Interactions of 28-Mev Protons with Helium-4†*

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When He^4 is bombarded with 28-Mev protons the dominant reaction is elastic scattering, exhibiting a strong peak in the forward direction and a slight rise in the backward direction. The dominant inelastic reaction is the inverse Butler or pickup deuteron process.

The two remaining inelastic reactions observed, $He^4(p,2p)H^3$ and $He^4(p,pn)He^3$, have cross sections of 8.9 ± 1.0 and 4.8 ± 1.3 mb, respectively. These are an order of magnitude or more smaller than the cross sections of the dominant processes.

Of the remaining possible reactions—(p,pd), $(p,n2p)$, $(p,p\gamma)$—only the last was energetically possible at the beam energy used. It was not observed. This indicates a lack of evidence for an excited level that decays principally by γ-ray emission; it also indicates that the inverse photodisintegration process, suggested by Flowers and Mandl, has too small a cross section to contribute in this energy region.

The rest-frame momentum spectrum of protons from the $He^4(p,2p)H^3$ reaction shows no evidence of an excited level in He^4 in the energy region explored.

I. INTRODUCTION

THE possibility of an excited level in the helium nucleus has been discussed in the literature at various times for two decades. Feenberg[1] in 1936 predicted at least one stable excited state for He^4. His work was reviewed and the problem further discussed by Bethe and Bacher[2] in the same year. On the basis of what was then known about nuclear forces they predicted three possible levels, two of which were supposed stable at 16 Mev and 10 Mev. Bethe and Bacher had available the experimental work of Crane *et al.*,[3] a study of the reaction of protons on Li^7 in which a 16-Mev γ ray had been detected. One of the possible interpretations suggested by the experimenters was

$$p+Li^7\rightarrow He^4+He^{4*}\rightarrow He^4+He^4+\gamma,$$

rather than the present-day interpretation $Li^7(p,\gamma)Be^8$. Subsequent knowledge, in particular the discovery of other than ordinary forces, invalidated the early theoretical predictions.

In 1949 several experimenters,[4–6] using thermal neutrons, observed the reaction $n+He^3\rightarrow He^{4*}$. King and Goldstein,[4] at Los Alamos, found no evidence of an excited state in He^4 in the energy region close to 20.5 Mev. Their work was extended in 1950 by Taschek *et al.*,[7,8] who used protons up to 2.5 Mev and observed the reaction $H^3(p,\gamma)He^4$. They detected a group of γ rays, showed that $E_\gamma>17.5$ Mev, and concluded that the γ-ray yield indicated an excited state in He^4 at about 21.6 Mev with a half-width of 1 Mev.

The publication of these results was followed by a theoretical paper by Flowers and Mandl in England.[9] Flowers and Mandl calculated the inverse process—the photodisintegration of He^4. A phase-space inversion was used to compare their theory with the Los Alamos data. The results indicated that the observed γ rays could have been part of an electric dipole emission spectrum; thus, the introduction of He^4 excited state was possible, but not demanded.

In 1952 a comprehensive search for an excited state was completed by Benveniste and Cork,[10] who used a counter telescope to detect protons and deuterons scattered from a 31.5-Mev linear accelerator proton beam by a helium target. They found no evidence of excited states in the energy region they were able to to investigate. Because of the energy cutoff limit required by the counter telescope, they would not have been able to detect a small group of protons having a range less than 50 mg/cm² (5 Mev). Since this brings the energy cutoff point in their experiment rather close to the region in which the Los Alamos workers observed an excited level, it was deemed desirable to use a cloud chamber to confirm and extend their results.

Shortly after the present work was started, a theoretical paper was published by Trainor.[11] On the basis of symmetry arguments Trainor concluded that the existence of an excited state at 21.6 Mev with a strong dipole-moment transition to the ground state would

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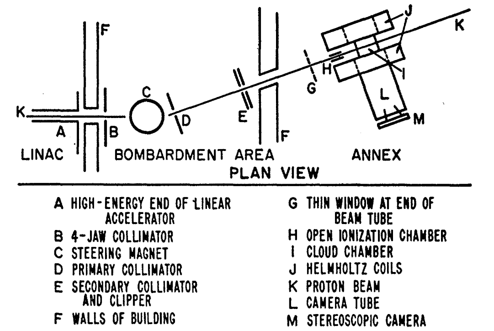

FIG. 1. Plan view of the experimental geometry.

imply the existence of a bound excited state in He^4. His paper included a summary of the experimental work done at that time.

