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Leon Kaufman, Victor Perez-Mendez, and John Sperinde

April 1968

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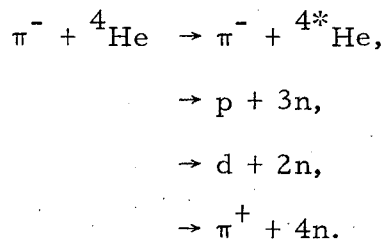
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ABSTRACT

A beam of 140 ± 0.5 -MeV π^- was produced at the Berkeley 184-inch cyclotron and used to study the final-state interactions of three and four neutrons, and to look for excited levels of the α particle through the reactions



Only one such level is found, with an excitation energy of 32 MeV and an intrinsic width smaller than our 1-MeV resolution. We find that our data on the four-neutron final state is best fitted by considering two neutrons interacting through a 1S_0 potential, and the two other neutrons as spectators. We find, too, that deuteron production is down by a factor of $\approx 10^3$ from proton production, and that the proton spectrum indicates a stronger than expected interaction between the three neutrons in the final state.

Lower limits for the production of a tri- or tetra-neutron are set.

The n-n interaction at low energies has been extensively studied through reactions such as $D(n, p)2n$,¹ ${}^3\text{H}(n, d)2n$,² and $T(d, {}^3\text{He})2n$,³ and through a different approach by the reaction $\pi^-D \rightarrow 2n\gamma$,⁴ where in the final state only the two neutrons are strongly interacting. The theory for the analysis of the data obtained in these experiments is well enough known^{3, 5-7} that it is not discussed here.

On the other hand, data on the three- and four-neutron systems are scarce and inadequate, and theoretical predictions are contradicting and inconclusive.

A. Three-Neutron System

The 3n has been searched for through the reaction ${}^3\text{H}(n, p)3n$. In 1965 Ajdacic et al. reported observing a proton distribution of energy that led to an 3n bound by about 1 MeV.⁸ This experiment was repeated later at Oak Ridge National Laboratory,⁹ and no evidence for the existence of the 3n system was observed.

A paper by Mitra and Bhasin¹⁰ predicts the existence of the 3n . They argue that only a moderate 3P attractive force is needed between all neutron pairs to yield a bound 3n system, and they predict an (LSJ) = (1, 3/2, 1/2) state as the most likely, with (1, 3/2, 3/2) a second best. Mitra and Bhasin comment that the existence of the 3n is independent of the 4n , for in the latter the 1S_0 repulsive interaction plays the bigger role, while such a force is negligible in the 3n case.

It is worthwhile noting that the rule of Baz', Goldanskii, and Zel'dovich, which states that the binding energy of the $(2m+2)$ th neutron is always greater than the binding energy of the $(2m+1)$ th neutron,

and which would tie the nonexistence of 3_n with the nonexistence of 4_n , does not necessarily apply to the lightest nuclei, for it is derived from shell-model considerations.

Okamoto and Davies¹¹ assume a (1, 3/2, 1/2) state too, but obtain an 3_n state unbound by about 10 MeV. They use potentials with parameters consistent with the known ${}^3\text{H}$ and ${}^3\text{He}$ data. They point out that light neutron nuclei should also be unbound according to the systematics of nuclei with $n = 3$ and $n = 2$.

Phillips, using the Faddeev equations and what is known of the two-nucleon interactions,¹² arrives at an unbound 3_n . All the authors referred to make the drastic assumption that the interactions in the three-nucleon systems are due to a combination of pair interactions. As pointed out by Noyes,¹³ these approaches are not far enough along to show if experimental data can be interpreted purely in this way or if actual three-body forces exist.

B. Four-Neutron System

The 4_n has been searched for by looking for its signature in breakup of medium-weight nuclei,¹⁴ or breakup of light nuclei such as $\pi^- {}^7\text{Li} \rightarrow {}^4_n {}^3\text{He}$.^{15, 16} (In this same experiment detection of the reaction $\pi^- {}^7\text{Li} \rightarrow {}^3\text{H} {}^4\text{H}$,¹⁵ with $T = 1$ or $T = 2$ for the ${}^4\text{H}$, was also reported.)

Another approach has been to observe the effects of the interactions of the four neutrons on the phase space of one observed particle. Such an experiment can shed light not only on the existence of a bound state, but also on the actual interactions between the neutrons.

The reaction studied was $\pi^- {}^4\text{He} \rightarrow \pi^+ 4n$.^{17,18} No 4n was found, and the CERN group¹⁸ that performed this experiment finds a phase space for the π^+ that can be explained by a final-state interaction between two neutrons only. The resolution in this experiment was an order of magnitude larger than the expected binding energy of the 4n , and therefore the results are not conclusive.

Tang and Bayman predict that two dineutron clusters will not be bound, and further, that the relative energy of the dineutron clusters goes down monotonically as a function of increasing radius.¹⁹ This would lead one to believe that no 4n resonance exists either. They use for their calculation the n-n singlet-even potential and a triplet-odd potential assumed to be zero except for a hard core of small radius. These authors point out that inclusion of a weak attractive potential in the triplet-odd state does not change their conclusion.

The question of the 4n is tied directly with excited states of ${}^4\text{He}$, and a review of this field is of consequence.

C. Excited States of ${}^4\text{He}$

The literature abounds with experimental data and theoretical analysis on the ${}^4\text{He}$ nucleus.²⁰⁻²⁹ An adequate review is afforded by Argan et al.²⁹ They summarize what is known about the problem as follows. One can believe either

1. (a) the triplet ${}^4\text{H} - {}^4\text{He}^* - {}^4\text{Li}$ exists,^{15, 30, 31} with $E \approx 24$ MeV, and $T = 1$;

(b) the reported levels at 21 and 22 MeV are the same, with $T = 0$ (they could represent the $P_{3/2} - P_{1/2}$ spin orbit splitting, but then a

$T = 1$ value would be expected as above. For such a T value excited states of ${}^4\text{Li}$ and ${}^4\text{H}$ should exist at ≈ 22 MeV. Experimentally they have not been seen);

(c) there exists a $T = 2$ state at 30 MeV;

(d) the 20-MeV level exists and has $T = 0$ or indefinite isospin; or
 2. The 20-, 24-, and 30-MeV levels are "quasi states,"³² the only "true" level being the one at 22 MeV with $T = 0$; there should exist a second "true" state with ≈ 24 MeV and $T = 1$.

They conclude with the observation that present knowledge of the nuclear structure of ${}^4\text{He}$ is scanty and sometimes contradictory.

A more recent review of the problem is afforded by Meyerhoff and Tombrello.³³ In their review of the problem they conclude that a series of levels exists in ${}^4\text{He}$ at excitation energies between 20.2 and 28.5 MeV, even though they mention that there are indications of the existence of a level "around 30 MeV."

II. EXPERIMENTAL METHOD AND APPARATUS

A. Introduction

We decided that the interaction of negative pions with ${}^4\text{He}$ nuclei, if studied at high resolution, could yield valuable information about the problems presented above.

Of the many reactions produced by the π^- at energies lower than those necessary for the production of a second π , we decided to study the channels

$$\pi^- + {}^4\text{He}^*, \quad (1)$$

$$p + 3n, \quad (2)$$

$$d + 2n, \quad (3)$$

and the double charge-exchange reaction



In all these channels one particle in the final state is charged, and this affords an easy measurement of its momentum. The reactions mentioned are of interest because:

- (1) it can yield excited states of ${}^4\text{He}$ with $T = 0, 1, \text{ and } 2$;
- (2) the high-momentum end of the proton spectrum will reflect the final-state interactions of the neutrons with low relative energy;
- (3) the deuteron spectrum is distorted by n-n interactions;
- (4) the phase-space distribution of the π^+ yields information on the final-state interactions of the four neutrons. The $\pi^+ \text{-N}$ interaction cross section is much smaller than the n-n cross section and does not affect the π^+ spectrum in an appreciable way.

We expect that the peaks produced by the channel (1) will be readily identifiable from the smooth background produced by inelastic scattering of the π^- in which the final state contains more than two particles (i.e., ${}^4\text{He}$ breakup). These breakup reactions, together with charge exchange, will produce low-energy protons and deuterons, the thresholds for these reactions being lower than the ones from (2) and (3) by about a pion's rest mass.

Since we are not interested in the low-energy end of the proton or deuteron spectra, these backgrounds can be discriminated against by kinematic considerations.

The π^0 's produced in charge exchange reactions yield e^+ 's through Dalitz decay. We studied this source of background by a Monte Carlo method and decided that the positron acceptance of our spectrometer was negligible in the region of interest, and no $\pi^+ \text{-} e^+$ discrimination was

necessary.

