and thus the absolute single-particle cross sections. Other experiments which give the single-particle cross sections in this region of A (but for quite different kinetic energies) are $O^{16}(n,d)$ and its inverse and $O^{16}(p,d)$.

Besides this, the $A=14$ polyad has higher p^{10} states which are unique (i.e., only one multiplet) and the $N^{15}(p,d)$ experiment to these levels (involving *two* unique states) would supply other values of the single-particle cross section for different kinetic energies and excitations. Table III lists all the higher states with their S values (few if any of these states have yet been experimentally identified). Besides these, there are three states with $T=0$, $J=1$ and two with $T=1$, $J=0$; the S values are given by Eq. (2) but the vectors, of course, are different. For $T=1$, $J=2$ there are two states; P, D are the amplitudes for the ^{33}P and ^{31}D components respectively; in the jj limit $(p_{\frac{3}{2}}{}^{7}p_{\frac{1}{2}})$, S has the large value 15/4. Measurement of the cross sections to any of these states would be very interesting.[15] We emphasize too that experimental S determinations for the higher "nonunique" $A=14$ states would supply additional parameters which should be considered in any theoretical study of the $A=14$ polyad.

[15] The determination of the channel spin ratio by angular correlation measurements would also be useful. [See T. Auerbach, thesis, University of Rochester, 1954 (unpublished); and for the $(d,p\gamma)$ case, in particular, O. Hittmair, Z. Physik **143**, 465 (1955).]

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p-He^3 Scattering at 9.75-Mev Proton Energy*

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The differential cross section for the elastic scattering of 9.75-Mev protons from He^3 has been measured in the range of center-of-mass angles from 30 to 150 degrees. The cross section varies from 345 millibarns/steradian at 30 degrees, through a minimum of 18.2 mb at 110 degrees, and rises to 84.5 mb at 150 degrees. Comparison of the data with the distributions calculated theoretically by Swan gives only rough agreement, the closest being for ordinary forces in the four-body system. This conflicts with the good agreement obtained by Swan with the 14-Mev n-T data of Coon *et al.*, in which a symmetric exchange force scheme was clearly preferable.

INTRODUCTION

THE elastic scattering of protons by He^3 has been studied at Van de Graaff energies,[1] and more recently, a beam of He^3 ions from a cyclotron has been used to extend these observations to the neighborhood of 4 Mev energy in the center-of-mass system.[2]

Swan[3] has compared these lower energy data, together with the 14-Mev n-T scattering measurements of Coon, Bockleman, and Barschall,[4] to angular distributions derived from a model of the four-particle system based on the resonating group structure of Wheeler.[5] In the case of the n-T data, this theory agrees well with experiment, provided that a symmetric mixture of exchange forces is assumed. However, Swan's agreement with the p-He^3 experiments is quite poor. Regardless of the exchange force scheme invoked, the theory predicts a continually decreasing differential scattering cross section with increasing scattering angle up to about 5-Mev proton energy, whereas all the experimental distributions exhibit pronounced minima at around 90 degrees in the center-of-mass system.

The availability of a homogeneous beam of protons of approximately 10-Mev energy from the first section of the Minnesota linear accelerator has made possible the extension of these measurements into an energy region where the agreement between experiment and theory might be expected to improve, as evidenced by the 14-Mev n-T data.

EXPERIMENTAL, GENERAL

The Minnesota proton linear accelerator is built in three sections, exclusive of the 500-kev injector, which raise the beam energy to 10, 38, and 68 Mev, respectively. Protons deflected from the machine axis into the area where this work was done have a precise energy of 9.89 Mev, and are homogeneous in energy to ± 70 kev. The total proton current available after deflection was about 1.4×10^{-7} ampere, but the collimation used in this experiment reduced the beam intensity to approximately 5×10^{-9} ampere.

The scattering occurred in a two-foot diameter chamber which was built as a general purpose facility for

