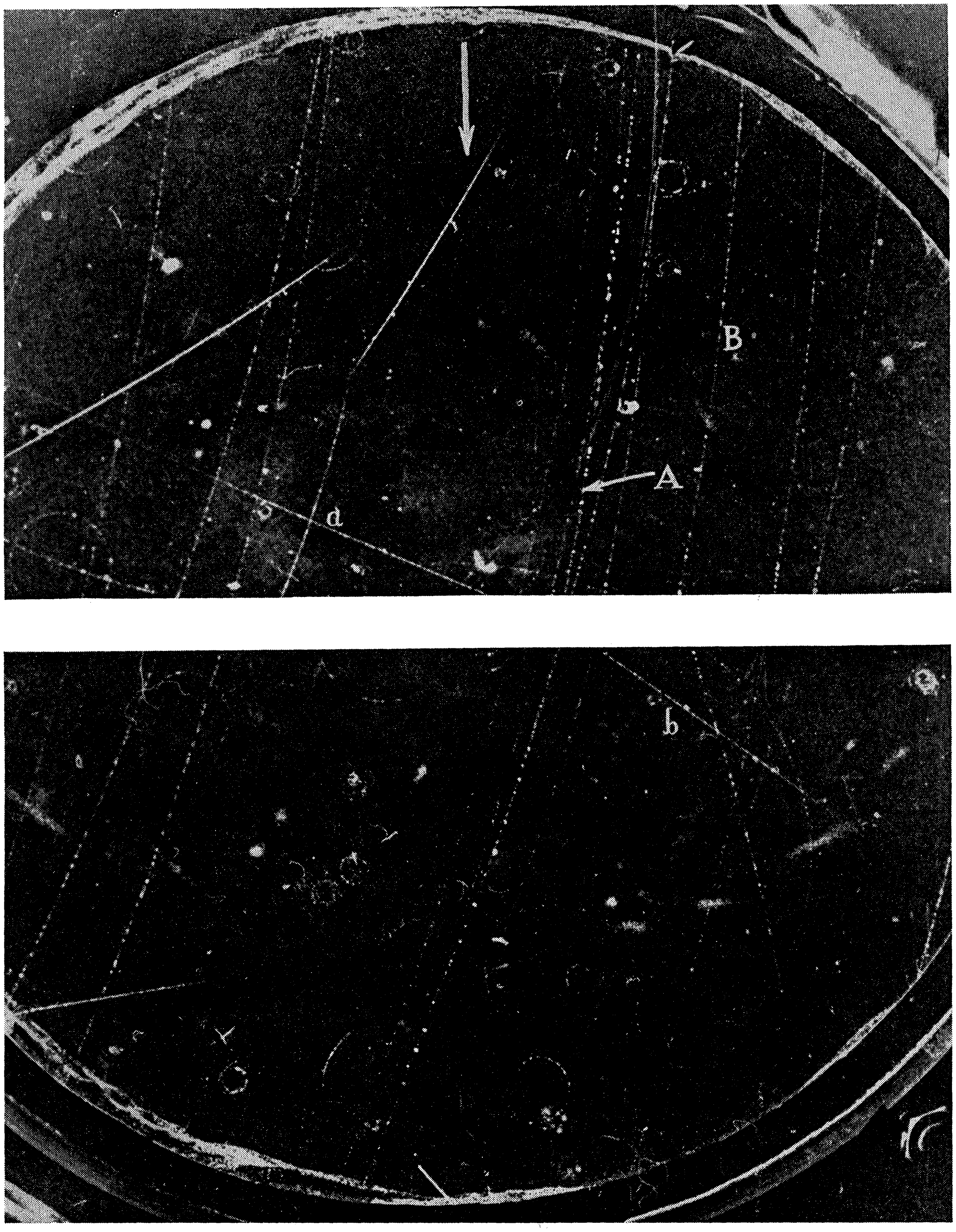

FIG. 1. 70-Mev π^+ meson beam photograph. Meson A yields a 2-proton star, prongs a and b. Meson B elastically scatters through an angle of 32°.

