# Positive Pi-Meson Interactions in Beryllium*

F. H. TENNEY† AND J. TINLOT
*University of Rochester, Rochester, New York*
(Received August 14, 1953)

A 10-in. diameter magnet cloud chamber containing a $\frac{1}{4}$-in. Be plate has been operated in both the 40-Mev and 50-Mev $\pi^+$-meson beams of the Rochester 130-in. cyclotron. Meson interactions in Be were obtained for three bands of energy: 15 to 30 Mev, 25 to 40 Mev, and 35 to 50 Mev. The events recorded as nuclear interactions were: stars, stops, and scatterings of greater than 30 degrees. From a survey of some 22 700 g/cm² of Be traversed, a total of 159 such events were found. Analysis of the data from each energy band indicates the absorption cross section to be energy dependent. The ratio of corrected stars to corrected scatterings was found to be roughly 2:1.

## INTRODUCTION

A CLOUD-CHAMBER study of $\pi^+$-meson interactions in the element beryllium has been made. A 10-in. diameter diaphragm type cloud chamber, with an illuminated depth of about 2 in. and containing a beryllium plate 1.24 g/cm² thick, was exposed to the 40-Mev and 50-Mev $\pi^+$-meson beams of the University of Rochester's 130-in. cyclotron in a series of three runs. Each run sampled a different range of incident meson energies: 15 to 30 Mev for run *A*, 25 to 40 Mev for run *B*, and 35 to 50 Mev for run *C*. The incident meson energy distributions are shown in Fig. 1. The low mean energy of run *A* was obtained by degrading the energy of the 40-Mev meson beam with a $\frac{3}{4}$-in. thick piece of polyethylene placed in front of the chamber. The chamber was operated in a pulsed magnetic field of from 12 to 15 kilogauss for runs *B* and *C* and in a steady field of about 8 kilogauss for run *A*. The pulsed field was provided by two air core coils. The steady field was provided by these coils in conjunction with an iron yoke. It is estimated that the magnetic field was known to within 5 percent. To reduce background radiation to a tolerable level, the cyclotron beam was pulsed in conjunction with the fast expansion of the chamber. The chamber was expanded and stereoptically photographed at regular intervals of time.

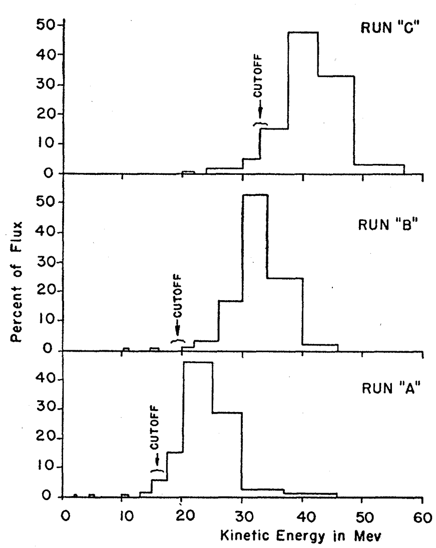


FIG. 1. Incident meson kinetic energy distribution.

## EXPERIMENTAL PROCEDURE

About 2000 useful photographs were obtained during run *A*, and approximately 1000 useful photographs were taken in each of runs *B* and *C*. These photographs were reprojected and scanned for the flux of mesons and for meson stars, stops, and scatterings of greater than 20 degrees projected angle. Pi-mu decays were generally noted and used to check geometrical measurements and momentum estimates. These checks were always satisfactory. In run *B* a systematic survey was made for $\pi$-$\mu$ decays for purposes of estimating flux contamination.