* Work supported in part by the U. S. Atomic Energy Commission.
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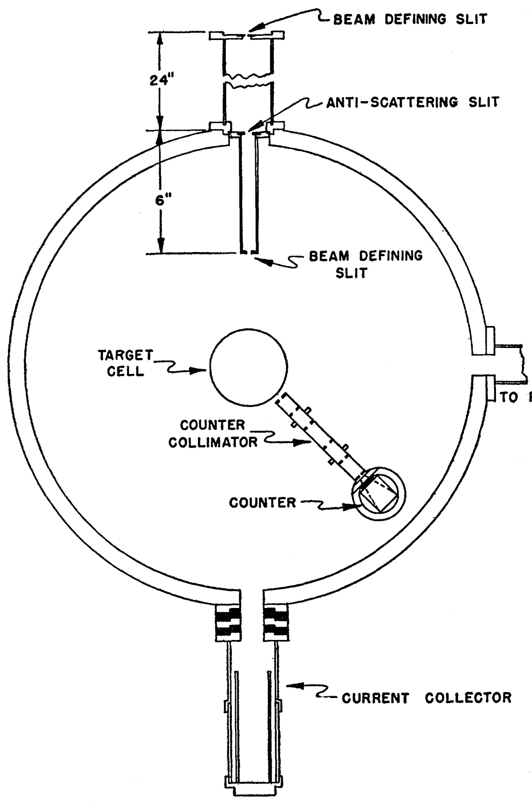

FIG. 1. General arrangement of scattering chamber.

this beam energy. Because of the very small amount of He^3 available, it was necessary to confine the target gas in a small, thin-walled cell at the center of the main chamber, such that the resulting pressure was high enough to be useful. Detection of the elastically scattered protons was accomplished with a scintillation counter and conventional associated electronics, and the total charge passed through the target gas was measured with an automatic-slideback current integrator connected to the Faraday cup at the output end of the scattering chamber.

SCATTERING CHAMBER AND COLLIMATION

The general layout of the scattering chamber is shown in Fig. 1. The chamber itself has an inside diameter of 24 inches and a height of 12 inches. The end covers are sealed to the side wall by O-ring gaskets. The top cover, rather than being bolted in place, as is the bottom, rests on a circle of roller bearings which allow rotation even under vacuum and thus make the cover useful as a rotating counter platform.

A system of three apertures punched in 0.010-inch tantalum sheet serves to collimate the incoming proton beam. The arrangement, as shown in the drawing, defines a beam having a maximum divergence of 0.00625 radian away from the central axis; however, the actual divergence is somewhat less, since the protons emerge from the deflecting magnet within a circle $\frac{1}{2}$ inch in diameter at a point 12 feet from the first collimating aperture.

The tube containing the counter collimators is mounted on the rotating cover, along with the counter itself. The two defining slits are approximately $\frac{1}{8}\times\frac{3}{8}$ inch, spaced 6 inches apart, with the front slit 3 inches from the center of the chamber. The resultant counter acceptance angle is ± 2.3 degrees.

COUNTER

The detector used in this apparatus is a scintillation counter employing a sodium iodide crystal and a DuMont 6292 photomultiplier. The tube is mounted parallel to the chamber axis in a well which protrudes into the chamber near the edge of the cover. Protons emerging from the counter collimating system enter the side of the counter housing near its bottom through a 0.0005-inch thick Dural window which separates the evacuated interior of the scattering chamber from the crystal region which is at atmospheric pressure. The crystal, a cleaved slab $\frac{1}{2}\times\frac{1}{4}\times 0.04$ inch and the end window of the phototube are cemented to two perpendicular faces of a Lucite prism which acts as a "light pipe." Activated alumina dries the air in the housing.

TARGET CELL

The cell used to contain the target of He^3 is one originally built for use in the multiplate scattering camera of Allred, Rosen, Tallmadge and Williams.[6] It is a cylinder $3\frac{3}{8}$ inches diameter by $1\frac{5}{8}$ inches high with a side wall of 0.0005-inch Dural, unobstructed except for a post on one side to which are attached the rigid end-plates.

GAS HANDLING

The He^3 sample used as the target for this experiment was stored between uses in a charcoal trap which was lowered to liquid nitrogen temperature just prior to each transfer of the gas to the target cell. Movement of the gas through the handling system was accomplished with a mercury Toepler pump. Contrary to usual practice, the absorbed impurities were not baked out of the charcoal after every removal of the He^3, since this would have resulted in a substantial loss of the He^3 itself, given the large number of gas transfers which were accomplished during the experiment. Rather, a careful watch was kept for contaminant peaks in the pulse-height spectrum from the counter; the energy resolution was good enough to allow clean separation of the He^3 peak from other peaks due to contaminants heavier than He^4 at any angle greater than about 40 degrees in the lab. When impurities were detected in

[6] Allred, Rosen, Tallmadge, and Williams, Rev. Sci. Instr. **22**, 191 (1951).

this manner, the trap was baked out before the following run. Figure 2(b) illustrates the separability of He^3 and air contaminant peaks at 38 degrees, lab. (50 degrees, cm for He^3).

Pressure measurement of the gas was done with a conventional mercury manometer and a precision cathetometer.