B. Experimental Layout

A 242 ± 0.50 -MeV/c π^- beam was focused on a liquid- ^4He target, and the products of the reactions were momentum-analyzed at 20 deg in the laboratory system (lab) by a magnetic spectrometer, to be described later.

This particular beam energy was chosen because it allowed simultaneous analysis of the π^+ , p, and D spectra at 20 deg when the maximum field attainable in our magnet was used (therefore, at maximum attainable resolution). The target exit angle of 20 deg was chosen for experimental convenience.

C. Beam

The pion beam was produced when the circulating 735-MeV proton beam of the 184-inch Berkeley cyclotron was allowed to strike an internal Be target. It was first bent through 90 deg in the cyclotron's own field and then another 90 deg in an external magnet. This large bend provided high momentum separation at the target, which consisted of a 9X2X2-in. liquid-He flask, the long axis being parallel to the beam direction.

The beam was monitored by two sets of counters (see Fig. 1). A_1 , A_2 , A_3 , and A_4 were four 6X1.5X1/32-in. counters overlapped in pairs (A_1 and A_2 , A_3 and A_4) so as to yield 3/4-in. horizontal resolution. B_1 , B_2 , and B_3 were 2X0.5X1/32-in. and were overlapped so that they covered a 2X1-in. area, with 1/4-in. horizontal resolution.

Scattering was minimized along the beam line by a combination of He gas bags and vacuum pipes. An integral range curve of the beam

was taken by the use of Cu absorbers, and it was found that it consisted of $58 \pm 10\%$ π^- 's, 28% μ^- 's, and 14% e^- 's.

For a fine determination of the beam spectrum a thin (3/16-in.) carbon target was positioned at 45 deg to the beam, and the elastically scattered negative pions were momentum-analyzed by the spectrometer. The total spread observed was ± 0.50 MeV/c HWHM at 237 MeV/c. (No correction was made for energy loss in the target.) This allowed us also to check the calibration by detecting at the same time the first excited level of C^{12} at 4.4 MeV, as seen in Fig. 2.

D. Spectrometer

Figure 1 shows the spectrometer layout. If the magnetic field, an entrance line, and an exit point are known in a particle's trajectory, the momentum of that particle is uniquely determined. If a second point on the exit path is known, the problem is overdetermined, and consistency can be checked for.

The field was produced by a 16×36-in. BeV "C" magnet with an 8-in. gap. A 2-in.-thick (S_1) iron shield with an 8-in. gap was provided to assure that no bending occurred in the particle's incoming path, and two 5/8-in. shields with 22×18-in. holes were added on the exit sides to reduce the extent of the magnet's stray field (S_2 and S_3).

The coordinates of the incoming track were determined by two 8×8-in. magnetostrictive readout spark chambers (Chambers 1 and 2). By each side of the magnet we placed a 22×18-in. spark chamber (Chamber 3 or 4) followed by a 49×17-in. chamber (Chamber 5 or 6). Counter C was 1/32 in. thick by 4 in. wide by 2-5/8 in. high on the side

farthest from the pion beam line and 2- 3/8 in. high on the side closest to it. The E and F counters were 25×18×0.25 in.

Helium gas bags (G_1 , G_2 , G_3 , and G_4) connected the chambers to minimize particle scattering.

Low-momentum protons and deuterons and all pions went through the "E" side of the spectrometer. The heavy particles did not reach the E counters because an aluminum slab placed between Chamber 5 and these counters acted as a filter, completely stopping the protons or deuterons, but having practically no effect on the pions.

The heavy particles in the momentum range of interest went through the F side of the setup, and the time of flight between the C counter and either F_1 or F_2 was recorded onto tape.

The time-of-flight data were used to calculate the masses of the particles from knowledge of the momentum and distance traveled (these two parameters were very accurately calculated by the computer). Given that we were seeking to separate particles whose masses went as M_p , $\approx 2 M_p$, $\approx 3 M_p$, no great accuracy in time resolution was necessary for the energy range we worked in. Other data stored consisted of a flag for each of the A, B, E, or F counters that produced the trigger.

For chambers 1, 2, 3, and 5 to be fired, the logic requirement was

$$[(A_1 \text{ or } A_2 \text{ or } A_3 \text{ or } A_4) \cdot (B_1 \text{ or } B_2 \text{ or } B_3) \cdot (C)] \cdot [(E_1 \text{ or } E_2) \cdot (E_3 \text{ or } E_4)];$$

similarly, for Chambers 1, 2, 4, and 6 to fire we required

$$[(A_1 \text{ or } A_2 \text{ or } A_3 \text{ or } A_4) \cdot (B_1 \text{ or } B_2 \text{ or } B_3) \cdot (C)] \cdot [(F_1 \text{ or } F_2) \cdot (F_3 \text{ or } F_4)].$$

We ran with the spectrometer in one of two modes:

- (i) π^- , where only ABCE coincidences were accepted, and the data on π^- -He elastic and inelastic scattering were taken; and
- (ii) π^+ , where both ABCE and ABCF coincidences were accepted, and both the π^+ spectra and protons and deuterons were observed.

Runs were effected for each spectrometer mode both with the target full and empty, to obtain the background cross sections from the target assembly.

The spark chambers consisted of four planes of wires: two high-voltage (HV) central planes and two grounded outside ones. Each HV-ground pair was fired by a different capacitor. This decoupled each gap so that we effectively had two spark chambers in each assembly, with only the 90% Ne-10% He gas mixture flowing through the chamber in common. A small amount of ethyl alcohol was added to the gas to act as a spark quencher, and a 35-V clearing field was used to reduce the sensitive time of the chambers.³⁴

Data were collected by the magnetostrictive-readout method³⁵⁻³⁸ onto magnetic tape. A novel feature was the use of delay lines to reduce the number of scalers needed. These storage devices are discussed in Ref. 39. Signals from the magnetostrictive lines were differentiated, zero-crossed, and then timed by 20-MHz scalers (Fig. 3). The output of each plane in the chambers consisted of a number for the spark position and another for the total length or "fiducial" distance.

Details on the construction and performance of these chambers can be found in the thesis by one of the authors (Leon Kaufman).⁴⁰ We summarize our findings here as follows.

- a. Accuracy. Track location accuracy was tested prior to the experiment by use of cosmic rays, and later by use of experimental data. We find that, using 20-MHz scalers and a wire separation of 1.04 mm, we can locate the position of the spark to within 0.33 mm. A typical distribution of the difference between the track location by a plane in the chamber and the actual track is seen in Fig. 4.
- b. Efficiency. Before running we checked chamber efficiency as a function of voltage, and found that optimum running conditions were achieved at approximately 10 kV.

Two efficiencies can be considered here:

(i) Efficiency per plane: For this case we say that a wire plane is 100% efficient if it contributes a coordinate for every event. Once the voltage, clearing field, gas mixture, and triggering delay were fixed (as they must be during running), we checked plane efficiency as a function of angle for cases in which no more than two sparks occurred. The results are presented in Table I.

Table I. Average plane efficiency.

<u>Chamber</u>	<u>$\theta < 10$ deg</u>	<u>$\theta \leq 20$ deg</u>	<u>$20 \text{ deg} \leq \theta \leq 40$ deg</u>
Front	98.9%	---	---
Back	---	96.7%	94.8%

(ii) Chamber efficiency: The data produced by the chambers will still be useful even though not every plane has contributed a coordinate. It is of interest to know the percentage of four-wire, three-wire, and two-wire fits that were present, because even though a two-wire fit is enough to

determine a point, if we want to resolve the location of two or more sparks we need at least three coordinates. Then we define as 100% efficient a chamber where all events are determined by three- or four-wire fits. The data were taken, as in (i), for cases in which no more than two sparks were present, and are summarized in Table II.

Table II. Average chamber efficiency.

<u>Chamber</u>	<u>Four-wire</u>	<u>Three-wire</u>	<u>Two-wire</u>	<u>Total</u>
Front	93.2%	6.7%	0.1%	99.9%
Back	87.7%	11.6%	0.7%	99.3%

III. DATA ANALYSIS

A. General Analysis

We describe now the program used for analysis of the data. The number of counts between the first and last wires in a chamber plane (fiducial counts) were continuously updated. As it turned out, this number did not vary by more than one count. The counts produced by sparks were then normalized by the fiducial distance, and a generalized least-square routine was used to determine the x, y coordinates of the sparks in the chambers. This coordinate was given as a projection on the center plane of the chamber, so that the information on the z coordinate of each one of the planes was not used.