Mesons and electrons were readily distinguished from protons on the basis of curvature and relative ionization. These criteria did not serve to distinguish $\pi^+$ mesons from $\mu^+$ mesons or high-energy positrons. The flux contamination of $\mu^+$ and $e^+$ was taken to be 10 percent. This estimate was based on considerations of: (a) the number of pi-mu decays observed in run *B*, (b) the energy loss of flux particles in passing through the beryllium plate for the low-energy run *A*, (c) a rough calculation of the expected number of $\mu^+$ mesons from pi-mu decays in the incident beam outside the chamber, and (d) scintillation counter data.[1]

Radii of curvature and projected angles were measured by means of arcs of different radii scribed on transparent sheets of cellulose acetate. The energy resolution obtained by this method is indicated by the width of the histogram blocks in Fig. 1. True angles were computed from knowledge of projected angles and the dip of the tracks involved. An angular error of $\pm 2.5°$ is placed on all true angles, except in cases of steeply dipping tracks the angular error is estimated to be as high as $\pm 10°$.

* This work was performed under the auspices of the U. S. Atomic Energy Commission.
† At present at Princeton University, Princeton, New Jersey.

[1] C. Angell and J. Perry (private communication).

TABLE I. Summary of data. The energy interval is defined for the $1/e$ points of energy distribution at the center of the Be plate. Uncorrected data are in parentheses.

| Energy range Mev | g/cm² traversed | Total No. of events | Stops | Stars $1p$ | Stars $2p$ | Stars $3p$ | Scatts $\theta \geq 30°$ | Total stars | Total scatts | $\sigma_{abs}$ mb | $\sigma_{scatt}$ mb |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 26.5–16 Run $A$ | 12 170 | 75 (111) | 18 (48) | 22 | 12 (39) | 0 | 23 (24) | 46 | 29 | 56±9 | 35±7 |
| 35.5–26 Run $B$ | 6399 | 45 (54) | 9 (15) | 16 | 9 (29) | 2 | 9 (10) | 32 | 13 | 74±13 | 30±8 |
| 46–34 Run $C$ | 4195 | 39 (52) | 12 (21) | 13 | 6 (23) | 0 | 8 (8) | 27 | 12 | 96±20 | 42±12 |

From samples of the incident flux, the energy and depth distributions of the incident flux were determined. Subsequently a low-energy cutoff was assigned for each run (see Fig. 1) and events caused by mesons of energy below the appropriate cutoff were rejected. Some events were also rejected on the basis of their depth in the chamber. The need for depth correction of events is most clearly illustrated by consideration of the stop events. A meson passing through the beryllium plate near the edge of the illumination may easily be confused with a meson that stops in the plate. Consequently, only those stops falling within a specified central portion of the flux depth distribution were considered valid. This fraction of the valid stops was then corrected with the help of the flux depth distribution, to obtain the total number of valid stops.

## RESULTS AND DISCUSSION

The results of this experiment are presented in Table I.

In view of the small cross section expected for charge exchange scattering in light elements,[2] the stop events have been considered to be stars or scattering events hidden by the beryllium plate. Approximately one third of the stops were assigned to the scattering events on the basis of a determination of the average solid angle available to detectable elastic scattering events.

### Absorption Data

The absorption cross sections measured are presented in Fig. 2. The energy dependence of the absorption cross section is consistent with similar data at somewhat higher energies for carbon,[3,4] nuclear emulsions,[5,6] and for aluminum.[7]

Brueckner, Serber, and Watson[8] relate the $\pi^+$-meson absorption cross section in complex nuclei to the meson absorption cross section in deuterium by the following relation:

$$\frac{1}{(A-Z)}\sigma[\pi^+ + \text{nucleus} \rightarrow \text{star}] = \Gamma \cdot \sigma[\pi^+ + d \rightarrow 2p].$$

This experiment yields a value of $\Gamma$ between $3.2_{-0.8}^{+1.1}$ at 39 Mev and $5.6_{-1.1}^{+2.1}$ at 20 Mev. In this calculation the experimental values for $\sigma[\pi^+ + d \rightarrow 2p]$ found by Durbin, Loar, and Steinberger[9] have been used. The significance of the energy dependence of $\Gamma$, if it is real, is not clear. One possible qualitative explanation is that mesic absorption may also proceed via nuclear substructures more complex than the deuteron substructure and that the probability of absorption by the more complex substructures does not fall off as rapidly with decreasing meson energy as does the probability of absorption by the deuteron structure. In fact, for the absorption of slow $\pi^-$ mesons in nuclear emulsions, the weight of evidence favors absorption via a multinucleon substructure.[10–12] More will be said concerning the absorption mechanisms in the following section on the analysis of star fragments.