ELECTRONICS

The electronic circuitry associated with the counter is conventional in nature. Positive pulses from the last photomultiplier dynode were fed through a cathode follower into a Chase-Higinbotham amplifier, through a low-gain booster amplifier, and into a ten-channel analyzer of the Johnstone type.[7] The current integrator, designed by L. H. Johnston of this laboratory, is of the automatic-slideback type.

CALIBRATIONS AND SYSTEM TESTS

Measurement of the size and spacing of the counter collimator elements was done with a micrometer microscope and precision vernier calipers. The cross-section error resulting from uncertainties in these dimensions is given in the section on errors. Alignment of the beam collimator and counter collimator was accomplished by the use of optical systems sighting on a reticle needle placed at the center of rotation of the chamber cover.

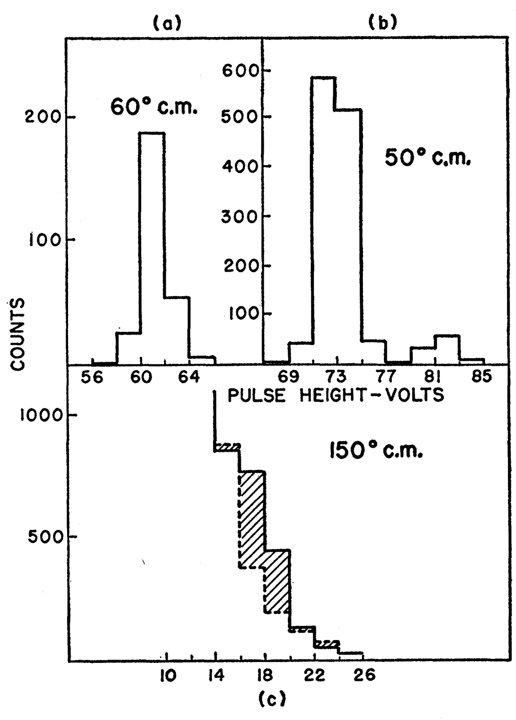

FIG. 2. Typical pulse-height distributions from the counter. (a) Protons scattered from pure He^3. (b) Protons from He^3 with a small higher energy peak from air contaminant. (c) Background subtraction at low energy. The shaded area represents true counts. (a) and (b) were taken at different amplifier gains and different collected charge; hence, they do not represent variations of cross section or pulse height with counter angle.

Calibration of the current integrator was done by the current-time method. A current of about 2×10^{-8} ampere was drawn from a potentiometer through a standard resistor for a time measured against WWV seconds markers. Correction was made for the slight variation of the integrator input voltage from zero due to the finite gain of the feedback loop.

Prior to the taking of p-He^3 data, the system was tested for: (1) angular symmetry, i.e., equal counting rates at equal indicated angles on either side of zero degrees, (2) counter background, (3) over-all calibration accuracy, obtained by p-He^4 scattering.

For the angular symmetry check, air was let into the target cell, and runs were made at $+30$ and -30 degrees where the differential cross sections for the elastic scattering of protons by nitrogen and oxygen vary sharply with angle. No significant difference in the counting rates at these angles was seen, where the number of counts taken would have clearly betrayed an angular error of $\frac{1}{3}$ degree.

Background tests of the counter were made with the target cell evacuated and closed off to allow for the effect of possible liberation of contaminants from the cell walls by the beam. It was found that the number of background counts corresponding to scattered protons of 3- to 10-Mev energy was almost negligible for angles greater than 25 degrees. However, at angles less than 25 degrees, the background was found to rise at a rapid rate with decreasing angle, and most of these counts were from protons of approximately the beam energy. After much searching, this background was accounted for, both as regards intensity and angular distribution by attributing it to a double Coulomb scattering in the walls of the target cell, the first occurring where the beam enters the cell, and the second taking place at that portion of the cell wall visible to the counter. This background placed a rather sharp lower limit of 20 degrees on the range of laboratory angles available for this experiment. A second troublesome background contribution came at counter pulse heights corresponding to proton energies of less than 3 Mev. The intensity of this background, which was present at all counter angles, rose exponentially with decreasing pulse height. Since the energy in the laboratory system of a proton scattered directly backward from He^3 is 2.5 Mev, even without the additional energy attenuation due to cell and counter window materials, it can be seen that again, a limit on the available angular range of the counter could be imposed by this background. It was concluded after extensive tests that several sources probably contributed to this contamination of the pulse-height spectrum; it appeared to be a mixture of neutrons and gammas from the cell walls, the last beam-defining slit, and the portion of the main chamber wall adjacent to the beam outlet port where the flux of

[7] C. W. Johnstone, Nucleonics 11, 36 (January, 1953).