The next step consisted of determining all the possible tracks between chambers 1 and 2 and between 3 and 5 (or 4 and 6). The former were checked to see that they came from the target and did not hit the

magnet pole piece, and then were matched with the lines in the back chambers. The target check was done by taking the intersection of the lines as given by the front chambers with the plane on which the trajectory of the incoming pion lay, this plane being determined by the A and B counters. Thus we could determine the location of the origin of the event within 0.4 cm. The matching of the entrance and exit lines of the spectrometer was performed by a polynomial fit, this polynomial having been constructed on the basis of a previous knowledge of the orbits through the magnet.

Once the correct combination of points was known, the program constructed new lines between them. This was done by a generalized least-square fit to the coordinate as given by each plane, thus taking into account the z positions of that plane. Such a line was called "best-line."

The best-line coordinates were used together with an integration and iteration routine to determine the particle's momentum. A second integration and iteration yielded values for the momentum that never varied by more than 0.1% from the values obtained in the previous step.

Since just three points and the magnetic field are needed to determine the momentum uniquely, the fourth point measured can be compared with the one predicted by the integration routine.

For this purpose the differences ($\Delta\theta$ in the horizontal and $\Delta\phi$ in the vertical planes) between the measured and predicted angles in the back chambers were determined, and only events within bands 1.5 deg and 3.5 deg wide, respectively, were accepted. Figure 5 shows $\Delta\theta$ and its acceptance band. Once the momentum was known, the program determined whether the particle was a pion, proton, or deuteron from

time-of-flight information and flags stored on tape, and corrected the momentum for energy loss in spectrometer and target. The energy loss of the incoming pion and scattering angle were computed too, and a transformation to the center-of-mass system was performed.

Finally events were weighted to correct for spectrometer acceptance and π decay in flight, and histogrammed in 0.5-MeV and 1-MeV bins.

B. Error Estimates

The main sources of error in the determination of the momentum are considered below.

1. Determination of the point of intersection in the target

This is an important parameter, since the program uses it to compute the correct length of liquid He the incoming and outgoing particles traversed, and then, using that distance, corrects for energy loss in the target.

The uncertainty in energy produced by the finite width of the A and B counters (see Secs. II. C and III. A) amounts to 0.1%, 0.1%, and 0.25% for pions, protons, and deuterons in the high-energy ends of their respective spectral distributions.

2. Determination of the scattering angle in the target

The uncertainty in this case is produced by scattering in the liquid He and by finite width of the A and B counters. The total uncertainty expected is $\Delta\theta \approx \pm 2.5$ deg, which produces momenta uncertainties approximately equal to the ones above.

3. Scattering in the spectrometer

This factor--and, to a lesser degree, chamber coordinate resolution--produced an uncertainty in the measured angle of entrance into the magnet.

We estimated this quantity by approximating the actual field by a uniform rectangular one.

We find that in most cases, including the effects of uncertainties in spark location in the chambers, the values are $dp/p < 0.6\%$ for pions, $dp/p < 0.2\%$ for protons, and $dp/p < 0.6\%$ for deuterons.

4. Energy resolution

We estimated then that in the high-energy end of the respective spectra we would have $dE(\pi) \leq 1.0$ MeV, $dE(p) \leq 0.6$ MeV and $dE(d) \leq 1.2$ MeV.

IV. RESULTS

A. $\pi^- + {}^4\text{He}$ and $\pi^- + {}^4\text{He}^*$ Channels

Figure 6 shows the scattered π^- energy spectrum in the c. m. system.

Our resolution is determined by the FWHM (≈ 1 MeV) of the elastic peak. The interesting feature of this spectrum is the large cross section observed at 32 MeV excitation energy of the α particle. This possible level is narrower than our experimental resolution.

The cross sections given are corrected for (a) μ^- and e^- contamination of the initial beam, (b) solid-angle acceptance of the helium target, (c) spectrometer acceptance, and (d) π decay in flight. The background has been subtracted, and can be seen in Fig. 6.

B. p + 3n Channel

Figures 7 and 8 show the proton energy spectrum in 2- and 5-MeV bins respectively. Superimposed on these we see the distributions to be expected from phase space, and the effect of adding the singlet-even interaction between two of the neutrons in the final state.

Cross sections are corrected for factors (a), (b), and (c) as in A. The background was negligible. An upper limit of 0.074 ± 0.015 $\mu\text{b}/\text{sr}$ is established for the cross section for production of a trineutron with $-3 \text{ MeV} < \text{B. E.} < 3 \text{ MeV}$ (where B. E. is the binding energy). The experimental resolution was $\approx 0.6 \text{ MeV}$.

C. d + 2n Channel

Only four deuterons were seen in the range from 470 MeV/c to threshold at 801 MeV/c in the lab. This yields the result

$$\frac{\sigma_{\pi^- + \text{He}^4 \rightarrow \text{p} + 3\text{n}}}{\sigma_{\pi^- + \text{He}^4 \rightarrow \text{d} + 2\text{n}}} = 1150 \pm 50\%.$$

The integrated cross section for this reaction in the c.m. system is $\sigma = 0.0012 \pm 50\%$ $\mu\text{b}/\text{sr-MeV}$. These cross sections are corrected as in Sec. B. Background was nonexistent here.

D. π^+ + 4n Channel

The resultant π^+ spectrum is shown in Fig. 9. Superimposed on it can be seen the spectrum predicted by phase space, and the effects of adding the singlet-even interaction between two of the neutrons in one pair, or between the two neutrons in each pair. We find a slightly better fit to the data by using the second possibility. An upper limit of $2.8 \pm 1.4 \times 10^{-3}$ $\mu\text{b}/\text{sr}$ is established for the formation of a tetra-neutron

with a B. E. between -10 and 10 MeV. The experimental resolution was 1 MeV, as above. Corrections were made as in A, and background was negligible.

V. INTERPRETATION AND CONCLUSIONS

A. $\pi^- + {}^4\text{He}^*$ Channel

The study of this reaction shows one inelastic peak located at 32 ± 1 MeV relative to the elastic scattering peak as shown in Fig. 6. This level can have a T spin of 0, 1, or 2. In a previous experiment Charpak et al.²¹ discovered a 30-MeV level formed in the reaction $\pi^+ + {}^6\text{Li} \rightarrow 2p + {}^4\text{He}^*$. This level is quite wide and overlaps ours, and although the authors considered it as a manifestation of peripheral reactions, Tang⁴¹ in a subsequent paper argues for the existence of a T=0 level at ≈ 30 MeV. Measday and Palmieri⁴² present arguments for the existence of a T = 1 contribution to the level at that energy.

There is evidence¹⁵ that ${}^4\text{H}$ unstable against dissociation exists, even though particle-stable ${}^4\text{H}$ has not been seen. As we mentioned before, Cohen et al. observed the reactions ${}^6\text{Li}(\pi^-, d){}^4\text{H}$ and ${}^7\text{Li}(\pi^-, T){}^4\text{H}$, finding ${}^4\text{H}$ with $0 < \text{B. E.} < 5$ MeV against its breakup into four free nucleons.

There is evidence for the existence of ${}^4\text{Li}$ as reported by Tombrello et al.;^{30, 33} furthermore, Beniston et al.³¹ observe that analysis of the π^- and p momenta in the decay of the ${}^4\text{He}_\Lambda$ hyperfragment (${}^4\text{He}_\Lambda \rightarrow \pi^- p {}^3\text{He}$) yields evidence of a ${}^4\text{Li}$ state with an energy that corresponds to ≈ 30 -MeV excitation of the α particle. Even though Beniston's data are questioned at this time, the existence of this level seems to be well determined.³³ Our

negative results in the $\pi^+ + 4n$ channel tend to indicate that 4n does not exist, therefore we believe that the present data indicate the existence of the I-spin triplet, and that it corresponds to an excited level of ${}^4\text{He}$ with $E \approx 32$ MeV (Fig. 10).

B. p + 3n Channel

In the reaction studied, the upper limit in the cross section for formation of a trineutron with $-3 \text{ MeV} < \text{B. E.} < 3 \text{ MeV}$ is determined to be $0.074 \pm 0.015 \times \mu\text{b/sr}$. The resolution is better than 1 MeV.

As seen in Fig. 7 and 8, the proton spectrum shows a pronounced peaking at 130 MeV. This corresponds to an energy of 53 MeV for the three neutrons in their center of mass. The proton spectrum was not measured below 80 MeV. The reason for this is that from approximately this point down the $\pi^- {}^4\text{He} \rightarrow p 3n \pi^0$ channel and ${}^4\text{He}$ breakup reactions contribute, and the spectrum of the proton is no longer uniquely determined by the reaction of interest. This makes the normalization non-unique too. On the other hand, we can reasonably assume that, from the quick drop in cross section observed around 90 MeV, most of the area of the curve concentrates in the region measured.