III. DISCUSSION

The general nature of the angular distributions strongly suggests a Coulomb interference effect. If this is true, the interference term and, in fact, practically all Coulomb contributions are eliminated by forming:

$$\sigma_{\text{nucl}}=\tfrac{1}{2}(\sigma_{\pi^+}+\sigma_{\pi^-})-\sigma_{\text{Coul}} \tag{1}$$

where σ_{Coul} is the Rutherford scattering, modified by the appropriate nuclear charge distribution. The result of the above procedure for a uniform distribution of charge is presented in Fig. 4. The total cross section for nuclear elastic scattering obtained is 148±30 mb. The pure nuclear data of Fig. 4 plus the absorption cross sections of Table I provide a test of nuclear models for pi-meson interactions.

Following the transparency theory,[5] the pi-meson in the nucleus may be thought to experience a potential which is capable of scattering, absorbing, and reflecting the meson wave. To investigate this model without neglecting any of the possible optical processes ($kR=2.5$), a partial wave solution of the Schrödinger equation was sought, in which the scattering potential is taken of the form $V_n+i\sigma_n$.[6] These parameters, plus the nuclear radius, were required to account for the total elastic scattering cross section (148 mb) and the total absorption cross section (average of π^+ and π^- results, 181 mb). For a nuclear radius of $1.47\times10^{-13}A^{\frac{1}{3}}$, the parameters which were found to fit the data are $V_n=18$ Mev, and $\sigma_n=9$ Mev. These results correspond to an argument of the inside solutions of $k'R=2.95+0.20i$ and, consequently, to a mean free path in nuclear matter of 8.3×10^{-13} cm.[7] To see if these results are consistent with the large charge dependence effect exhibited by the data, a Born approximation

TABLE I. Pion-carbon cross sections in millibarns, cloud chamber.

	Stars Protons >40 Mev				Elastic scattering		Inelastic scattering
	0	1	2	Total	20–180°	65–180°	$\Delta E>15$ Mev
π^-	110	34	4	148±18	165±15	63	46±10
π^+	34	77	42	153±22	89±10	38	15±8

calculation was carried out for the potential

$$\begin{aligned} &V=\pm Ze^2/r, \quad r>R \\ &V=\pm Ze^2/2R(3-r^2/R^2)-V_n+i\sigma_n, \quad r<R \end{aligned} \tag{2}$$

corresponding to a uniform charge distribution over the region of the nucleus. The result is plotted in Fig. 5. The lack of good agreement is not surprising in view of the crudeness of the approximation. However, the results indicate that a Coulomb interference is, in fact, being observed. It is noted that the interference is a quite sensitive test of the nuclear parameters acting upon the meson. In fact, the observation of the interference immediately limits both the real and imaginary well depths to $\lesssim30$ Mev. With these limitations, the nuclear parameters obtained for the model become unique. The angular distribution predicted by the square well model has the general shape of Fig. 4 but falls more slowly from the forward peak and fails by a factor of 8 to give the large backward scattering

[5] Fernbach, Serber, and Taylor, Phys. Rev. **75**, 1352 (1949).

[6] The meson mass in the Schrödinger equation is replaced by the total energy.

[7] The results here given differ from those calculated for the same model by a WKB approximation [H. A. Bethe and R. R. Wilson, Phys. Rev. **83**, 690 (1951)], chiefly in that we obtain the same opacity with a much longer mean free path, which is a sensitive function of the real well depth. The exact solution has also been studied independently by J. Steinberger (private communication).

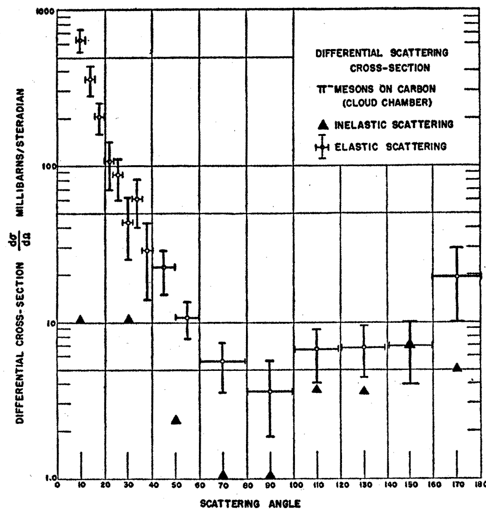

FIG. 2. Differential elastic and inelastic scattering of negative pions on carbon.

observed. A partial suppression of the odd angular momentum phase shifts would produce agreement with experiment, but the physical interpretation of V_n would then become even more difficult.