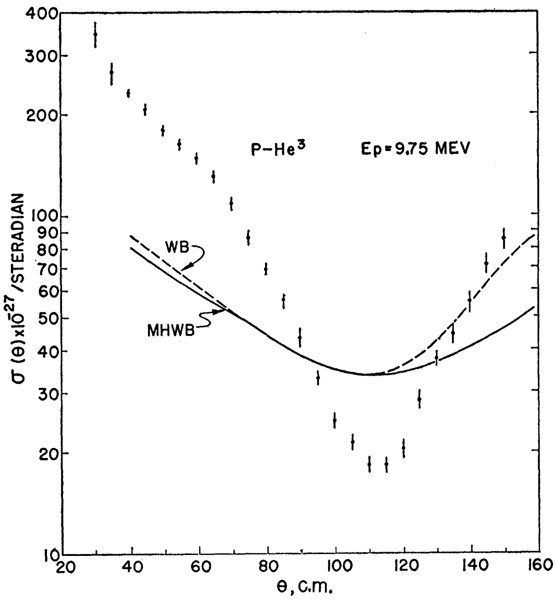

FIG. 3. Experimental results. Differential cross section *vs* center-of-mass angle for p-He^3 scattering. $E_p=9.75$ Mev. The dashed curve is Swan's predicted distribution for ordinary forces; the solid curve is for the symmetric exchange force mixture.

Coulomb-scattered protons was heavy. While this background was not eliminated entirely, the addition of a lead shield around the counter collimator allowed the useful counter angle to be extended to 140 degrees for this experiment.

The final system check was made by taking a partial angular distribution of protons scattered from He^4. Three other sets of p-He^4 data are available at this energy,[8–10] all in agreement as to the distribution at forward angles, with the results of one of the investigations[10] differing from the others by about 20% at rear angles. At the points measured here, approximately 40, 60, 90, and 120 degrees cm, excellent agreement with the results of Putnam was obtained.

ACCUMULATION AND TREATMENT OF DATA

In the actual measurement of the p-He^3 angular distribution, an effort was made to detect systematic errors which might have crept into the apparatus by taking each day's data at a wide range of angles, and making the following day's observations at points intermediate to these.

The combination of low gas pressure (9 to 15 mm Hg) and a maximum beam current of 6×10^{-9} ampere, together with the geometrical design of the counter collimator, proved restrictive on the total number of counts it was practical to accumulate for many of the points in the distribution. Also, the background subtraction necessary at the highest angles required the taking of very large numbers of counts in order to obtain only modest accuracy in the computed cross sections. Figure 2(c) illustrates the pulse-height spectrum for a run at 150 degrees, c.m. The shaded region represents true counts.

When all the observations on a particular point were completed, the several computed cross-section values were averaged, with each value weighted according to the inverse square of its probable error. The tentative error assigned to this average was the reciprocal square root of the sum of these weighting factors.

DISCUSSION OF ERRORS

In the computation of the total probable error for each point, the square root of the sum of the squares of the probable errors assigned to the geometrical factors, charge measurement, and pressure and temperature measurements was calculated, and this figure, which was taken as a constant for the experiment, was finally combined with the individual point counting errors to give the total uncertainty as quoted in Table I and plotted in Fig. 3.

The factors making up the constant error of 2.5% were the following: Geometry: counter slit geometry, 0.4%; angle measurement, including alignment, 0.5 degree, or 1% maximum corresponding cross section error. Current collection: meter reading error, 0.1%; calibration error 0.6%. Pressure measurement: 2%. Temperature: less than 0.5%.

RESULTS AND CONCLUSIONS

The angular distribution measured in this experiment for the scattering of 9.75-Mev protons by He^3 is given in Fig. 3, and the data are summarized numerically in Table I. The solid and dashed curves are the theoretical distributions obtained by Swan in his treatment of the four-body scattering problem using the resonating group structure method. The notation of Swan's paper is maintained, where WB designates ordinary forces, and MHWB is the symmetric mixture of exchange forces. Figure 4 gives the results of two additional scattering experiments of this type, the 14-Mev n-T

TABLE I. Differential cross section *vs* center-of-mass angle for p-He^3 scattering. $E_p=9.75$ Mev.