The comparison of immediate interest is made with respect to phase space and phase space altered by the 1S_0 interaction between two of the neutrons in the final state. (The Pauli principle voids the possibility that more neutrons can be in a relative S state.) For this interaction we use standard effective-range theory with a 70-keV scattering length.

The results are shown normalized in two ways. In Figs. 7 and 8 we compare the spectra with equal areas in the region where measurements

were performed; in Fig. 11 we see the same spectra normalized in such a way that the peaks are at the same height. It is easy to see that the spectra shown differ widely from that observed. We call the reader's attention to the fact that addition of a final-state interaction between the proton and one (or more) of the neutrons will shift the proton spectrum towards the low-energy end, contrary to what is seen.

As a purely phenomenological fit we used a Breit-Wigner-like resonance among the three neutrons, assuming the decay of the p - $3n$ system to go through an $\ell = 1$ channel. This makes the width proportional to the third power of the relative momentum. The results provide a satisfactory fit to the data, and can be seen in Fig. 12, curve C.

A possibility to consider is that we are dealing with a direct-reaction mechanism. In this case, the high-energy protons would arise from π^- absorption by p - p pairs, producing a proton and a neutron which share the energy of the pion, and two other neutrons that are spectators and carry energies of the order of their Fermi momenta in the α nucleus. Were this to be a purely two-body absorption, we would expect the proton to carry about 122 MeV in the c.m. system; this is lower than the observed most probable proton energy of 130 MeV. The width of this peak (caused by the internal energy of the target nucleons) should be approximately 20 MeV, narrower than the observed width. Since this mechanism does not seem to match the data, we should consider the possibility that the observed effects are due to a three-body interaction.

With the data available at present we can give no simple answer. Further experiments providing considerably more data will be needed in order to clarify these points.

C. d + 2n Channel

The low cross section found for this reaction yields a low probability for the dnp and dd components of the wave function of the α particle. Furthermore, it tends to indicate that the final-state interaction between the proton and one of the neutrons in the p + 3n channel is small.

D. π^+ + 4n Channel

The 1-MeV resolution achieved in this experiment allowed careful search for a tetraneutron. For a binding energy between -10 MeV and 10 MeV, an upper limit of $1.38 \pm 0.69 \times 10^{-34}$ cm²/sr-MeV is set for tetraneutron formation under the given conditions.

The π^+ energy spectrum is in agreement with that obtained by Gilly et al.¹⁸ in that the best fit corresponds to two neutrons interacting through a 1S_0 potential, the interaction of the other not being strong enough to affect the spectrum appreciably. Our method of measurement does not allow us to determine whether the two neutrons in the 1S_0 state were produced by double charge exchange or were spectators.

No effects from the three-neutron interaction seen in Sec. C. manifest themselves here. This would follow from the arguments, presented by Mitra and Bhasin,¹⁰ that P forces play the dominant role in the three-neutron system, while the kernel for the 1S_0 -wave part of the force (which predominates in the two- and four-neutron case) is repulsive.^{9, 10}

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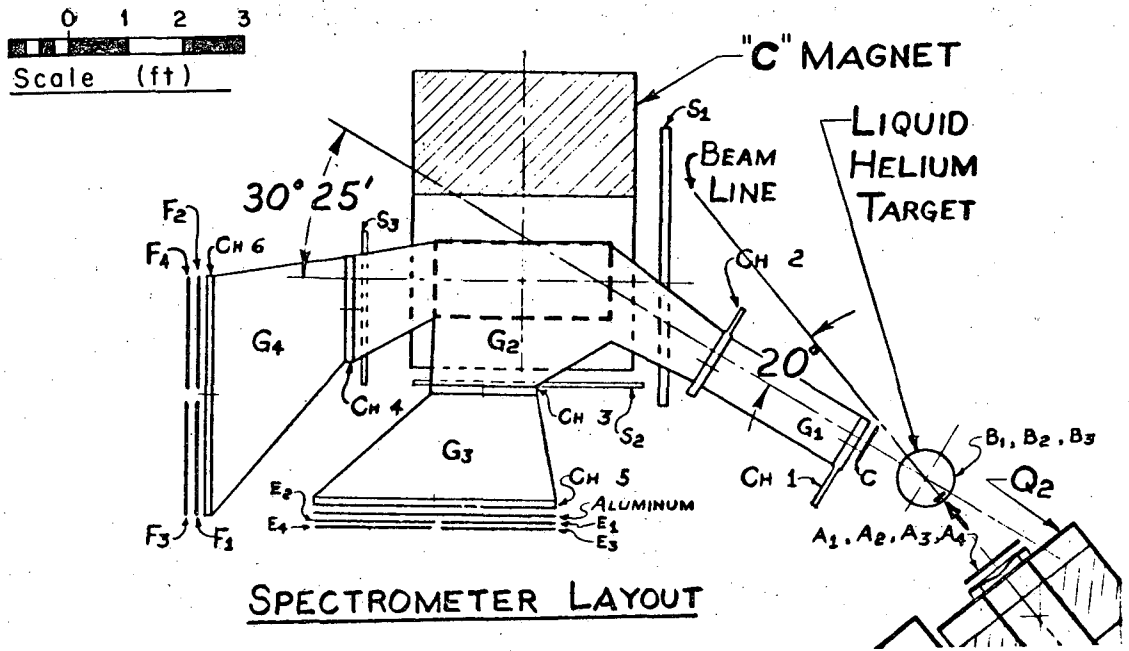
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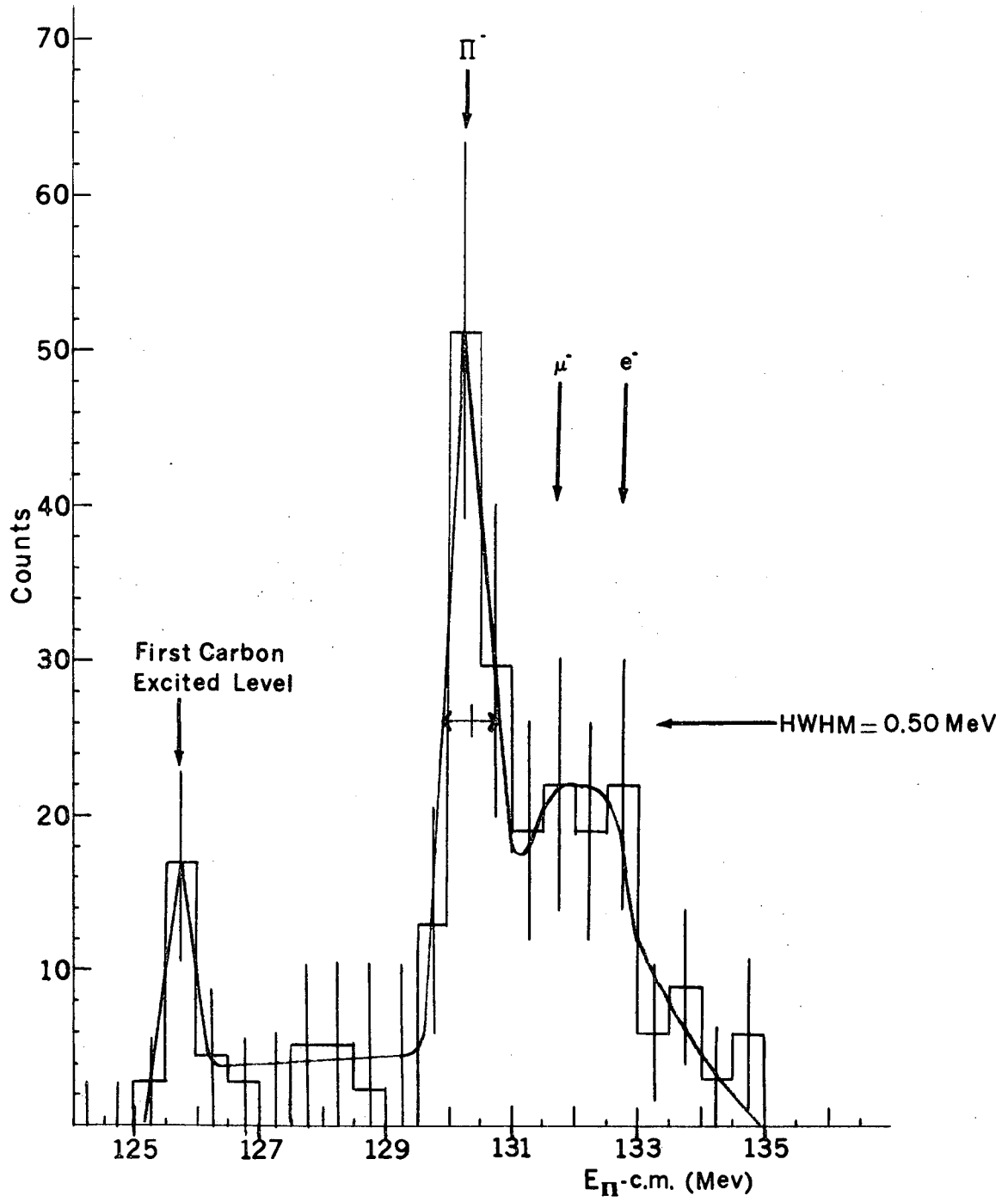
FIGURE CAPTIONS