An immediate result of the Coulomb interference is that the potential experienced by the meson in carbon is proved to be attractive. This is in disagreement with Schiff's[8] formulation of nonlinear meson theory, in which the nonlinearity corresponds to a point-contact repulsion between mesons. Another result of the Coulomb contribution is that the π^- to π^+ ratio of total absorption cross sections (sum of star and inelastic scattering) should (for $\sim$60-Mev mesons) go as: $(HV_c(R)/E/(1-V_c(R)/E)$. This ratio for carbon is 1.08, in fair agreement with the experiment. The

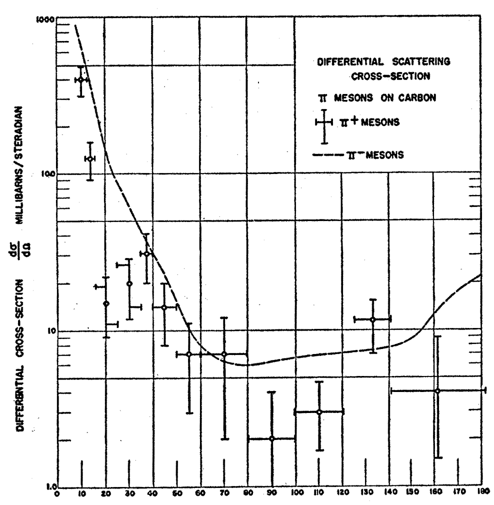

FIG. 3. Differential elastic scattering of positive ions in carbon. The dotted curve reproduces the negative cross section.

[8] L. I. Schiff, Phys. Rev. **84**, 1 (1951).

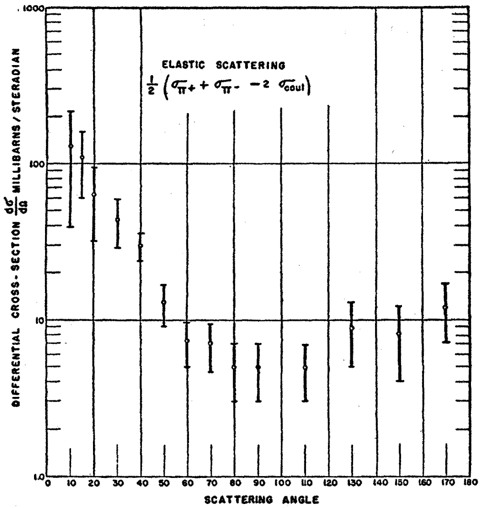

FIG. 4. Differential elastic scattering cross section for pions on carbon obtained by averaging the π^+ and π^- results and subtracting the contribution of a uniformly charged sphere (Born approximation).

Coulomb barrier (2.6 Mev) must also account for a decreased number of inelastically scattered π^+ mesons, although the observed effect appears still to be too large. Poor statistics and ambiguity caused by the thickness of the plate leave this point still uncertain.

The good correlation double-proton stars observed with π^+ mesons are interesting in view of the two nucleon models for meson absorption.[9,10] The assumption is made that pairs of nucleons, inside the nucleus, retain their interaction property of meson absorption as exhibited in the elementary process: $\pi^+ + d \rightarrow 2p$.[11] The probability that neither recoiling nucleon suffers a collision in escaping from the carbon nucleus, when averaged over all possible absorption position, is ~ 0.22. For this (classical) calculation, the mean free path for 90-Mev neutrons in nuclear matters was employed.[5] Thus, the 12 percent of observed proton pair stars corresponds to ~ 60 percent of all the stars observed. Allowing for a contribution from absorption by n-n pairs, it is seen that the two-nucleon model can account for most of the π^+ absorptions.[12]

