Title
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Publication Date
1959-01-07

UCRL-8591

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Contract No. W-7405-eng-48

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Printed for the U. S. Atomic Energy Commission

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ABSTRACT

The distributions of charged particles resulting from antiproton annihilations in hydrogen and deuterium are compared with the predictions resulting from the "normalized" statistical theory of Fermi. Multiplicities and momentum distributions are shown to be in agreement with the theory if the radius of the interaction volume is chosen to be about two fermis. The values given for the average multiplicities observed in hydrogen and deuterium are 4.94 ± .31 and 5.03 ± .44 respectively, both somewhat lower than found in the emulsion experiments. K-meson production in annihilations was found to be consistent with previous experiments, but the number of events is statistically inadequate to warrant any new conclusions. The total and elastic scattering cross sections in hydrogen, though of small statistical significance, are in agreement with recent theoretical calculations.

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* Work done under the auspices of the U. S. Atomic Energy Commission.

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I. INTRODUCTION

The major features of the annihilation process in complex nuclei have been investigated by several emulsion groups.[1,2] Since the characteristics of the primary annihilation in a complex nucleus are necessarily modified by secondary interactions, it is desirable to study annihilation directly on individual nucleons. To this end we have exposed the Berkeley 15-inch bubble chamber to an antiproton beam "enriched" by a coaxial electromagnetic spectrometer.[3] For the initial exposure, liquid hydrogen was used as the sensitive medium in the bubble chamber; for the second exposure, the chamber was filled with liquid deuterium.

II. BEAM

A schematic diagram of the antiproton beam is shown in Fig. 1. The characteristics of the beam have been discussed in detail elsewhere[3] and only a brief description is given here. The 6.2-Bev/c internal proton beam of the Berkeley Bevatron struck a 3.5-inch copper target. Particles produced in the forward direction with momentum 450 Mev/c were deflected through 90° by the Bevatron magnetic field. The transverse dispersion of the beam was removed by a suitable deflection in magnet M1. In the absence of spectrometer forces the beam was focused by the fields of the Bevatron, M1, and quadrupole Q1, to an image near the end of the coaxial spectrometer. When the spectrometer presented the beam with a radial electric field, E, and an azimuthal magnetic field, $H = E/\beta$, where βc was the antiproton velocity, pions were deflected outward and stopped in collimator C1 while the antiprotons were transmitted essentially undeflected. After additional focusing by Q2 and collimation by C2, the antiprotons passed through a suitably chosen absorber and stopped in the bubble chamber. Approximately 1 antiproton entered the chamber per 4000 background tracks.

III. IDENTIFICATION AND ANALYSIS OF EVENTS

A. Procedure

All film was scanned twice for heavily ionizing particles entering the chamber, and if the direction and curvature of a track were approximately consistent with the known properties of beam particles, the event was recorded for analysis. Tracks of interest either (a) produced characteristic annihilation events in the chamber, (b) appeared to stop with no charged particles emerging from the ending, or (c) traveled the full length of the chamber and left. Because of the possibility of missing prongs near the diffuse edges of the illuminated region, and the uncertainty in momentum measurements on short tracks, only those events were accepted which occurred in a selected volume of the chamber.

Pertinent coordinates of all tracks were digitized and punched onto IBM cards by means of the precision measuring machine, "Franckenstein," developed at the Radiation Laboratory. For each track, direction cosines, momentum, and momentum error (due to fitting and multiple Coulomb scattering) were then calculated by means of an IBM 650 program. Since two sets of stereoviews had been taken of each event, it was possible to check the internal consistency of the measuring techniques and programs used.

B. Charged-Prong Events

With the bubble chamber operating in an ionization-sensitive region, minimum-ionizing particles produced light tracks with gaps, whereas the 200- to 350-Mev/c incident antiprotons produced dark, gap-free tracks. This feature, together with a curvature measurement and the characteristic appearance of the annihilation event, allowed unambiguous identification of antiproton annihilations that resulted in the production of charged particles. Identification of zero-prong annihilations was more difficult, but was approached as follows.

C. Zero-Prong Events

Despite extensive shielding there remained a substantial background of fast neutrons passing through the chamber. Some of these created recoil protons in the chamber which traveled opposite to the beam direction and left the chamber through the entrance window. They therefore had the same sign of curvature as antiprotons and, if they were of low momentum, appeared to have about the correct average curvature. Twenty-six "zero-prong events" were observed to fit rather loose scanning requirements on entrance angle, position, and momentum, and were admitted for measurement. By means of the following observations, however, most of these events were eliminated as possible antiproton annihilations.

Because the incident beam was highly collimated, the entrance position and entrance angle of the antiproton in charged-prong events were correlated to a high degree, whereas the zero-prong events exhibited no such correlation. In addition it was noted that in charged-prong events, the apparent momentum of the antiproton was nearly always lower in the stopping half of its track than in the entering half, although a few of the antiprotons scattered so as to appear to gain momentum as they came to rest. The zero-prong events displayed the opposite behavior. From these comparisons it was possible to conclude on a statistical basis that only two of the 26 zero-prong events fitted sufficiently well to be classified as antiprotons. We assign an uncertainty of ± 1 to this result, not including the statistical uncertainty of the number two.