- Fig. 1. Spectrometer layout.
- Fig. 2. $\pi^- + C$ elastic-scattering spectrum.
- Fig. 3. Simplified logic for magnetostrictive signal processing.
- Fig. 4. Deviation of measured coordinate from best line for chamber 2, plane 1.
- Fig. 5. Distribution of $\Delta\theta$. The displacement of the center of the distribution is due to a 1/32-in. displacement of the rig used to map the field.
- Fig. 6. (a) Full spectrum, (b) inelastic-region spectrum, and (c) background events. Bin width for (a) is 1 MeV; for (b) and (c), 0.5 MeV.
- Fig. 7. Proton spectrum, with 2-MeV bins, $p + 3n$ channel.
- Fig. 8. Proton spectrum, with 5-MeV bins, $p + 3n$ channel.
- Fig. 9. π^+ spectrum, $\pi^+ + 4n$ channel. (a) 5-MeV bins, (b) 1-MeV bins around threshold for n^4 production.
- Fig. 10. Some observed levels and thresholds for the $A = 4$ system.
- Fig. 11. A comparison of the observed with the computed spectra, $p + 3n$ channel.
- Fig. 12. Proton spectra.
- A. Phase space.
 - B. Phase space distorted by n - n interaction.
 - C. Breit-Wigner fit for a 3- n system unbound by 15 MeV, and a width $\Gamma = 65 \times 10^{-8} k^3$ (k in MeV).



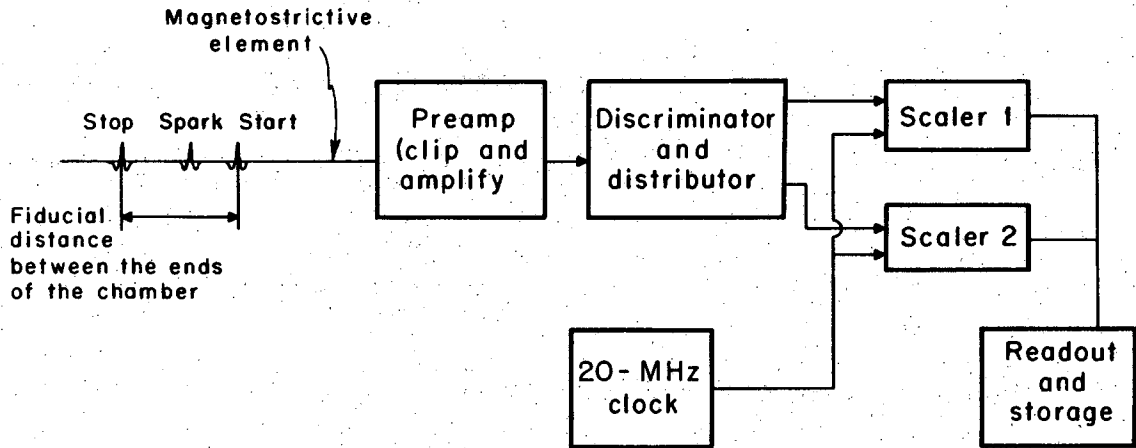
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Fig. 1



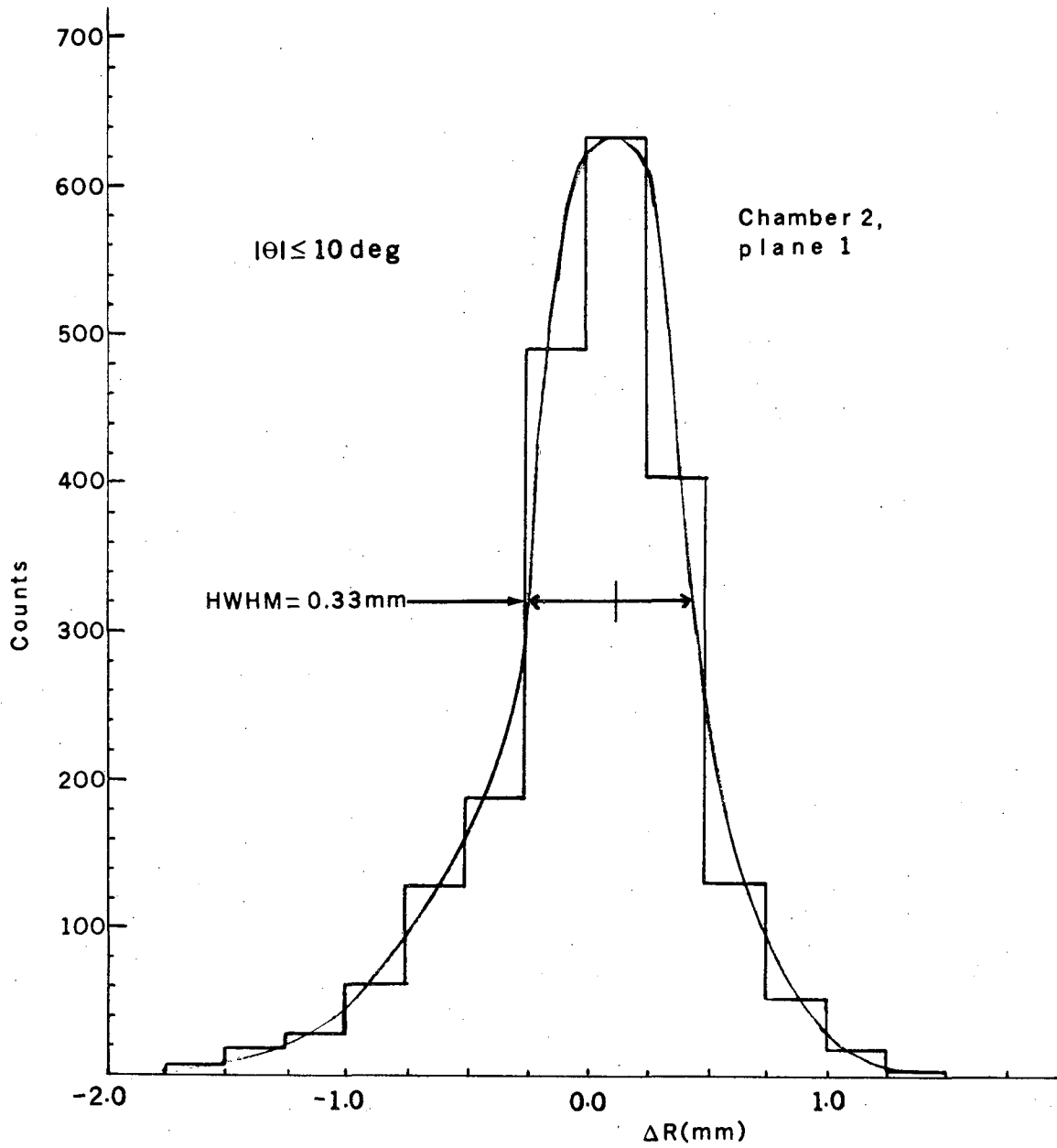
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Fig. 2