The assumption that bound nucleons retain their meson interaction properties implies that we may separate the mean free path in nuclear matter:

$$\lambda^{-1} = 0.120 \times 10^{13}\ \text{cm}^{-1} = \lambda^{-1}(\text{scatt}) + \lambda^{-1}(\text{star}).$$

Then, in terms of elementary cross sections, the simplest considerations suggest

$$\lambda(\text{star}) = (4/3)\pi R^3 / Z\sigma_a^* \tag{3}$$

where σ_a^* is the cross section per proton for absorption in the nucleus. Brueckner, Serber, and Watson[10] have set $\sigma_a^* = \Gamma\sigma(\pi^+ + d)$ where $\sigma(\pi^+ + d)$ is the observed[11] cross section and Γ measures the degree of two-nucleon correlation in nuclear structure. Similarly, one may investigate

$$\lambda(\text{scatt}) = \frac{(4/3)\pi R^3}{\frac{1}{2}\gamma A[\sigma(\pi^+ + p) + \sigma(\pi^- + p)]}, \tag{4}$$

where $\sigma(\pi^\pm + p)$ is assumed equal to $\sigma(\pi^\mp + n)$. γ measures the alteration in the free cross sections produced by the binding. This would include the Pauli principle[13] and the effect of the change in relative energy of the meson-nucleon system.[14] If it is assumed that the inelastic scatterings observed in carbon are due to meson-nucleon collisions,[15] then $\lambda(\text{scatt})$ may be obtained from the data on π^- mesons. The probability of subsequent absorptions of the scattered meson is estimated[16] as 0.2, and this leads to $\lambda(\text{scatt})/\lambda(\text{star}) \lesssim 2.9$

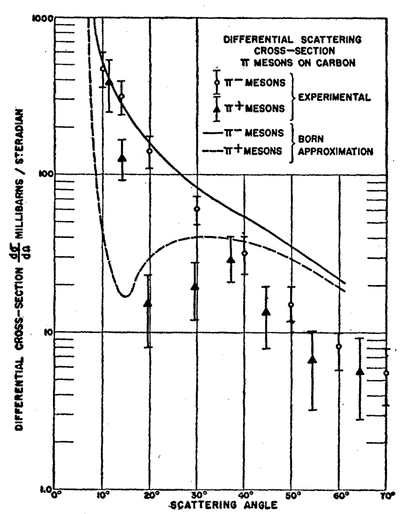

FIG. 5. Differential elastic scattering of positive and negative mesons on carbon computed from the Born approximation. The nuclear well depths are $V = 18$ Mev, $\sigma = 9$ Mev. The charge distribution is taken as uniform over a sphere of radius $1.47 \times 10^{-13} A^{\frac{1}{3}}$ cm.

[9] S. Tamor, Phys. Rev. **77**, 412 (1950).
[10] Brueckner, Serber, and Watson, Phys. Rev. **84**, 258 (1951).
[11] Durbin, Loar, and Steinberger, Phys. Rev. **83**, 646, **84**, 581 (1951); Clark, Roberts, and Wilson, Phys. Rev. **83**, 649 (1951).
[12] Occasional stars are observed, both in emulsions and in this cloud-chamber experiment, of a single proton with almost all of the meson energy ($\sim$200 Mev).

[13] M. H. Johnson, Phys. Rev. **83**, 510 (1951).
[14] Nagle, Anderson, Fermi, Long, and Martin, Bull. Am. Phys. Soc. **27**, No. 1, 28 (1952).
[15] This is in contrast to the conclusions drawn from the strongly inelastic scatterings observed in emulsions: Bernardini, Booth, and Lederman, Phys. Rev. **83**, 1277 (1951). The probability of two successive scatterings is now seen not to be negligible.
[16] The probability of subsequent absorptions of the scattered meson depends on the longer mean free path at reduced energy (Bernardini, Booth, and Lederman, Phys. Rev. **83**, 1075 (1951)); Isaacs, Sachs, and Steinberger, Phys. Rev. **85**, 803 (1951). Although an exact phase shift treatment of the model is preferable, this quantity was here obtained entirely via the "particle" picture [see Eq. (6), reference 10].