IV. RESULTS FROM HYDROGEN AND COMPARISON WITH THEORY

A. Selection-Rule Theory

Many authors have pointed out the consequences in antiproton annihilation of strong selection rules stemming from conservation of angular momentum, isotopic spin, and parity. In general these consequences are revealed most strongly in annihilations that result in low pion multiplicity. Since only 5% of all annihilations result in 2 or 3 pions, our data are insufficient to test any of the predictions based on selection rules.

1. Fermi Statistical Theory

Fermi has suggested that processes involving the release of large amounts of energy might be described by a statistical theory in which the details of the initial state do not play an important part.[4] In his original formulation for collisions involving nucleons, Fermi assumed that the available energy of the interacting particles was deposited in a volume equal to that occupied by the nucleon pion cloud. Then, because of the strong pion-nucleon couplings, a statistical equilibrium among the possible final states of the system was reached before the emergence of the particles from the interaction volume. Because of the poor agreement of the detailed predictions of the theory with experiment, Fermi and others introduced modifications to include the Lorentz contraction of the interaction volume, and the effects of final-state interactions. These additions have produced small changes in the correct direction, but the discrepancy is still large.

The predictions of the "normalized" statistical theory of Fermi and a more refined version by Lepore and Neuman[5] as applied to the annihilation process have both been evaluated by Barkas et al. in the Antiproton Collaboration Experiment (hereafter referred to as the ACE).[1] Normalization was achieved by considering the interaction volume as an arbitrary parameter to be adjusted to fit the observed meson multiplicity. Since the two theories were shown to be in qualitative agreement, we shall consider only the Fermi version. In the ACE, average meson multiplicities were determined with and without the inclusion of K-pair production. Average multiplicities for several values of the interaction volume Ω (in units of $\frac{4}{3}\pi\left(\frac{\hbar}{m_\pi c}\right)^3$) are given in Table I.

A summary of the data for antiproton annihilations in hydrogen is presented in Table II. We obtained an average charged-prong multiplicity, $n_c = 3.21 \pm .12$. If it is assumed that the energy distribution for neutral pions is the same as that for charged pions, we may divide n_c by the fractional energy in charged prongs, $0.65 \pm .03$ from Table II, to obtain the average total multiplicity, $n = 4.94 \pm .31$. Comparison with Table I shows that this value of the average total multiplicity corresponds to an interaction volume Ω of about 10.

Since in the statistical theory the possible final isotopic spin states are assumed to be occupied in proportion to their statistical weights, the expected charged-prong distributions may also be evaluated.[6] In Fig. 2 we have plotted the observed charged-prong multiplicity distribution for the 81 antiproton annihilations occurring in hydrogen, together with the multiplicity distributions predicted by the statistical theory. Though annihilation of antiprotons captured in atomic orbitals may occur mostly from p states, while annihilation of low-energy antiprotons in flight occurs from s states, it is not necessary to separate these two groups in a comparison with the Fermi theory as used here, since no account is taken of the conservation of angular momentum. The small kinematic effects due to the few antiprotons interacting in flight may be taken into account separately.

Table I

Meson multiplicities in the statistical theory for several values of the interaction volume Ω

	Interaction volume, Ω^{a}					
	7.5		10		15	
	n^{b}	n_c [c]	n	n_c	n	n_c
K pairs neglected	4.8	3.1	5.0	3.4	5.4	3.6
With K pairs	4.6	3.0	4.8	3.2	5.2	3.4
Fraction of stars in which K pair produced	0.27		0.18		0.12	

[a] Given in units of $(4/3)\pi\,(\hbar/m_{\pi}c)^3$

[b] n = average number of particles produced

[c] n_c = average number of charged particles produced

Table II

Summary for antiproton annihilations in hydrogen.

Charged-prong multiplicity	Number of events	Energy per prong[(a)] (Mev)	Fraction of annihilation energy appearing in charged prongs	Number of π^0's emitted per annihilation
0	2 ± 1	...	...	...
2	33	478	0.51	1.9
4	41	357	0.76	1.3
6	5	291	0.93	0.5

Over-all averages.

3.21 ± .12	81 ± 1	380 ± 12	0.65 ± .03	1.7

(a) Includes $m_\pi c^2 = 139.6$ Mev.

1
66
164
30
260

2. Theory of Koba and Takeda

Koba and Takeda have attempted to explain the dominant features of the annihilation process by recourse to a specific model.[7] They argue that even though the detailed predictions of the statistical theory may not be expected to agree with the observations, the fact that the interaction volume must be chosen so large presents a compelling reason for believing that the annihilation process reflects characteristics of the nucleon structure and that--in contrast to the assumption of the Fermi statistical theory--the initial state of the system is of great importance. They assume that when the antinucleon core "touches" the nucleon core, annihilation proceeds in times of about $\hbar/m_p c^2$, i.e., short compared with oscillation periods in the pion cloud. Therefore, the pions present in the nucleon clouds materialize directly. The remainder of the energy is assumed to be deposited in the core volume and to become distributed among accessible final states according to the predictions of the statistical theory. On the assumption of an average of 1.3 mesons in each nucleon cloud and a core radius of $2/3 \hbar/m_\pi c$, the model yields an average meson multiplicity of 4.8. Since the energy available in the core annihilation is now reduced to about 1 Bev, K-pair production is greatly suppressed.

Koba and Takeda have calculated, in addition to the average multiplicity, the distribution of multiplicites expected from their model. If we again assume that the accessible meson isotopic spin states are statistically occupied, the charged-prong multiplicity may be extracted. The result of this calculation is also plotted in Fig. 2.