In the present experiment the use of a cloud chamber made it possible to detect inelastic protons having a range greater than 1.8 cm (0.6 Mev), which should permit observation of an excited state below 22 Mev; in addition, the cloud-chamber technique was capable of of associating the inelastic protons with the various types of reactions that produced them since particle ionization, momentum of charged particles, and the number of charged particles per event could be determined.

The experiment was performed by admitting the linear accelerator proton beam directly into a cloud chamber filled with helium. The cloud chamber was mounted between a pair of pulse-operated Helmholtz coils that produced a magnetic field transverse to the beam. A plan view of the experimental arrangement, including some of the details of collimation, is shown in Fig. 1. Additional details of the technique and the accuracy of measurements are discussed in Secs. III, IV, and V.

II. RESULTS

In this experiment four interactions could occur when protons were scattered in helium: (a) elastic proton-helium scattering; (b) pickup deuteron processes; (c) $He^4(p,2p)H^3$ collisions; (d) $He^4(p,pn)He^3$ collisions. They are listed here in order of decreasing abundance. More complicated processes were not possible at the energy available in this experiment.

A. Elastic Proton-Helium Scattering

The center-of-mass proton distribution resulting from elastic proton-helium scattering events is given by the circles in Fig. 2. Vertical lines on all cloud-chamber results indicate probable errors. Crosses represent the results obtained by Cork,[12] who used a counter telescope. The cloud-chamber results indicate that a minimum occurs at a c.m. angle of about 115 degrees. No attempt

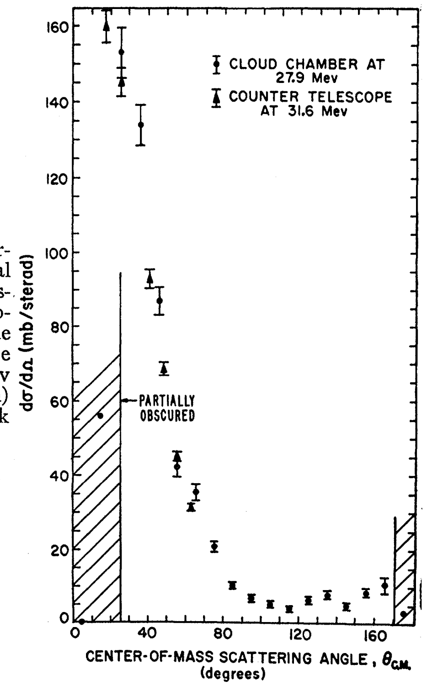

FIG. 2. Center-of-mass differential cross section for elastic scattering of protons on helium. The counter telescope data (at 31.6-Mev laboratory system) are taken from Cork (reference 12).

was made to subtract Coulomb scattering from the forward peak. The normalization at 27.9 Mev was achieved by interpolation between Cork's results at 31.6 Mev and at 19.5 Mev.

Normalization to Cork's results permitted the assignment of absolute cross sections to cloud-chamber data. The normalization factor obtained and used in the construction of Fig. 2 is $d\sigma/d\Omega=0.1643N$, where $d\sigma/d\Omega$ is in millibarns per steradian and N is the number of events seen in the cloud chamber in a 10° interval of scattering angle θ and in an azimuthal range of $-45°\leqslant\phi\leqslant+45°$. From this result one can compute the normalization factor for total cross section,

$$\sigma=0.0901(\Phi\Theta)n,$$

where σ is in millibarns, n is the cloud-chamber event count, and the factors Φ and Θ (given in Table I) are inserted to correct for the limited visibility in azimuth angle ϕ and polar angle θ.