where the inequality reflects the experimental uncertainty discussed in Sec. I. Using this ratio, Eq. (3) yields $\Gamma \lesssim 3.3$. Equation (4) yields

$$\gamma[\sigma(\pi^+ + p) + \sigma(\pi^- + p)] \gtrsim 8 \text{ mb}.$$

For meson energy losses greater than 15 Mev, γ is estimated to be of the order of 1. The non-charge exchange scattering of pions on protons has not yet been measured, but should, when compared with improved data of the above kind, indicate whether the binding effects are as simple as has been here assumed.[17]

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[17] If the charge exchange contribution is small, the results of Isaacs, Sachs, and Steinberger give $\sigma(\pi^+ + p) + \sigma(\pi^- + p) = 45$ mb. This would imply that neglected interference effects add up destructively in carbon.

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Spontaneous Fission*

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This paper summarizes part of the work on spontaneous nuclear fission performed at Los Alamos before 1945. The experimental technique used to detect spontaneous fission in the heavy alpha-active elements has been described, and the decay constants for spontaneous fission observed in a number of substances have been listed. The number of neutrons emitted per spontaneous fission of U^{238} has also been measured and found to be 2.2 ± 0.3.

HISTORICAL

THE first attempt to discover spontaneous fission in uranium was made by Libby,[1] who, however, failed to detect it on account of the smallness of effect. In 1940, Petrzhak and Flerov,[2] using more sensitive methods, discovered spontaneous fission in uranium and gave some rough estimates of the spontaneous fission decay constant of this substance. Subsequently, extensive experimental work on the subject has been performed by several investigators and will be quoted in the various sections of this article.

Bohr and Wheeler[3] have given a theory of the effect based on the usual ideas of penetration of potential barriers.

On this project spontaneous fission has been studied for the past several years in an effort to obtain a complete picture of the phenomenon. For this purpose the spontaneous fission decay constants λ have been measured for separated isotopes of the heavy elements wherever possible. Moreover, the number ν of neutrons emitted per fission has been measured wherever feasible, and other characteristics of the spontaneous fission process have been studied. This report summarizes part of the spontaneous work done at Los Alamos up to January 1, 1946. A chronological record of the work is contained in the Los Alamos reports. The experiments were conducted mainly by O. Chamberlain, G. Farwell, J. Jungerman, E. Segrè, and C. Wiegand.

EXPERIMENTAL TECHNIQUES

The experiments directed to the measurement of λ consisted in principle of putting a certain amount of the material to be investigated in ionization chambers connected to linear amplifiers, and counting the fission pulses. The material was deposited on platinum disks as a thin layer.[4]

In all these experiments one of the main difficulties is offered by the alpha-activity of the samples. As a matter of fact, this often limits the amount of a substance that can be studied at one time in an ionization chamber. The reason for this is that the fissions are recognized from the large size pulses that they give in the ionization chambers. Now the pulses generated by single alphas are from 10 to 20 times smaller; however, if the alpha-emission is very strong, fluctuations in the alpha-activity background may simulate large pulses and cause spurious fission counts to be recorded.

Qualitatively, these fluctuations will be roughly proportional to the square root of the number of alphas emitted during the "resolving time" of the apparatus. Attempts have been made to obtain a more quantitative picture of this effect by developing a suitable theory, but the phenomena that give rise to spurious pulses are too complex to be analyzed in a really satisfactory way,

* This paper is based on work performed under the auspices of the Manhattan District and was reported more fully in a classified Los Alamos document issued in 1945.
[1] W. F. Libby, Phys. Rev. **55**, 1269 (1939).
[2] K. A. Petrzhak and G. N. Flerov, Compt. Rend. Acad. Sci. U.S.S.R. **28**, 500 (1940); J. Phys. U.S.S.R. **3**, 275 (1940).
[3] N. Bohr and J. Wheeler, Phys. Rev. **56**, 426 (1940).

[4] Most of the samples were prepared by D. Hufford, Mary Miller, J. Miskel, and R. Potter.