B. Momentum Distributions

The statistical theories may be used to predict pion-momentum distributions. The pure phase-space distributions have been calculated in the ACE for several values of the total meson multiplicity, n. Suitable averages of these distributions yield the phase-space distributions for annihilations resulting in n_c

charged pions. The results for the 2-, 4-, and 6-prong stars are compared with the observed distributions in Fig. 3. Each curve has been normalized to the observed number of pions so that the shapes of the distributions may be compared. We have also evaluated the predicted over-all charged-pion momentum distribution. This is shown in Fig. 4 together with the observed distributions.

C. Energy in Charged Pions

For each group of stars the average energy emitted in charged pions has been calculated. Assuming that the energy spectrum for neutral pions is the same as for charged pions, we have calculated the average number of neutral pions emitted per annihilation. The results are summarized in Table II.

It is important to note that for the proton-antiproton system the pion charge distribution cannot be predicted from charge independence alone. However, when the average multiplicity is as large as observed and many meson isotopic spin states are accessible, any statistical theory involving only the π-meson isotopic triplet will predict appearance of approximately 2/3 of the annihilation energy in charged pions, whether the interaction occurs from the initial $I = 0$ or $I = 1$ state or a combination thereof. For deuterium, on the other hand, the property of charge independence for the interaction[9] is sufficient to ensure that exactly 2/3 of the annihilation mesons will be charged.

D. Interactions in Flight

Because of multiple scattering, the measured momentum of the incident antiproton does not provide a very sensitive indication of whether or not the interaction occurred at rest. Nevertheless, comparison of the correlation of measured momentum and track length exhibited by the antiprotons with the known momentum-range curve for stopping protons did provide a useful statistical basis for identification of in-flight annihilations.

By this means we estimate that in the hydrogen exposure, 6 ± 2 annihilations occurred in flight where the statistical uncertainty of the number 6 is not included. Five scatterings with visible recoils were observed. The total path length examined was 1520 cm in the energy interval 5 to 80 Mev. From this we calculate $\sigma_{\text{total}} = 210 \pm 70$ mb and $\sigma_{\text{elastic}} = 96 \pm 43$ mb at a mean energy of 50 Mev.

This result may be compared to recent calculations. Using a model in which only the effects of the long-range pion interactions are considered, Ball and Chew calculated the p-$\bar{p}$ cross section at 140 Mev.[10] The predictions are in good agreement with experimental results obtained with counters[11, 12] and nuclear emulsions.[13] The calculations have now been extended by Ball and Fulco[14] to energies of 50 and 260 Mev. At 50 Mev their model yields $\sigma_{\text{total}} = 232$ mb and $\sigma_{\text{elastic}} = 91$ mb.

V. DEUTERIUM

Thirty-four stopping antiprotons were identified in the acceptable region of the chamber. In Figs. 5 and 6 we have compared the predictions of the normalized Fermi theory for an interaction volume of $\Omega = 10$ with the observed charged-pion multiplicity and momentum distributions.

In three cases of annihilations into odd charged-pion multiplicities, proton recoils of 110, 180, and 235 Mev/c were observed. This is not inconsistent with the predictions of the impulse approximation applied to a deuteron described by a Hulthen wave function. In the computation of the average total multiplicity appearing in the following summary of deuterium results we have, therefore, included a small correction to account for the average energy carried off by the nucleon on the assumption that its momentum distribution is the same as the internal momentum distribution of the deuteron. We have also made a small correction for the probable number of K mesons included among the charged prongs. The results in deuterium are as follows:

Average number of charged prongs	3.23 ± .18
Average total energy per charged prong	371 ± 17 Mev
Fraction of annihilation energy in charged prongs	0.64 ± .04
Average total multiplicity (charged plus neutral)	5.03 ± .44.

VI. K-MESON PRODUCTION

A systematic effort was made to determine the number of charged K mesons among the pions in both hydrogen and deuterium. Many tracks with dip angles less than 30° could be identified as pions from momentum and ionization measurements. However, there remained a group whose identification was uncertain because of inhomogeneity of illumination or obscuration by background tracks. No charged K mesons were observed to stop in the chamber. Consequently, we can place only an upper limit of 20% for the fraction of annihilations yielding charged K mesons.

For neutral K mesons, the bubble chamber provides a detector of high efficiency (the mean decay length of an 820-Mev/c θ meson is 5.5 cm), and in effect complements the emulsion observations. Two annihilations were observed involving the production of θ_1 mesons. In event No. 1, two θ_1 mesons decaying into charged pions originated from a two-prong antiproton annihilation in hydrogen.

A total momentum-energy balance indicated that an additional π^0 meson had been produced in the annihilation. In event No. 2, a single θ_1 meson decaying in two charged pions was produced in a two-prong annihilation in deuterium. Momentum and ionization measurements proved that neither visible prong could be a K meson.

Chamberlain et al. have identified three certain and six probable charged K's resulting from 221 annihilations in emulsion nuclei.[2] Correcting for geometrical factors, nuclear absorption, and loss of neutral K mesons, they estimate that 3.5 ± 1.5% of all annihilations yield $K\overline{K}$ pairs. If we now assume that $K^+ K^-$, $K^+ \overline{K^0}$, $K^0 K^-$, and $K^0 \overline{K^0}$ meson pairs are produced in equal numbers, the probability is 11/36 for observing at least one θ_1 in an annihilation in which a K pair is produced. Thus, we might have expected to observe $(11/36)(.035)(115) \approx 1$ annihilation accompanied by a θ_1 meson among the total of 115 annihilations in hydrogen and deuterium combined.