B. Pickup Deuteron Process [$He^4(p,d)He^3$]

The c.m. angular distribution for pickup deuterons, $He^4(p,d)He^3$, is given by the circles of Fig. 3. The triangular marks represent the results of Benveniste and Cork,[10] and the solid line is given by Butler's theory for 31.6-Mev bombarding protons.[13] Because the spin of He^4 is known the results are primarily only of interest in checking the reliability of the cloud-chamber technique. For the cloud-chamber data the vertical scale indicates differential cross section, obtained by normalization to the elastic $p-\alpha$ scattering results.

[12] B. Cork, University of California Radiation Laboratory Report UCRL-1673, February, 1952 (unpublished).

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TABLE I. Results of various reactions of 28-Mev protons with helium-4.

1 Type of event	2 Number observed	3 Number observed, $\|\phi\| \leq 45°$	4 Azimuthal visibility (per event) $(\Phi)^{-1}$	5 Column 3, corrected for azimuthal visibility	6 Polar angle visibility $(\Theta)^{-1}$	7 Column 5, corrected for polar-angle visibility	8 Total cross section σ (millibarns)
Elastic $p-\alpha$		2125	$\frac{1}{2}$	4250			[a]
$He^4(p,d)He^3$	185	167	$\frac{1}{2}$	334			[b]
$He^4(p,pn)He^3$	9	7	$\frac{1}{4}$	28	0.527±0.032	53.1±34.9	4.8±1.3[c]
$He^4(p,2p)H^3$	58	40	$\frac{1}{2}$	80	0.813±0.036	98.4±11.4	8.9±1.0
$He^4(p,p\gamma)He^4$	Not observed						0.23[d]

[a] Differential cross section given in Fig. 2.
[b] Differential cross section given in Fig. 3.
[c] All errors are probable errors unless otherwise stated. In computing the errors shown here no attempt was made to include the fact that four events were seen that could not be identified.
[d] The value 0.23 mb is the median of the *a posteriori* distribution of the cross section, which has the density function $(0.693/0.23)\exp(-0.693\sigma/0.23)$ per mb.

C. $He^4(p,2p)H^3$ Collisions

A differential cross section in θ cannot be given for the $(p,2p)$ event because of the several ways in which it can be observed: as two protons; one proton and one triton; two protons and one triton. A total cross section is given in Table I. In only 10 out of the 58 of these events observed were all three particles visible.

The c.m. proton momentum distribution of the $(p,2p)$ events (Fig. 4) shows a peak at $B\rho=1.8\times10^5$ gauss centimeters, or about 1.6 Mev. This observed proton spectrum is interpreted as arising from the bombardment of a He^4 nucleus in which there are no energy levels, i.e., from a process in which the transition matrix is independent, or a slowly varying function, of the final momentum of the beam proton.

The resultant momentum distribution of such transition is dependent not only on the nature of the transition matrix but also on the density of energy levels, or phase volume, in the final state. The computation of the unrestricted phase volume available to a proton from this reaction gives the result

$$V=N\int_0^{p_0} p^2(p_0^2-p^2)^{\frac{1}{2}}dp=\frac{N\pi}{16}p_0^4,$$

where p_0 is the maximum proton momentum possible (determined to be 2.05×10^5 gauss cm from the beam energy) and N is a constant. N was chosen by equating the phase volume to the area under the momentum histogram representing the experimental results. A plot of the integrand is the differential proton momentum distribution in momentum space to be expected when the transition matrix is nearly constant. The maximum value of the integrand is

$$p_{\max}=(\sqrt{\tfrac{2}{3}})p_0=1.67\times10^5 \text{ gauss cm.}$$

A plot of the integrand is shown in Fig. 5. The curve agreed well enough with the experimental points to encourage correcting it for the photographic visibility limitations of the cloud chamber.