The absolute value of $\Gamma$ found in this work may be

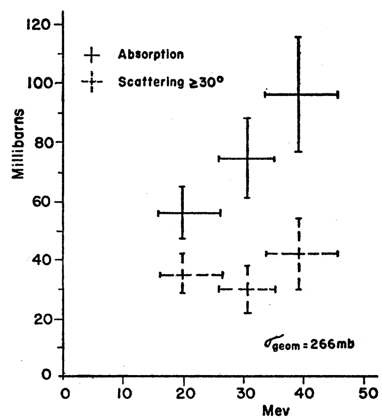


FIG. 2. Absorption and scattering cross sections, $\pi^+$ on Be *vs* $\pi^+$ kinetic energy.

[2] A. Roberts and J. Tinlot, Phys. Rev. **90**, 951 (1953).
[3] L. Lederman (private communication).
[4] Isaacs, Sachs, and Steinberger, Phys. Rev. **85**, 803 (1952).
[5] Bernardini, Booth, and Lederman, Phys. Rev. **83**, 1075 (1951).
[6] G. Bernardini and F. Levy, Phys. Rev. **84**, 610 (1951).
[7] James F. Tracy, Phys. Rev. **91**, 960 (1953).
[8] Brueckner, Serber, and Watson, Phys. Rev. **84**, 258 (1951).
[9] Durbin, Loar, and Steinberger, Phys. Rev. **84**, 581 (1951).
[10] D. Perkins, Phil. Mag. **40**, 601 (1949).
[11] W. Cheston and L. Goldfarb, Phys. Rev. **78**, 683 (1950).
[12] F. L. Adelman, Phys. Rev. **85**, 249 (1952).

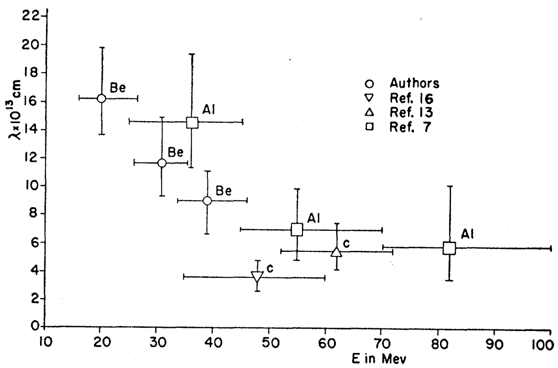


FIG. 3. Mean free path for absorption in nuclear matter *vs* meson kinetic energy.

compared to the value of $\Gamma\sim3.3$ found by Byfield *et al.*[13] in carbon at 62 Mev and to the value of $\Gamma\sim10$ found by Bernardini *et al.*[6] in nuclear emulsions at 50 Mev.

Finally, following the optical model,[14] the absorption data is presented in Fig. 3 in terms of the mean free path for $\pi^+$ absorption in nuclear matter.[15] For comparison the $\pi^+$ absorption data of other workers[7,13,16] are also presented.

## Scattering Data

All observed scattering events were elastic. This result is consistent with the results from plate data[5] and cloud-chamber data for carbon[3] which indicate that the inelastic scattering of pi mesons has a threshold energy between 50 and 70 Mev. The scattering cross section found (Fig. 2) is about half the absorption cross section. The total number of scattering events was too low to warrant more than the rough angular distribution presented in Fig. 4. In this plot the stops assigned to the scattering events have been equally divided between the angular intervals 60°–90° and 90°–120°. A study of the meson scattering between 5° and 15° projected angle was also made. The results were entirely consistent with multiple scattering in the beryllium plate.

## Analysis of Star Fragments

The analysis of the star fragments can throw light on the important mechanisms for mesic absorption in beryllium. The two absorption mechanisms considered are:[8,10,17] (a) absorption by a pair of nucleons ($\pi^+ +$ "$d$" $\rightarrow 2p$ or $\pi^+ + 2n \rightarrow n + p$) and (b) absorption by a nuclear substructure of several nucleons, e.g., $\pi^+ + He^4 \rightarrow He^3 + p$. If a 30-Mev $\pi^+$ meson is absorbed by a deuteron structure, the resulting star fragments will have energies of 85 Mev or less. In contrast mesic absorption by a multinucleon structure may lead to the emission of a single proton having a kinetic energy of 140 Mev or more.