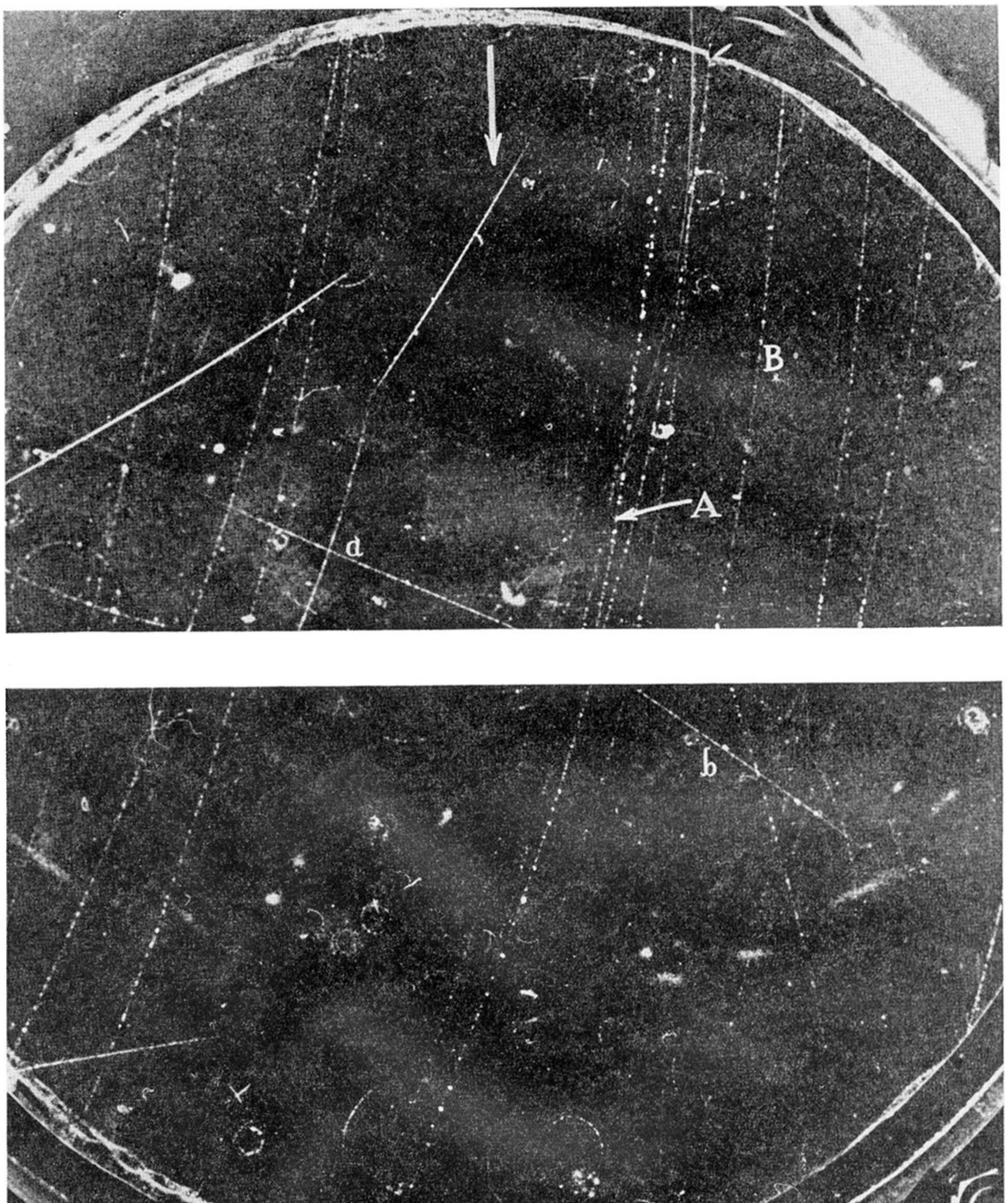

FIG. 1. 70-Mev π^+ meson beam photograph. Meson A yields a 2-proton star, prongs a and b. Meson B elastically scatters through an angle of 32°.