To study the effects of the scattering angle and momentum limitations, regions of limited visibility were mapped on $p-\theta$ planes, where p is momentum in the laboratory system and θ is the laboratory scattering angle, by geometrically reconstructing and computing the visibility of the protons and tritons in the cloud chamber. From the results of such plots it was seen that the size of the limited visibility region in θ and p was a very slowly varying function of ϕ, the azimuthal angle. The region for $\phi\leq55°$ was then transformed into the c.m. system and plotted on a $(p')^2-vs-\cos\theta'$ plane, where primes indicate quantities referred to the c.m. system. Since $d(p'^2)$ and $d(\cos\theta')$ are elements of phase volume for one of the particles, the size of this region compared with the entire plane below the kinematical limit was now a measure of the region of limited visibility. From such graphs it was found that for $(p,2p)$ protons the volume of limited visibility was only 10.5% of the total volume available, and it appreciably affected the momentum distribution only in the region of 0.3×10^5 gauss cm. A similar computation for the tritons showed that only 5.6% of the triton space was excluded.

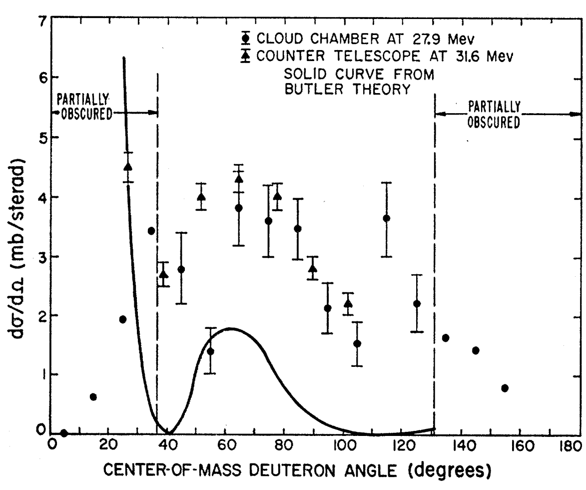

FIG. 3. Angular distribution (in the center-of-mass system) of deuterons from $H^4(p,d)He^3$. The counter telescope data at 31.6 Mev are taken from Benveniste and Cork (reference 10). The solid curve is given by Butler's theory (reference 13); the normalization of the curve is that of Benveniste and Cork.

From these results it was concluded that no significant differences between the observed spectrum and the phase spectrum would arise because of the regions in θ and p excluded by the presence of the beam.

The azimuthal angle limitation, $-45° \leqslant \phi \leqslant 45°$, cannot be so dismissed. It is large—half of the available geometric volume—and may have strong correlations with momentum. An as example of such correlation, consider that two prongs of a three-prong event are seen. Conservation of momentum then implies that frequently the azimuthal plane of the third prong will be perpendicular to the mean plane of the first two, and thus there is a high probability that the prong will be in an azimuthally excluded region.

Since such correlations could significantly affect the final momentum distribution, it was necessary to introduce functions representing the azimuthal limitations and recalculate the phase-volume integral. When suitable approximations were made the result was expressible in terms of elliptic integrals, which when evaluated gave the function shown as a solid line in Fig. 4.

This resultant corrected phase-volume curve agrees with the observed distribution in shape and in position of maximum. There is nothing in the observed spectrum to suggest a resonance, or energy level. Had there been a resonance one would have expected to see, in the c.m. system, a peak due to the bombarding proton and an additional broader peak consisting of decay protons.

D. $He^4(p,pn)He^3$ Collisions

Only nine $He^4(p,pn)He^3$ events were seen and identified. This did not imply a cross section small compared with that for $He^4(p,2p)H^3$. When appropriate allowance was made for the fact that the neutron could not be seen in the cloud chamber, the cross sections were found to be of the same order of magnitude. Seven of the events had azimuthal angles less than 45°, and only these were counted for comparing the yield with that of other types of events. Because of the small number of observations no angular distribution is given; however, the total number is used for the calculation of an absolute cross section (Table I).