VII. CONCLUSION

Measurements have been made on antiproton annihilations observed in hydrogen and deuterium. Momenta and multiplicity distributions are consistent with the Fermi statistical model when the interaction volume Ω is adjusted to fit the average multiplicity. However, the momentum spectra are very insensitive to the details of the theory. It is observed that 2/3 of the annihilation energy appears in charged pions, as would be expected from a statistical process involving only the π-meson isotopic triplet. There was no apparent structure in the pion momentum spectrum that could be correlated with the detailed model proposed by Koba and Takeda.

The calculations by Ball and Chew have demonstrated that it is not necessary to assume any long-range annihilation interaction in order to obtain agreement with experiments for interactions at laboratory-system energies greater than 50 Mev. It is therefore probable that the radius of the anomalously large interaction volume in the statistical theory has no physical significance but relates to the limitations of the theory.

ACKNOWLEDGMENT

It is a pleasure to thank Dr. Gerson Goldhaber for several informative discussions on results for annihilations in nuclear emulsion.

We would also like to thank Professor Luis W. Alvarez for his interest and guidance during the course of this experiment. We are indebted to J. Donald Gow and the bubble chamber crew, Dr. Hugh Bradner and the scanners, and Dr. Edward J. Lofgren and the Bevatron crew for the technical assistance which made this experiment possible.

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LEGENDS

Figure 1. Schematic diagram for separated 450-Mev/c antiproton beam using coaxial velocity spectrometer.

Figure 2. Multiplicity distribution for 81 antiproton annihilations in hydrogen ($\bar{n}_c$ = 3.21 ± .12)

Figure 3. Histograms of momenta for charged pions from antiproton annihilations in H_2. Smooth curves represent predictions according to the statistical theory for $\Omega = 10$.

(a) Two-prong events (33 events).

(b) Four-prong events (41).

(c) Six-prong events (5).

Figure 4. Momentum histogram of all charged particles emitted in antiproton annihilations in H_2, compared with predictions (smooth curve) according to statistical theory for $\Omega = 10$.

Figure 5. ______ Charged-prong multiplicity distribution for $\bar{p}$ annihilation in deuterium ($\bar{n}_c$ = 3.23 ± .18).

\- - - - Prediction by statistical theory for Ω - 10 ($\bar{n}_c$ = 3.34).

Figure 6. Momentum histogram for all prongs from $\bar{p}$ annihilation in deuterium (110 prongs).

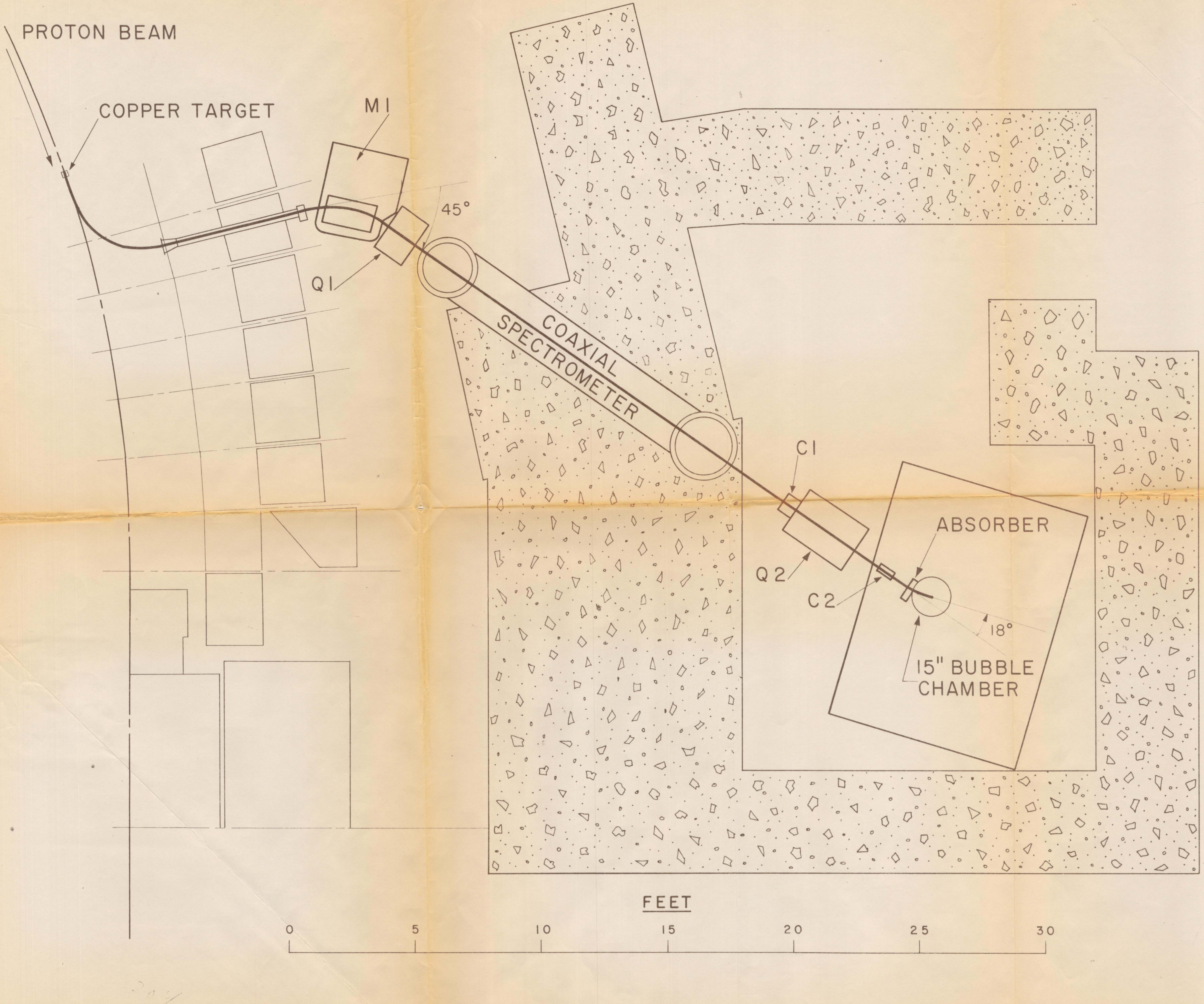
PROTON BEAM
COPPER TARGET
M1
45°
Q1
COAXIAL SPECTROMETER
C1
ABSORBER
Q2
C2
18°
15" BUBBLE CHAMBER
FEET
0
5
10
15
20
25
30