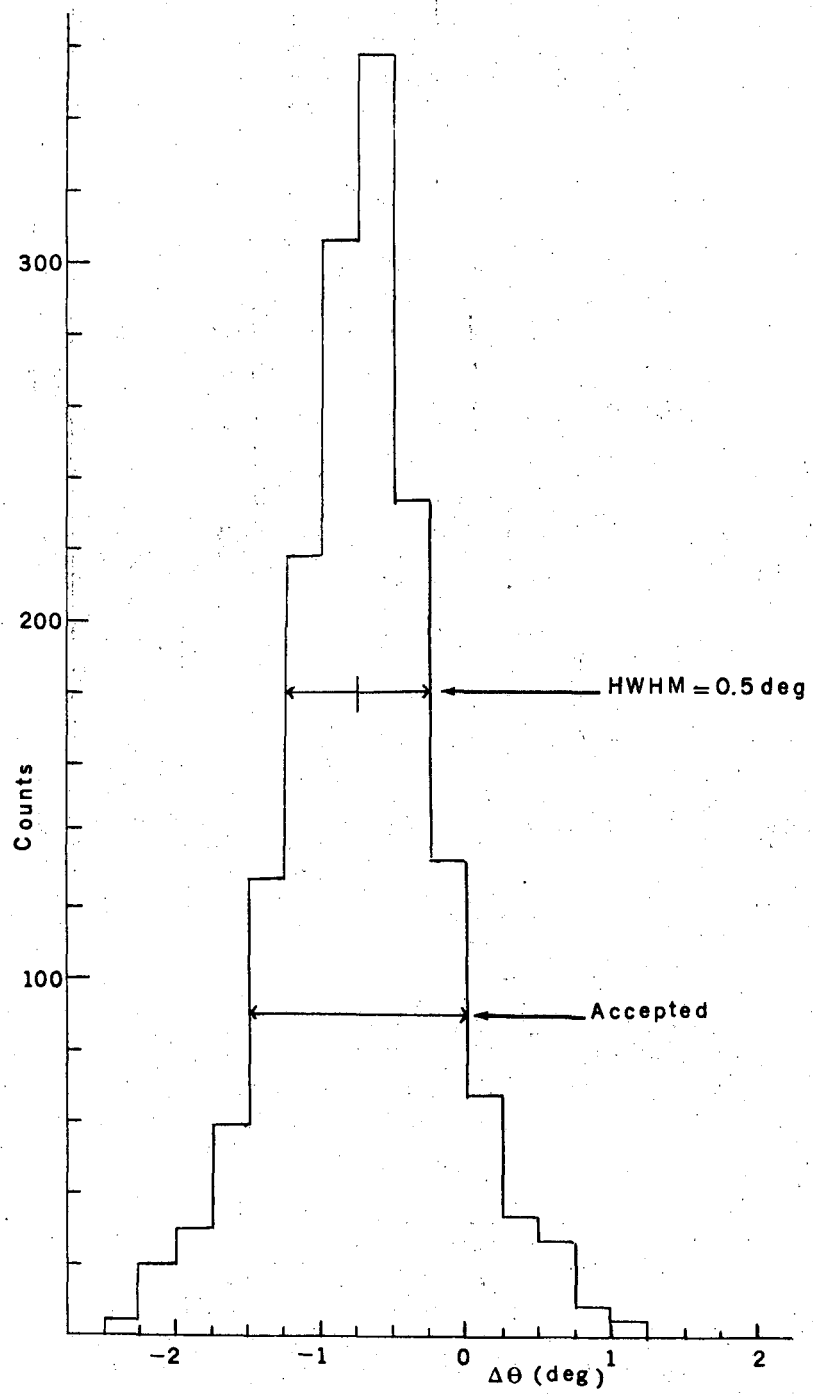
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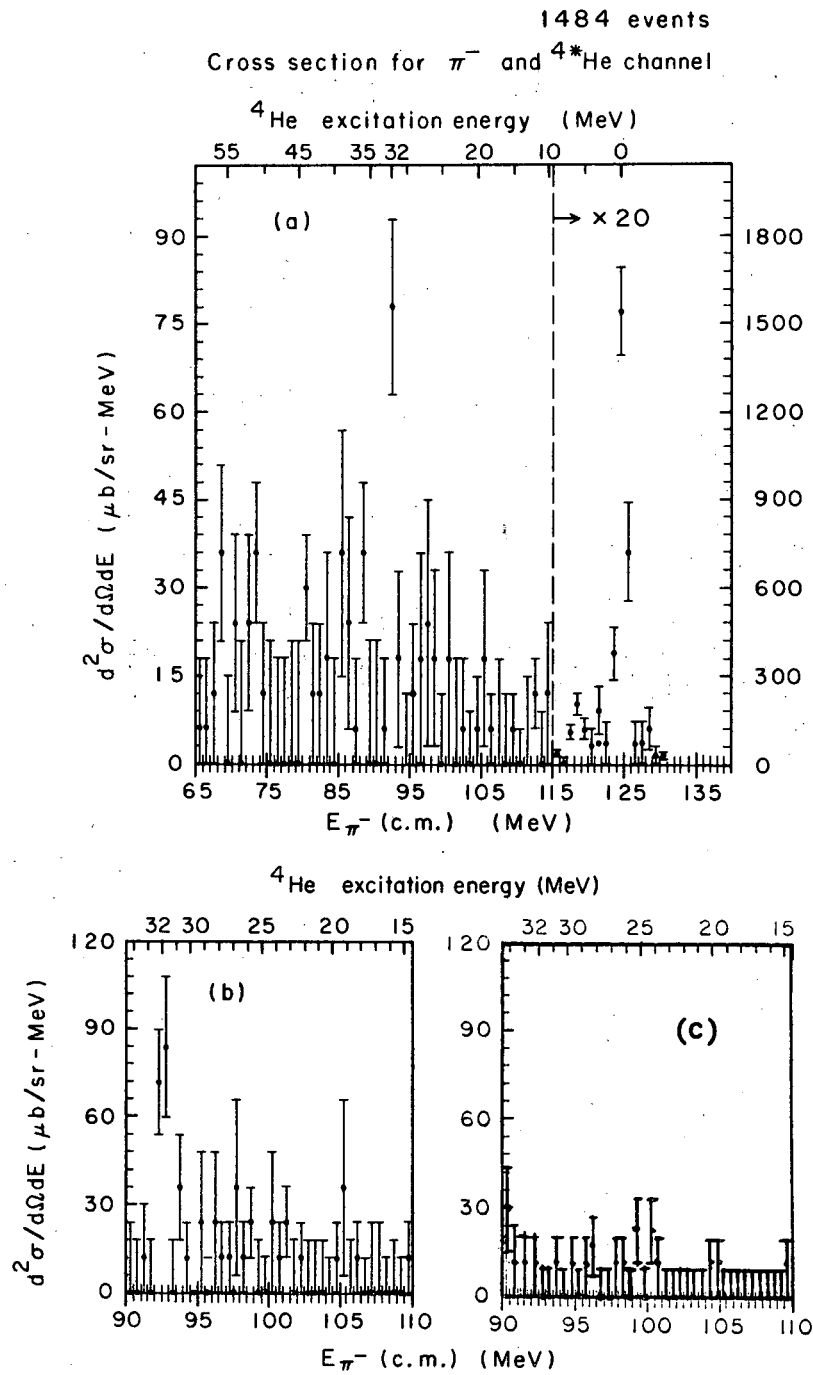
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Fig. 4



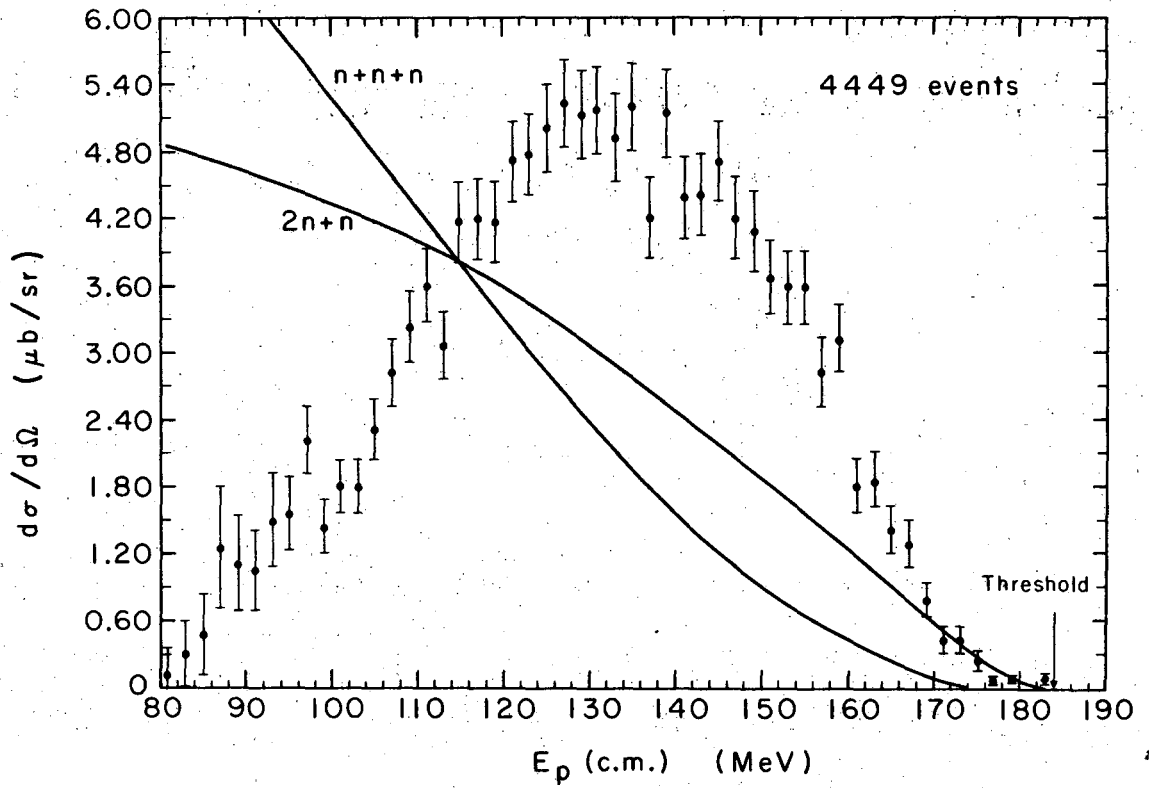
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Fig. 5