No other events were observed. The fact that no positively identifiable $He^4(p,p\gamma)He^4$ events were seen is discussed in the section on analysis. This result places an upper limit on the cross section for $He^4(p,p\gamma)He^4$ events (Table I) and the process suggested by Flowers and Mandl.[9]

Table I summarizes the yields of the various reactions. Column 3 lists the number of events seen, identified, and satisfying the condition $|\phi| \leqslant 45$ degrees. Column 4 shows the factors that correspond to azimuthal visibility probability for the various events, and Column 6 those factors arising from the scatter-angle limitations on visibility. By normalization of the elastic proton-helium events to Cork's results,[12] total cross-section values are assigned to the different reactions in Column 8. These total cross-section values are obtained by assuming an isotropic c.m. angular distribution for the inelastic three-body reactions, an assumption borne out by experimental evidence obtained from the $(p,2p)$ reaction. Column 2 lists the total number of each type of event seen when azimuthal angle ϕ is unrestricted.

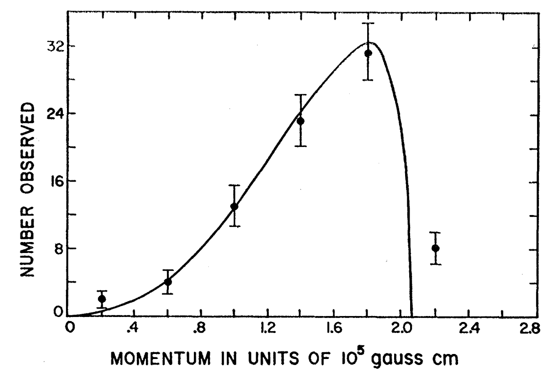

FIG. 4. Center-of-mass momentum distribution of protons from $He^4(p,2p)H^3$. The solid curve represents available momentum volume corrected for cloud chamber visibility limitations.

Notice that in Table I the polar angle corrections and the azimuthal angle corrections were handled as separate factors; i.e., possible correlations between the two effects were ignored. This was justified by simultaneously introducing both the azimuthal and polar-angle correction terms into the phase-volume integral and carrying out the integration graphically. This was done for the $He^4(p,pn)He^3$ type of event, an event for which the correction factors were largest. The result so obtained agreed to within 3% with the result obtained by considering the polar-angle correction as a separate and independent factor; consequently, it was assumed that the separate-factor correction procedure was also allowable for $He^4(p,2p)H^3$ events.

III. EXPERIMENTAL PROCEDURE

The beam of protons from the linear accelerator, shown in Fig. 1, was bent through a 15° angle by steer-

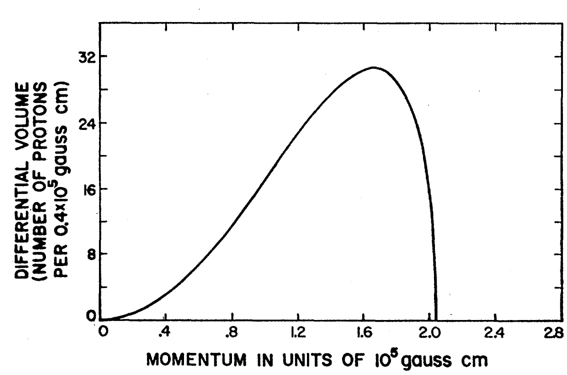

FIG. 5. Rest-frame momentum volume available to $He^4(p,2p)H^3$.

ing magnet C and passed through the 100-mil-diameter carbon collimator D. Fifteen feet from the magnet there was a $\frac{1}{8}$-in.-diameter collimator shadowing a $\frac{5}{32}$-in.-diameter collimator a foot beyond at F. The beam then passed through a thin window G, through a monitor ionization chamber H, and through an iron tube placed between the coils of magnet J. The iron tube provided shielding from the magnetic field. The beam entered the cloud chamber I in a field of 7000 gauss.

The sensitive volume of the cylindrical cloud chamber was 16 in. in diameter and 6 in. deep, and it contained $1\frac{1}{3}$ atmospheres of helium with water vapor. Pictures were taken every 2 minutes.

IV. ANALYSIS

Elastic events were easily recognized by their coplanarity and the low ionization of the protons. More than 2000 elastic scattering events were rapidly separated from the residual data.