Fig. 1

50,757-5

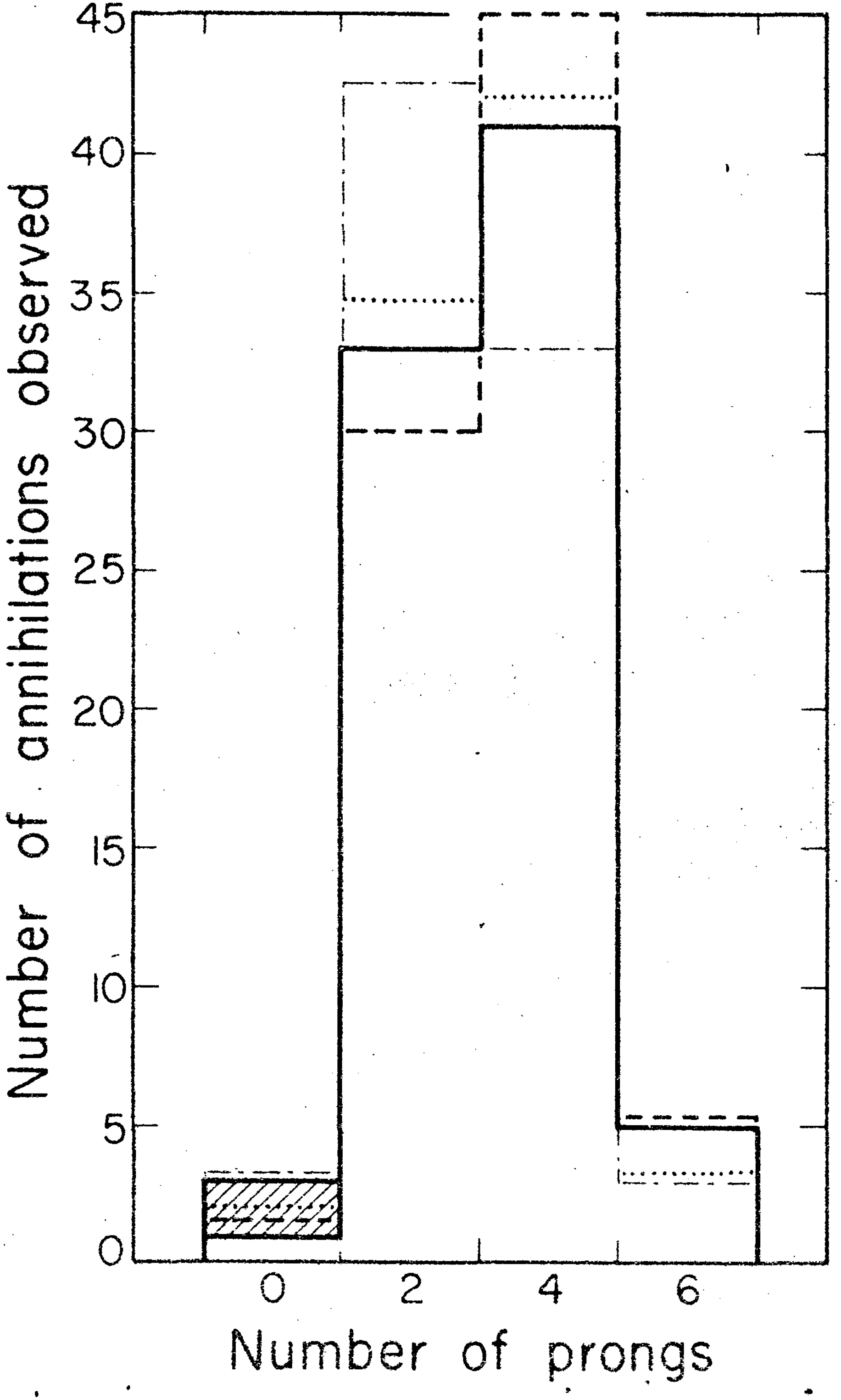
Number of annihilations observed
0
5
10
15
20
25
30
35
40
45
0
2
4
6
Number of prongs