θ cm	$d\sigma(\theta)/d\Omega$ mb/sterad	Error mb/sterad	θ cm	$d\sigma(\theta)/d\Omega$ mb/sterad	Error mb/sterad
30	345	30	95	33.0	1.6
35	266	20	100	24.8	1.3
40	232	6.6	105	21.3	1.1
45	208	6.6	110	18.2	1.1
50	180	5.9	115	18.2	1.0
55	164	5.6	120	20.3	1.3
60	148	6.3	125	28.3	2.0
65	130	5.5	130	37.5	2.3
70	108	5.0	135	44.2	3.0
75	86.1	4.3	140	55.2	4.5
80	69.1	3.5	145	71.7	4.9
85	56.0	2.6	150	84.5	6.3
90	43.4	2.7			

[8] T. M. Putnam, Phys. Rev. **87**, 932 (1952).
[9] J. H. Williams and S. W. Rasmussen, Phys. Rev. **98**, 56 (1955).
[10] B. Cork and W. Hartsough, Phys. Rev. **96**, 1267 (1954).

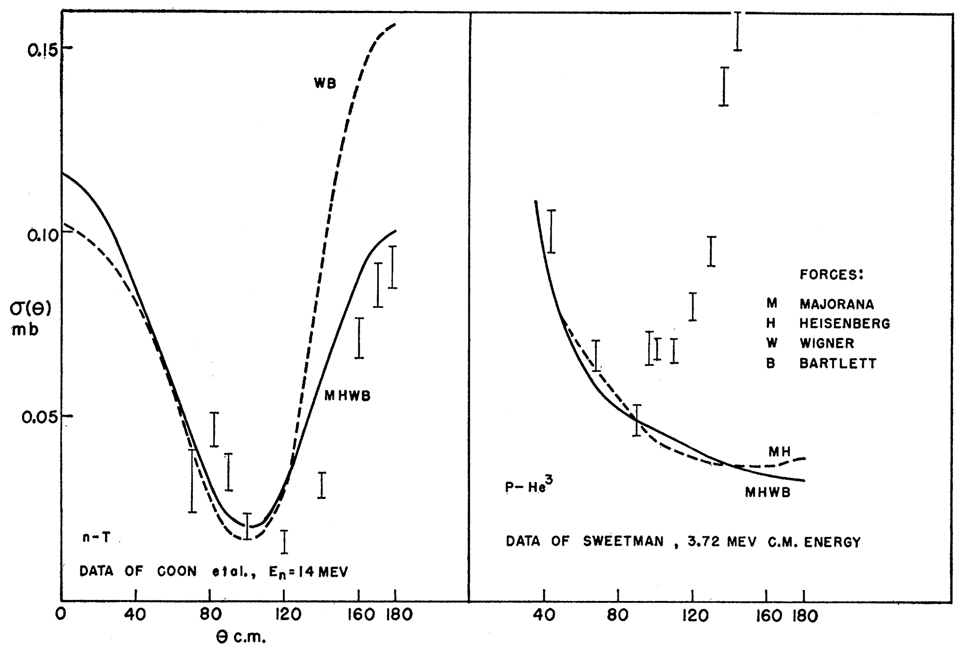

FIG. 4. The 14-Mev *n*-T data of Coon *et al.*, and the *p*-He³ data of Sweetman. The solid and dashed curves are the theoretical distributions of Swan.

data of Coon *et al.*, and the 3.72-Mev (cm) data of Sweetman, together with the predicted distributions.

It is of interest to note that while the results of the *n*-T experiment are fitted fairly well by the theoretical distribution based on the MHWB force mixture, the *p*-He³ data from the present experiment as well as that taken at lower energies does not confirm the theoretical predictions. The *p*-He³ data obtained by the Minnesota electrostatic accelerator group shows a distribution in angle similar to that of Sweetman, although their lower energy curves are displaced upward in cross section. In neither of these latter two sets of data, however, do the angular distributions exhibit the continually decreasing cross section with increasing angle that is required in Swan's analysis at these energies. The data of this experiment are in better agreement with the resonating group structure model only to the extent that both the theoretical and experimental distributions have minima at around 110 degrees; beyond this, the similarity is so rough as to hardly constitute real agreement at all.

Furthermore, the predicted curve which comes closest to matching the experimental data is the one calculated for ordinary forces, and this is in contradiction to the *n*-T case where the symmetric force mixture applies best. Various *n*-D scattering data at energies from 10 to 14 Mev[11–13] have also agreed very well with predictions based on the resonating group structure using symmetric forces.[14]

ACKNOWLEDGMENTS

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[14] Buckingham, Hubbard, and Massey, Proc. Roy. Soc. (London) **A211**, 183 (1952).