The number of proton-proton scattering events was found to be consistent with the amount of water vapor in the chamber. The 23 oxygen events observed were obvious and easily discarded. Some 286 inelastic reactions remained to be analyzed.

The inverse Butler[13] or pickup-deuteron process $He^4(p,d)He^3$ is the only coplanar inelastic reaction observed. It is the most abundant inelastic reaction, accounting for 185 of the inelastic events. A calibration of the energy of the proton beam was made by use of such events. Since 18.3 Mev is needed to produce the two fragments, the beam-energy determination was relatively accurate: half the determinations fell within ± 0.36 Mev of the mean (27.88 Mev). A measurement of the curvature of the proton beam gave an energy of 28.2 ± 0.5 Mev, but the former value was used in the reduction of the data.

The remaining 101 events could consist of only the following three reactions in He^4: $(p,2p)$, (p,pn), and $(p,p\gamma)$. There was not enough beam energy to produce reactions more intricate than these.

The first two reactions were difficult to distinguish from each other chiefly because one of the prongs in the $(p,2p)$ reaction frequently was obscured by the proton beam. The identification technique involved the use of transverse and longitudinal momentum conservation; energy conservation; estimation of relative ionization; and, frequently, the identification of fragments from curvature and range measurements. When only two of the three prongs were observed, the measured energy and momentum balance had to be such that it would direct the unseen particle into a region of space in which particles could not be seen. Of course this criterion did not apply in the case in which the third fragment was the nonionizing neutron, but it was sometimes useful in separating the triton and He^3 reactions by elimination of the triton possibility.

This procedure resolved the remaining data into 58 $He^4(p,2p)H^3$; 9 $He^4(p,pn)He^3$; and no $He^4(p,p\gamma)He^4$ reactions; and a final residuum of 34 events analyzed as follows: 23 events which probably were inelastic collisions of protons with oxygen; 7 elastic proton-helium collisions of slightly degraded energy (20 to 25 Mev); and 4 unidentifiable reactions.

The work of Argo and others at Los Alamos indicated that the reaction $H^3(p,\gamma)He^4$ existed, and suggested the possibility of a level in helium in the region of 21 to 23 Mev.[7,8] Because 28-Mev protons can supply enough energy to the c.m. system to produce an excited state of He^4 in this energy range, a search was made for the reaction $He^4(p,p\gamma)He^4$, but no events were found that could be identified as such. Since the reaction $He^4(p,d)He^3$ can imitate the approximate coplanarity of the gamma-ray reaction and can also imitate it in relative ionization, an additional study of all (p,d) events was made.

The momenta of all the deuterons were transformed to the c.m. system, where their values were found to group around 3.1×10^5 gauss centimeters. Now if there were a level in the 21- to 23-Mev region, and if this level decayed by gamma emission, and if the momenta of the excitation protons associated with such a process were mistakenly transformed into the c.m. system as deuterons from a (p,d) reaction, then their transformed momenta would have appeared in the region of 0 to 2.1×10^5 gauss centimeters. No such momenta appeared.

A similar statement cannot be made concerning possible confusion of $(p,p\gamma)$ events with $(p,2p)$ events. However, it is seen from the c.m. momentum spectrum of $(p,2p)$ protons that no significant contribution to that spectrum could have been made by protons of constant momentum.

In addition, at the close of the analysis all the remaining inelastic reactions—$(p,2p)$ and (p,pn)—were specifically re-examined for any possible $(p,p\gamma)$ reactions, but none was found. A re-examination of the residuum disclosed nothing that could reasonably be identified as a $(p,p\gamma)$ reaction.

V. ERRORS AND CORRECTIONS

It has been shown that the identification of an event required measurements of range, radius of curvature, scattering angle, magnetic field strength, and beam energy. Determination of beam energy has been included in the discussion of pickup deuteron analysis in Sec. IV.