FIG 2

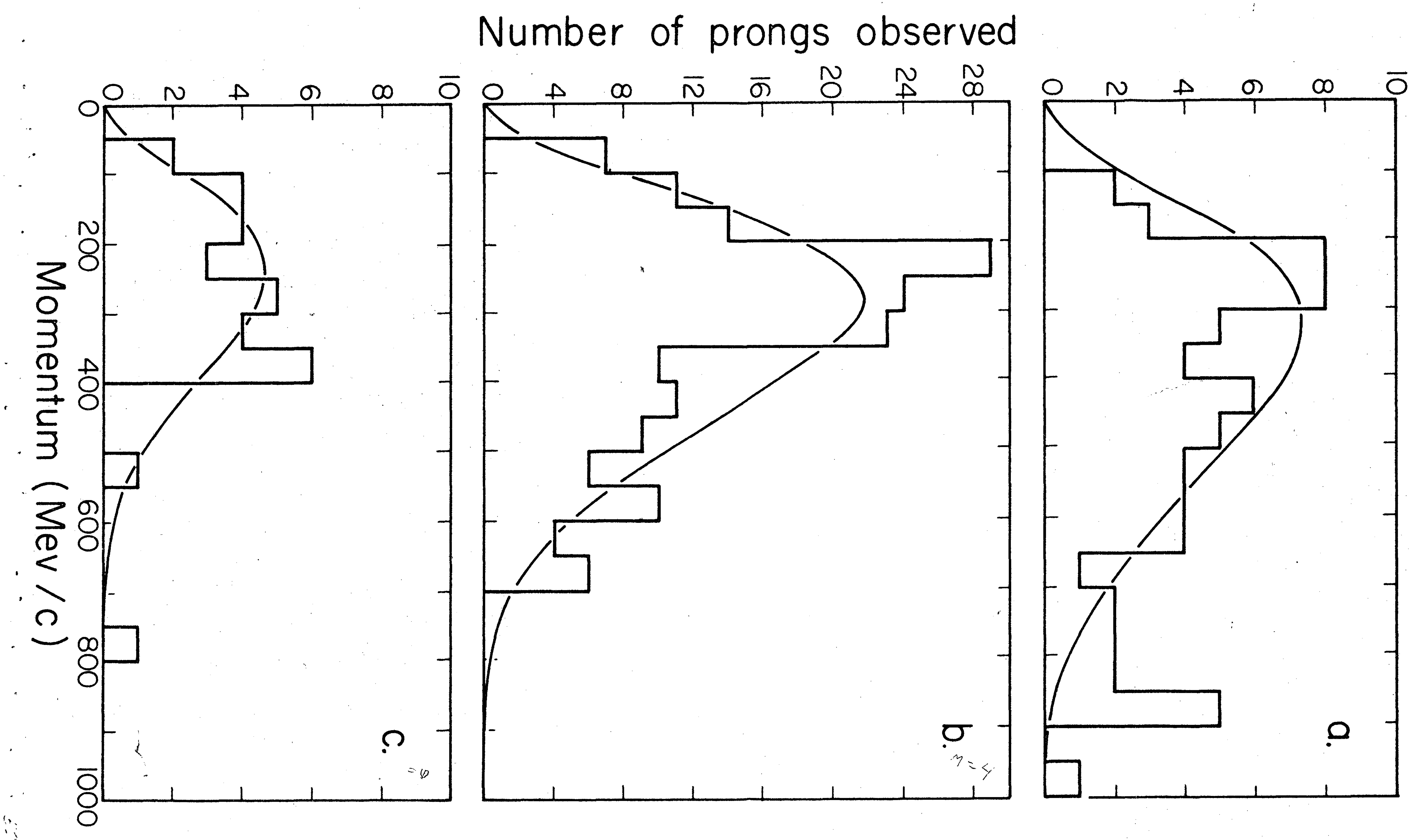
Number of prongs observed
Momentum (Mev/c)
0
200
400
600
800
1000
0
2
4
6
8
10
0
4
8
12
16
20
24
28
a.
b.
c.
m=4