All of the ionizing star fragments were assumed to be protons with one exception. In this case the single visible star fragment appeared to be doubly charged. Eighty-six percent of the visible star fragments had energies exceeding 30 Mev and 21 percent probably had energies of more than 100 Mev. We consider that the appreciable number of star fragments of energy greater than 100 Mev constitute clear evidence for a multinucleon absorption mechanism.

Of the 2-prong stars, about 65 percent exhibited a correlation angle between prongs of 140° or greater. About 10 percent (2 or 3 stars) of the 2-prong stars exhibited an angle of 170°–180° between their prongs. This prong correlation may be considered evidence for the absorption of the $\pi^+$ meson by a deuteron structure in the beryllium nucleus. It is estimated[18] that about 30 percent of the time the two protons arising from such a "deuteron" absorption should escape from the beryllium nucleus without undergoing any nuclear interactions en route. If one accepts 140° between prongs as "good" correlation, then at most about two thirds of the visible stars can be accounted for on the basis of a deuteron absorption.

In 19 cases of 2-prong stars it was possible to measure the energy of both prongs. In Fig. 5 the sum of the kinetic energy of the two prongs is plotted against the true angle between the prongs. For comparison the energy-angle correlation has been computed for a 30-Mev $\pi^+$ meson absorbed by a deuteron structure. This relation is shown by the dotted curve in Fig. 5 where it has been further assumed that: (a) the nucleons are at rest in the nucleus, (b) collisions between the initial fast protons and other nucleons can be treated as if the nucleons were free, and (c) only one of the ejected protons undergoes a nuclear collision within the nucleus. At most 9 of the 19 stars exhibit this energy-angle correlation. This corresponds to 47 percent of the 2-prong stars plotted or 16 percent of all visible stars. On this basis, not more than 54 percent of the visible stars are results of a "deuteron" absorption. These estimates may be compared with the estimate of Byfield, Kessler, and Lederman[13] that about 60 percent

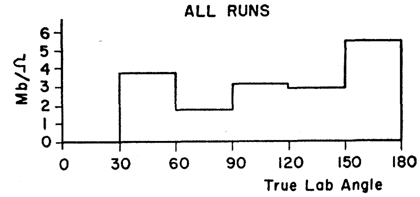


FIG. 4. Scattering angular distribution, $\pi^+$ on Be. Combined data from all runs.

[13] Byfield, Kessler, and Lederman, Phys. Rev. **86**, 17 (1952).
[14] Fernbach, Serber, and Taylor, Phys. Rev. **75**, 1352 (1949).
[15] Admittedly the applicability of the optical model is questionable since ƛ for mesons of such low energy is of the same order of magnitude as the diameter of the Be nucleus.
[16] A. M. Shapiro, Phys. Rev. **84**, 1063 (1951).
[17] S. Tamor, Phys. Rev. **77**, 412 (1950).

[18] This estimate is based on the assumption that the meson is absorbed at random in the nucleus and that the subsequent protons have a mean free path in nuclear matter of $3.3\times10^{-3}$ cm (see reference 14).

of the stars produced in carbon by 62-Mev $\pi^+$ mesons may be attributed to a deuteron absorption. Mesic absorption by a "dineutron" substructure cannot easily be distinguished in these experiments. On an *a priori* basis, however, this process is less probable than absorption by a deuteron substructure and cannot account for the remainder of the stars.

The three 2-prong stars (Fig. 5) for which the correlation angle is about 90° are thought to be the result of multinucleon absorption. These three stars may be thought to result from the collision of the single fast proton emitted by the multinucleon substructure with another proton in the nucleus, both protons then appearing as star fragments.