The probable error in range measurement was ± 3.6 mm, of which 2 mm was caused by straggling and 3 mm was caused by uncertainty in the position of the origin of a track (a point that had to be determined by projection back into the opaque beam). The range-energy calculation was checked by comparing the measured range of several elastic α recoils that stopped in the chamber with the energy of such recoils, the energy being computed from

$$E_\alpha = \frac{4E_0 M_\alpha M_p \cos^2\theta_\alpha}{(M_\alpha + M_p)^2},$$

where E_0 is the beam energy and θ_α the measured scattering angle of the α recoil.

Radius of curvature was measured by matching templates to stereoscopically reprojected images of the tracks. From the result of several tests it has been our experience that the error made in this measurement is about 0.1 mm in the sagitta, irrespective of the particular curvature and track length available. For a typical track such error in sagitta is equivalent to a probable error of $\pm 2.4\%$ in radius of curvature. From the calculation of the root mean square deflection owing to multiple scattering, again for a typical track, it was estimated that there would be an additional probable error in radius of curvature of $\pm 3.0\%$. Thus the total probable error in radius of curvature was about $\pm 3.8\%$ and the probable error in $B\rho$ also $\pm 3.8\%$, the error in B being negligible.

The magnetic field was determined by recording the peak current reading of each pulse during the running time of the experiment. After the experiment the field was measured with a search coil and integrator. These were electronically synchronized with the cloud chamber cycle so that the field value was measured at the instant the beam pulse of protons traversed the chamber. Measurements were taken throughout the volume occupied by the cloud chamber. The search coil and associated equipment was calibrated in a test field, the test field in turn being measured by a proton magnetic moment apparatus. The results, thus obtained, expressed magnetic flux density in terms of current readings taken on the same ammeter that was used in the course of the experiment. The probable error in the field measurement was $\pm 0.3\%$, which is small compared to the errors in curvature measurements of individual tracks.

The scattering angle, θ, was calculated from $\cos\theta = \cos\alpha \cos\beta$, where β, the beam angle, is the angle between the beam and the projection of the track onto a horizontal plane, and α is the angle of elevation of the track from the horizontal plane. By means of optical reprojection apparatus the elevation angle could be determined within $\pm 0.6°$, and the beam angle within $\pm 1.0°$. There was, however, an additional error of $\pm 0.5°$ in β owing to the necessity of projecting back into the opaque beam to the origin or the event; this value, $\pm 0.5°$, derives from a probable error in ρ of $\pm 3.8\%$. For a typical track the preceding errors combine to give a probable error of $\pm 1.03°$ in scattering angle. In addition, there were errors in the measurement of scattering angle owing to multiple scattering, $\pm 0.2°$; determination of initial direction of the beam, $\pm 0.5°$; measurement of curvature, $\pm 0.2°$; and divergence of the beam as it traversed the cloud chamber, $\pm 0.7°$. Thus the total probable error in scattering angle was $\pm 1.4°$.

The preceding discussion of errors in $B\rho$ and θ pertains to a "typical" track (that of a 2-Mev proton) and is not meant to be representative of the errors in measurement in all types of tracks. In the case of pickup deuterons, for example, the probable error in a single observation of center-of-mass momentum of a deuteron was $\pm 7.02\%$, expressed in percent of the arithmetic mean of the center-of-mass momenta. In the case of short prongs, associated with many of the inelastic events, errors in measured scattering angle were as large as 5 to 10 degrees. On the other hand, the probable error in a measurement of scattering angle of elastic proton-proton collisions was only $\pm 0.63°$; here the probable error was computed on the basis that the angle between the tracks should be very close to 90°. These events came from the water vapor present in the cloud chamber, and the relatively high energy of the recoiling particles permitted the greater accuracy in the measurement of scattering angle.

For the proton-helium elastic collisions, geometrical calculations indicated that all events were visible over an azimuthal angular range of $\pm 45°$ when the protons were scattered between 25° and 170° in the center-of-mass system. This was verified in the forward direction by comparing the angular distribution with that obtained by Cork (Fig. 2). In addition, a histogram was made of the number of observed elastic collisions *vs* azimuthal angle, and this also indicated that events with tracks lying between $\pm 45°$ in azimuth and between 25° and 170° in scattering angle were always observed.

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