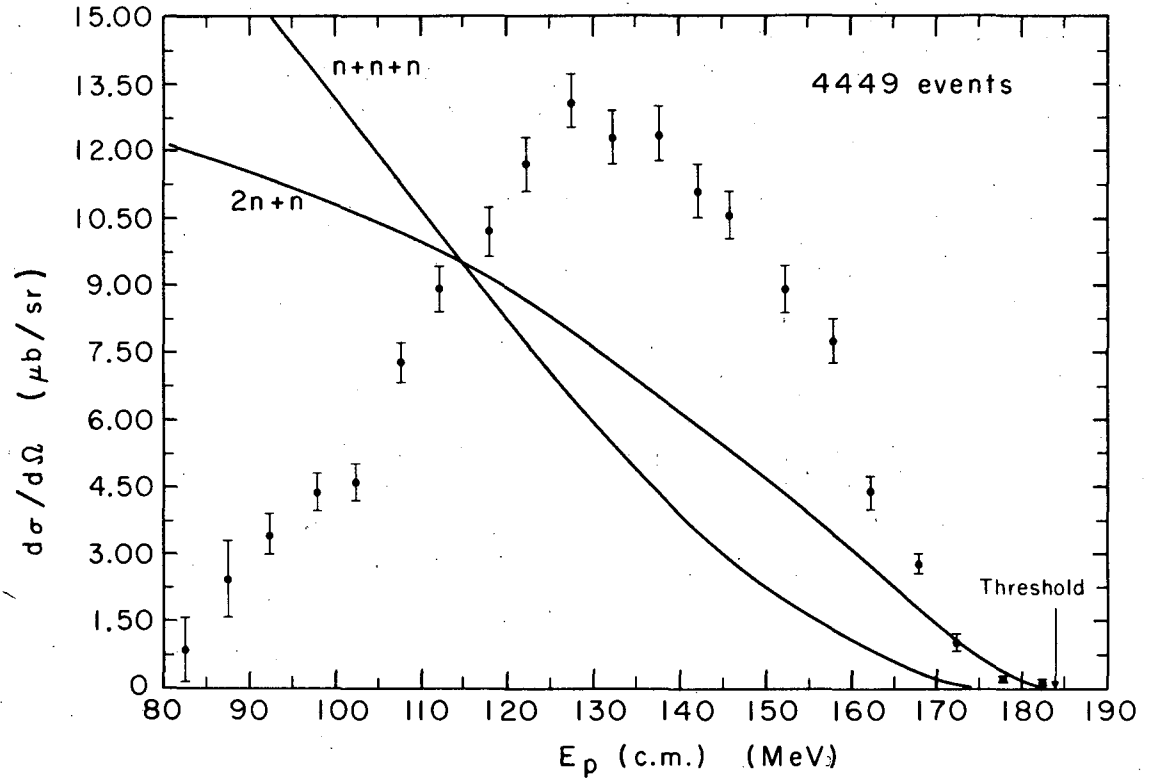
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Fig. 6



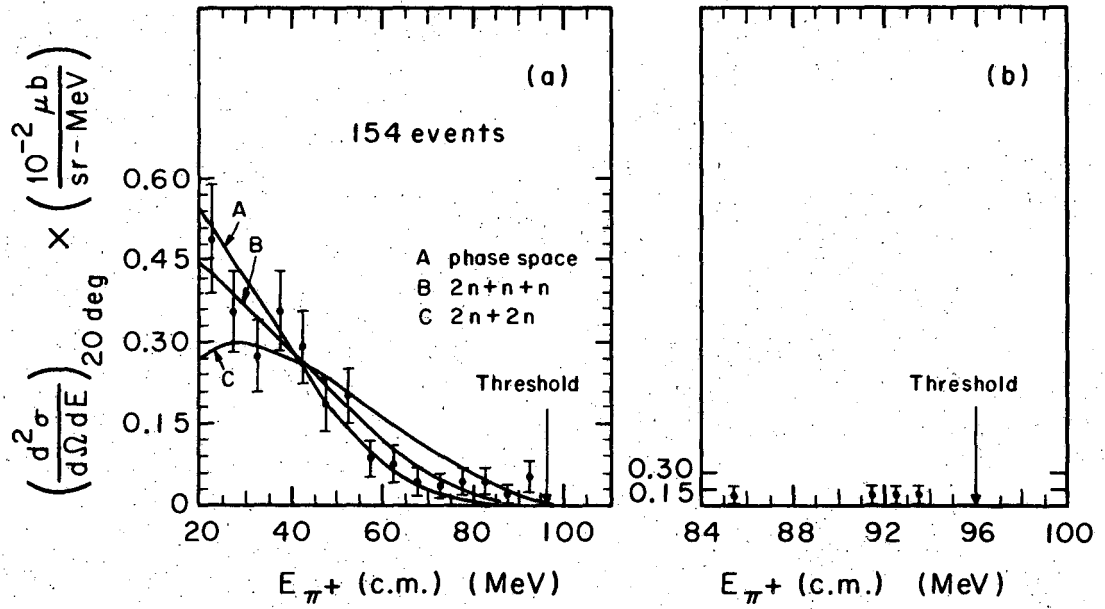
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Fig. 7



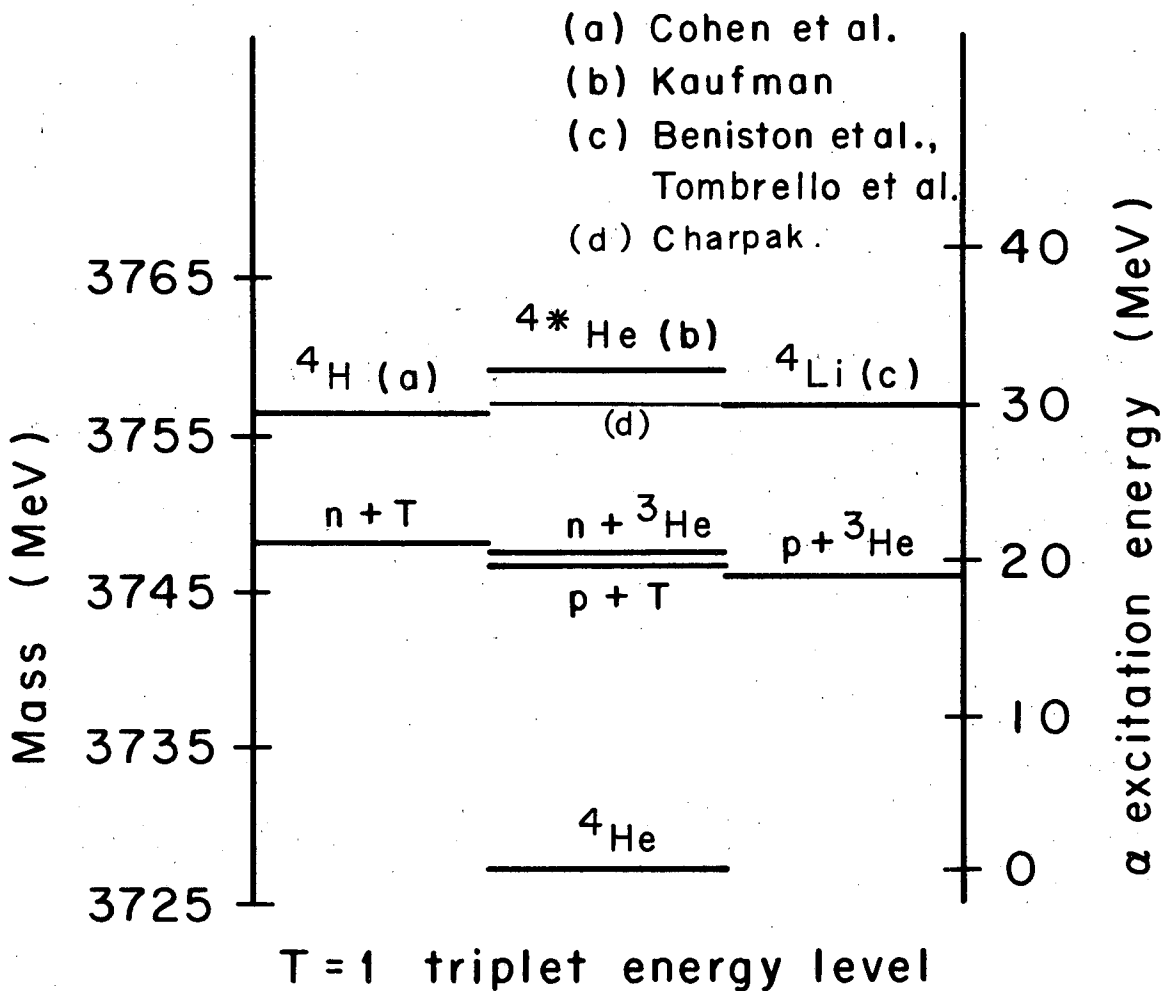
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Fig. 8