Finally, one can examine the angular distribution of the star prongs for a clue as to the validity of the two absorption models. The angular distribution of protons from the reaction $\pi^+ + d \rightarrow 2p$ has been measured by Durbin, Loar, and Steinberger[19] who find the differential cross sections at 0° and 90° in the center-of-mass system to be in the ratio of about 3:1. On this basis one expects some forward and backward peaking of the star prong angular distribution. It is not clear what angular distribution to expect on the basis of the multinucleon absorption model.

The angular distribution of star prongs having energies greater than 50 Mev was analyzed on the basis of

TABLE II. Computed and average experimental ratios.

| | Computed | | Experimental |
|---|---|---|---|
| | $P_1$ | $P_2$ | |
| $R$ | 0.42 | 0.77 | 0.52±0.19 |
| $F/B$ | 1.44 | 1.29 | 2.7 ±1.0 |

two ratios, namely: $R = f/(1-f)$, where $f$ is the fraction of star prongs found in the interval 0°–45° and 135°–180°, and $F/B$ equal to the ratio of prongs in the angular interval 0°–60° to those in the interval 120°–180°. In determining these ratios, star prongs of unknown energy were considered to have a kinetic energy of more than 50 Mev, and two-thirds of the stops were added into the figure $(1-f)$. The experimental ratios may be compared (Table II) with those expected for the following center-of-mass angular distributions:

$$P_1(\theta) = 1/2, \quad P_2(\theta) = (6/10)\cos^2(\theta) + 3/10.$$

The greatest asymmetry in the laboratory system would be predicted for the smallest number of interacting particles, e.g., two nucleons. The corresponding

[19] Durbin, Loar, and Steinberger, Phys. Rev. 83, 646 (1951).

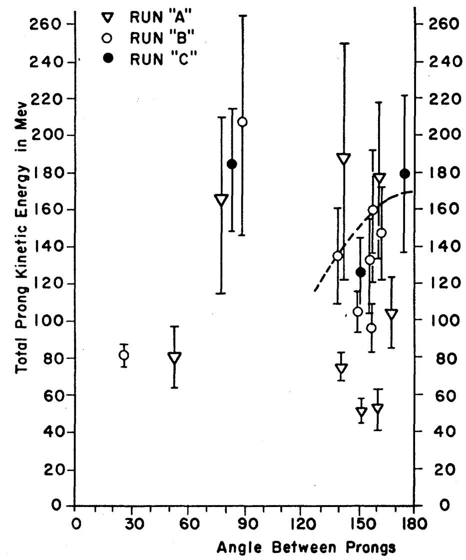


FIG. 5. Two-prong star energy *vs* angle between prongs, $\pi^+$ on Be.

ratios $R$ and $F/B$ are computed on this basis, for the case of a 30-Mev meson energy (Table II). $P_2(\theta)$ simulates the angular distribution[19] of protons for the reaction $\pi^+ + d \rightarrow 2p$. The computed and average experimental ratios are presented in Table II.

The angular distribution of the star prongs appears to have some forward peaking but cannot be said to be inconsistent with isotropy. The disagreement between the experimental and calculated values of the ratio $F/B$ for the $P_2$ distribution is more severe, however, and constitutes further evidence that the deuteron absorption cannot be the only absorption mechanism

## CONCLUSIONS

The principle conclusions drawn from this work are: (a) the absorption cross section, $\sigma_{abs}$, decreases with decreasing meson kinetic energy to 59±9 millibarns at 20 Mev; (b) $\sigma_{abs}/\sigma_{scatt} \sim 2:1$; (c) at most 60 percent of the absorptions may occur via a deuteron structure, but the fraction of absorptions attributable to a nucleon pair absorption mechanism is somewhat higher; and (d) definite evidence exists for mesic absorption by a multinucleon structure in beryllium.

## ACKNOWLEDGMENTS

We are indebted to Messrs. Coombs and H. Logeman for efficient operation of the cyclotron, and to Messrs. R. Mortenson and J. Dungan for invaluable assistance in design of the cloud chamber and magnet. I. Goldberg, M. Halbert, R. Harding, and J. Wyckoff assisted in the preparation and operation of the apparatus.