Fig. 3

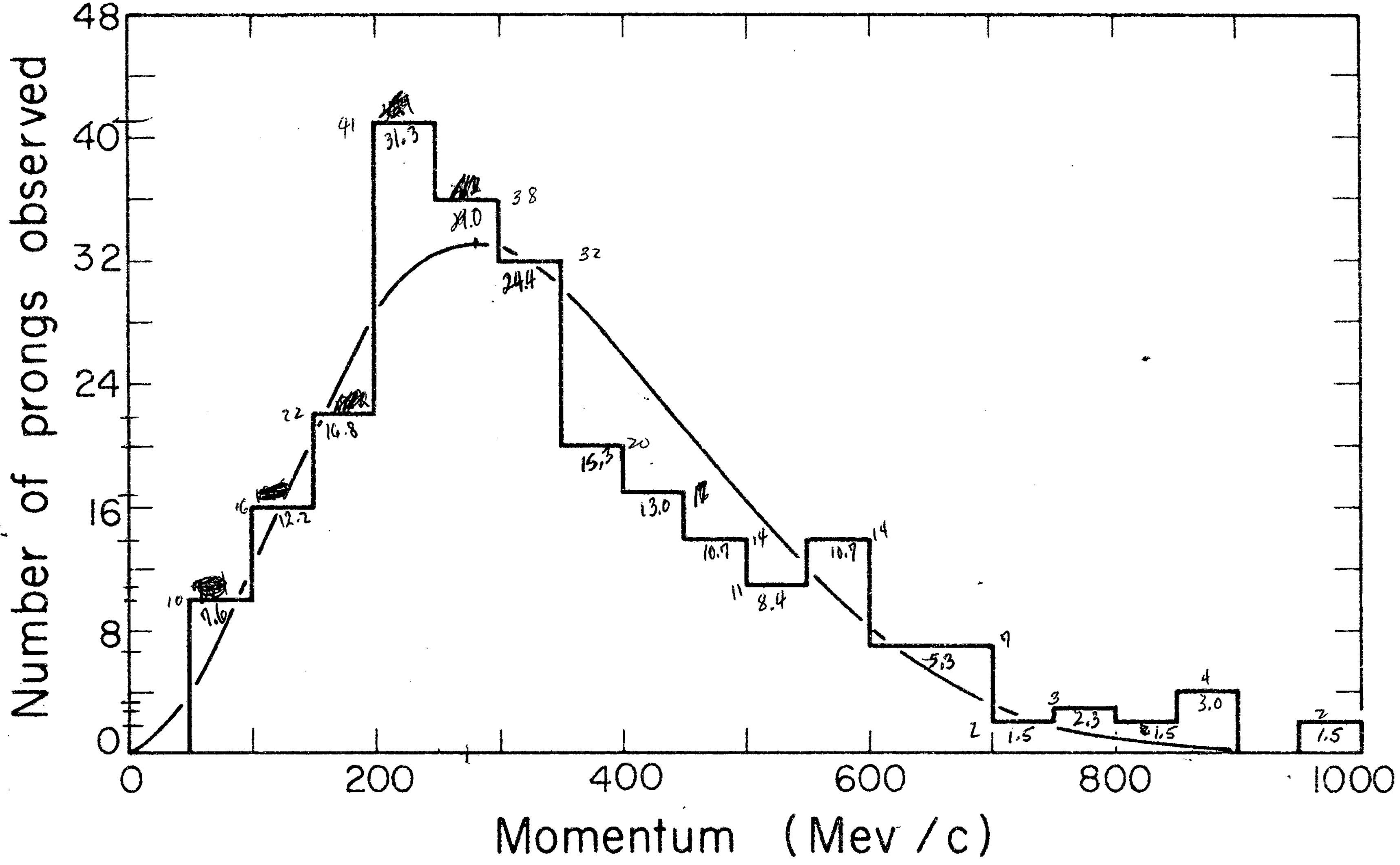
Number of prongs observed
0
8
16
24
32
40
48
Momentum (Mev / c)
0
200
400
600
800
1000
10
7.6
16
12.2
22
16.8
41
31.3
38
29.0
32
24.4
20
15.3
13.0
14
10.7
11
8.4
14
10.7
9
5.3
2
1.5
3
2.3
1.5
4
3.0
2
1.5

*Fig 4

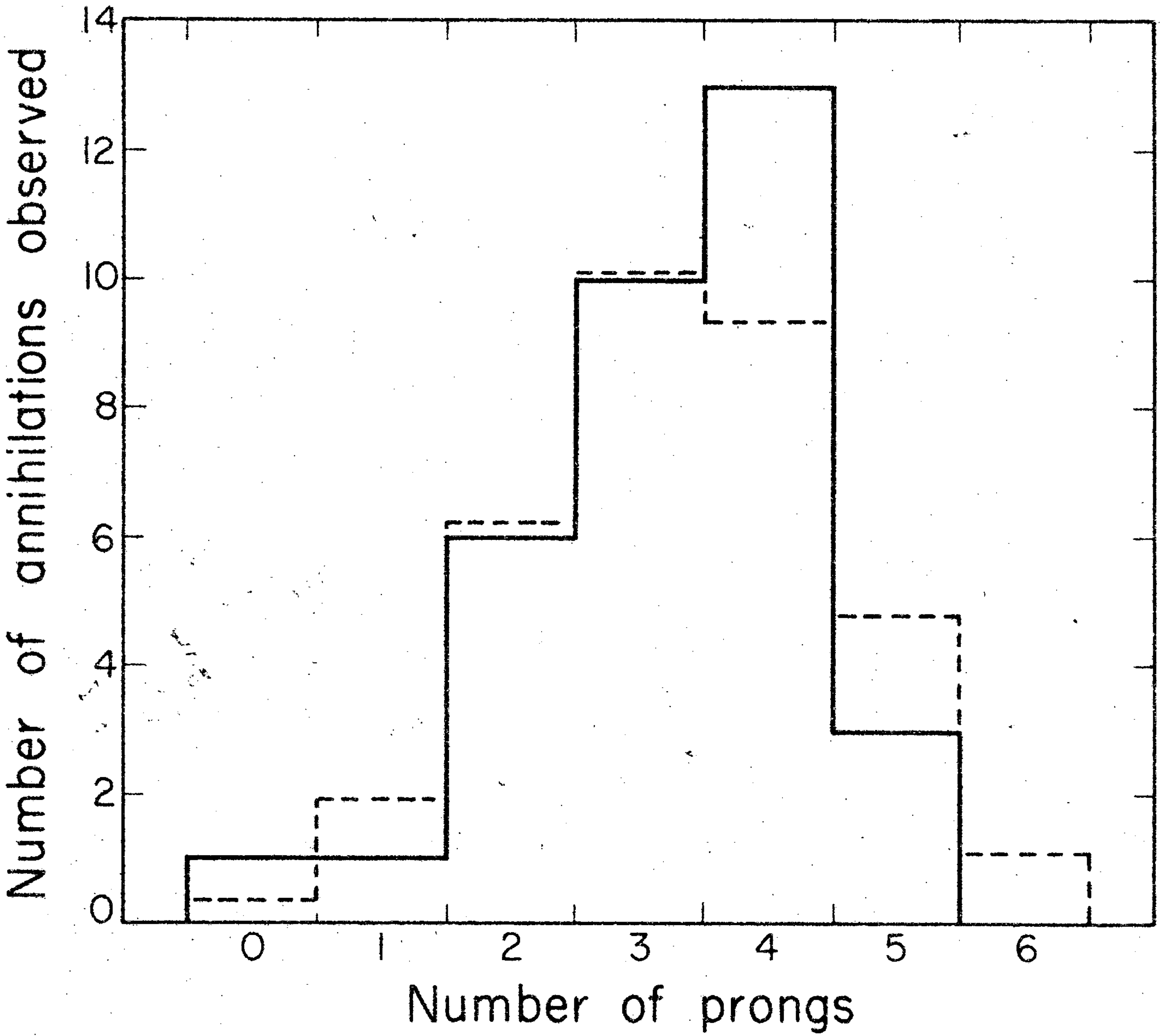
Number of annihilations observed
0
2
4
6
8
10
12
14
0
1
2
3
4
5
6
Number of prongs