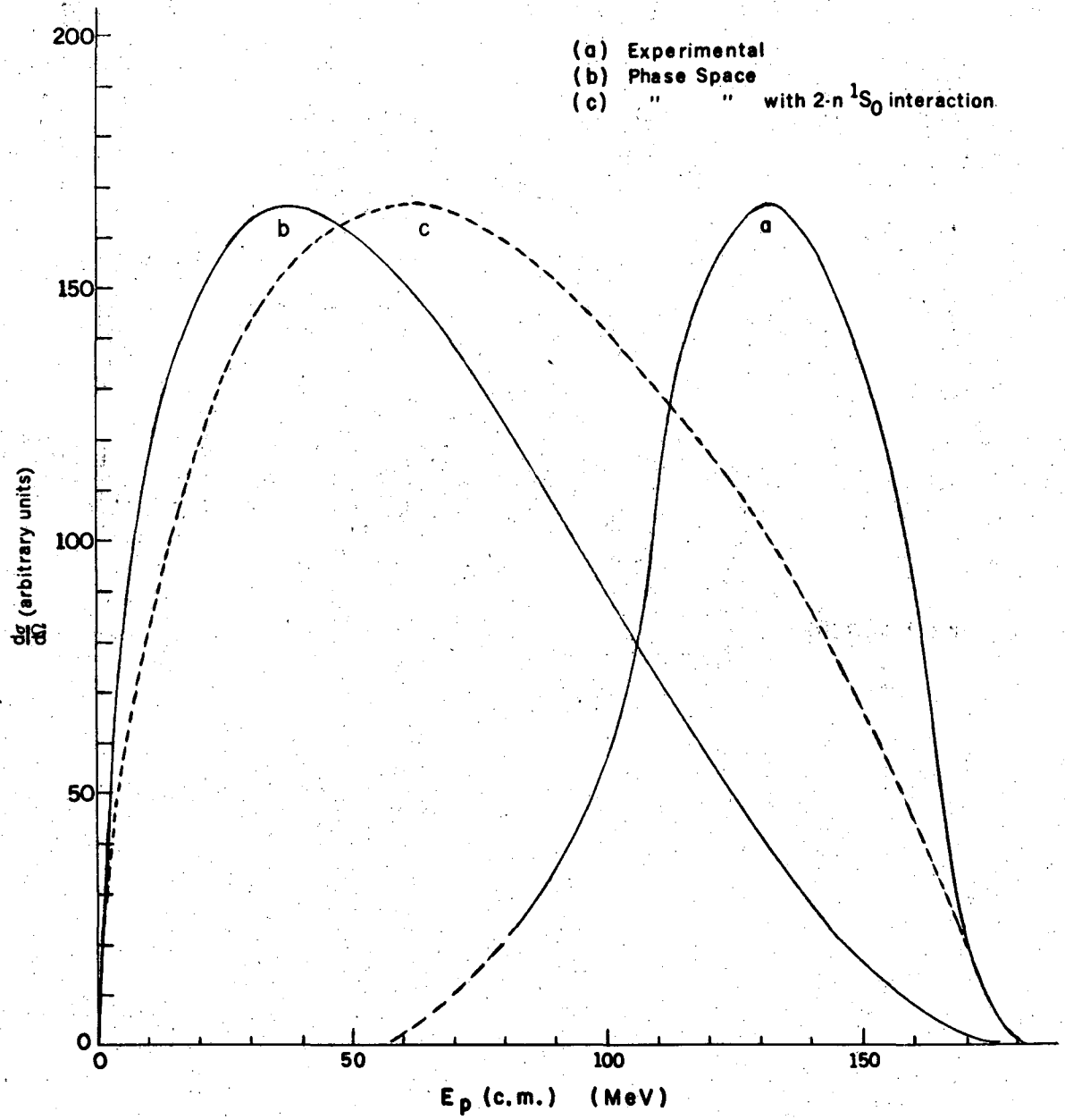
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Fig. 9



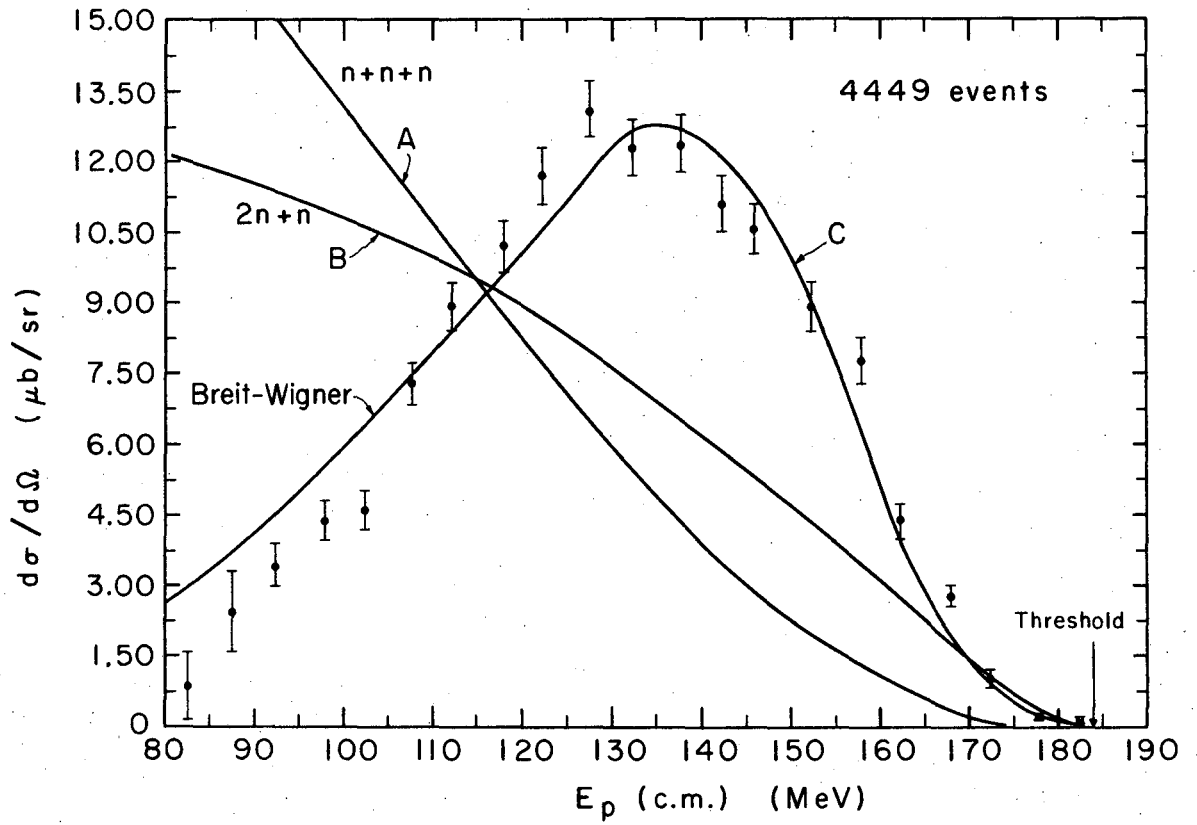
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Fig. 10



XBL677-3595A

Fig. 11



XBL676-3298-A

Fig. 12

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