FIG 5

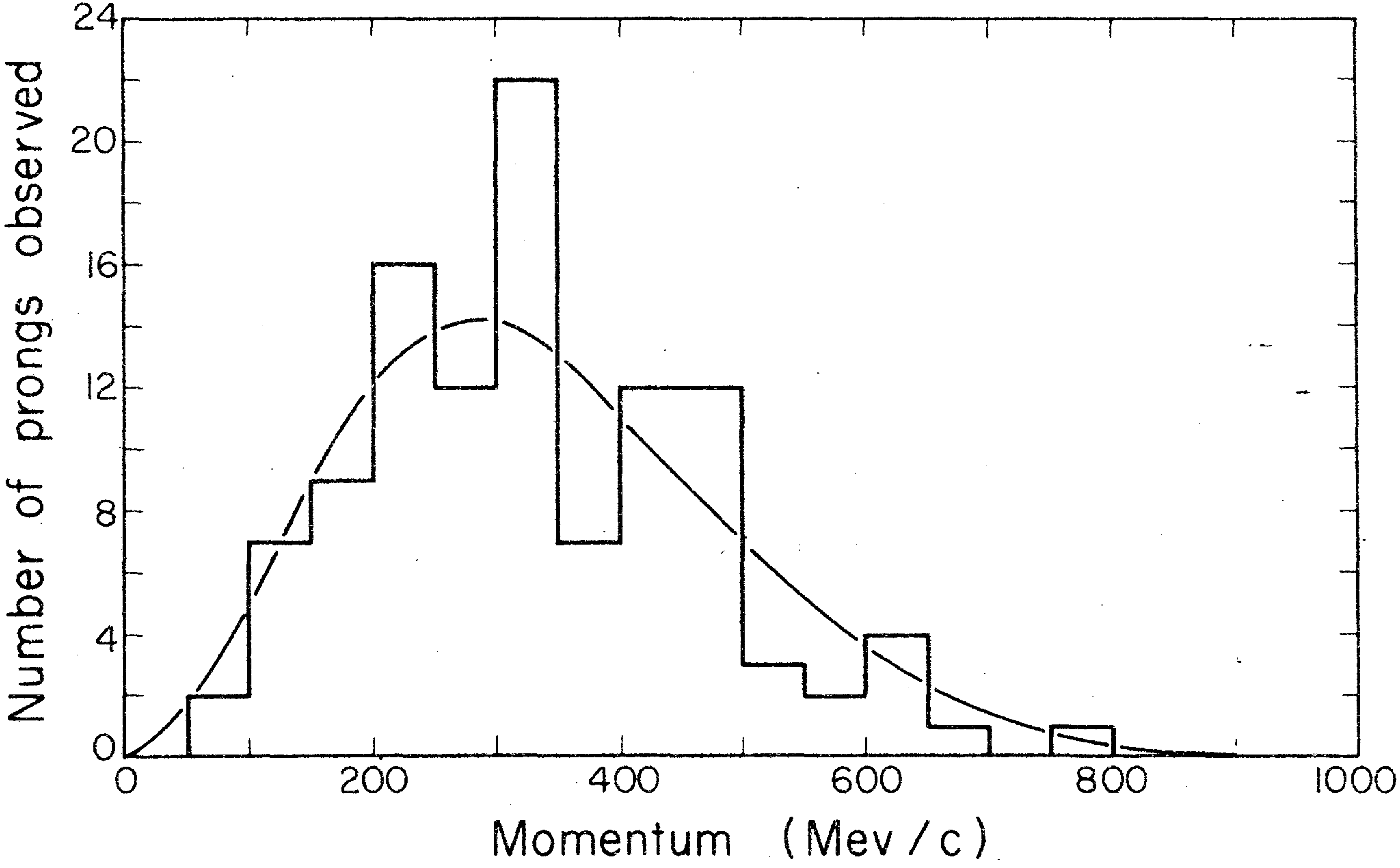
Number of prongs observed
0
4
8
12
16
20
24
0
200
400
600
800
1000
Momentum (Mev / c)

Fig 6