A series of measurements of the absorption of the Ir beta-rays in Al were made using an ion chamber with 1-mil aluminum window filled with Freon (CCl_2F_2) at 1 atmosphere, and which was connected to an FP-54 amplifier. The range obtained was 0.970 ± 0.030 g/cm^2. From Feather's empirical range-energy relation, as recently corrected by Widdowson and Champion,[27] we have energy (Mev) $= [0.165 \pm \text{range (g/cm}^2)]/0.536$. This gives a value of 2.11 ± 0.07 Mev for the end point, in good agreement with the spectrometer value. The absorption curve gives evidence for the presence of a soft gamma-radiation almost completely stopped by 3-mm of Pb.

The author would like to express his sincere thanks to Professor J. R. Dunning for the suggestion of designing the lens spectrometer described here, and for his constant advice and encouragement. He is likewise indebted to Dr. C. J. Davisson of the Bell Telephone Laboratories for his invaluable contributions to the theory outlined. The cooperation of Mr. M. Hartley Dodge and Mr. W. W. Kelley in supplying the copper tubing and the brass cylinder for the spectrometer is gratefully acknowledged.

The author wishes to express his sincere appreciation of the assistance given him throughout the work by his co-workers Miss E. Haggstrom and Father J. S. O'Conor; of the aid given by Dr. J. Steigman and Dr. A. V. Grosse in the chemical processes, and to the many others in the Department of Physics who have helped in designing and building the instrument.

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[27] E. E. Widdowson and F. C. Champion, Phys. Soc. Proc. **50**, 185 (1938).

JULY 1, 1941 PHYSICAL REVIEW VOLUME 60

The Scattering of One- to Three-Mev Protons by Helium

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(Received April 30, 1941)

The scattering of protons of from one- to three-Mev energy by helium has been experimentally examined for the existence of resonance scattering analogous to the neutron-helium resonance observed for one-Mev neutrons by Staub and Stephens. If *n-n* and *p-p* nuclear forces are equal, such a resonance should occur in *p*-He scattering for protons of approximately two Mev. The number of protons scattered through 140° were observed as a function of their energy. This number passed through a maximum at two Mev as expected, but the sharpness and height of the maximum were several times less than for the *n*-He resonance. However, this greater width and lesser intensity can be qualitatively justified. The number of protons scattered through 76° did not show the presence of a resonance scattering as the energy was varied. Observations of the angular distribution of the scattered protons for angles of scattering between 30° and 140° for proton energies of 1.0, 1.5, 2.0, 2.5 and 3.0 Mev, respectively, have been obtained.

Introduction

PROTON-helium scattering experiments for protons of energy one- to three-million electron volts are of especial interest because of the similarity of the proton-helium scattering problem to that of neutron-helium scattering. The dependence of the neutron-helium scattering cross section upon the neutron energy has been investigated experimentally by Staub and Stephens.[1] They have found that the ratio of the *n*-He cross section for the production of recoils to the similar *n-p* cross section is a maximum for neutrons of about one-Mev energy. This maximum they attribute to a resonance in the compound He^5 nucleus. The existence of this large amount of scattering of one-Mev neutrons by He has since been confirmed by a number of workers,[2]

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[1] H. Staub and W. E. Stephens, Phys. Rev. **55**, 131–139 (1939).

[2] E. Hudspeth and H. Dunlap, Phys. Rev. **57**, 971–975 (1940).

most of whom agree that the half-width of the maximum is about 0.5 Mev and the height about a factor of five. Recently Staub and Tatel[3] have found a splitting of this resonance into two peaks, with an energy separation of 0.4 Mev. Now Primakoff and Goldsmith[4] and others have pointed out that if one assumes the equality of *n-n* and *p-p* forces, except for the Coulomb forces in the latter case, there should be a similar resonance in the scattering of protons by He but that the resonance should be nearer two than one Mev, the difference being due to the greater Coulomb energy of the compound Li^5 nucleus as compared to He^5.

Previous proton-helium scattering experiments have been carried out by Roberts and Heydenburg[5] but they had available only protons of one-Mev energy and the observations were consequently below the interesting region. In fact they were able to detect only a small departure from Coulomb scattering. Experiments on the scattering of α-particles by hydrogen yield the same information as those on the scattering of protons by helium and have been performed by several workers.[6] These have been done with α-particles of up to 8.5-Mev energy which corresponds to protons of up to 2.1 Mev. These energies are not sufficient to carry the observations over the resonance peak, as found in our proton-helium scattering experiments.

In the present experiments artificially accelerated protons of up to three-Mev energy have been used, so that an investigation of the entire predicted resonance region has been possible.

APPARATUS

The protons used in this experiment were accelerated with our pressure electrostatic generator. A detailed description of the apparatus will be published in the future. The voltage was measured by means of a generating voltmeter calibrated in terms of the 0.867-Mev γ-ray resonance of fluorine and the 1.368-Mev γ-ray resonance of Al. The voltage on the electrostatic generator was manually monitored so that it did not fluctuate more than 50 kv during a run.

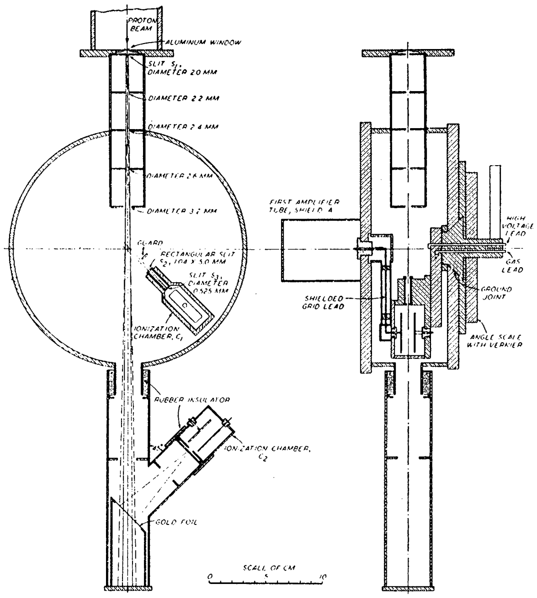

FIG. 1. Scattering chamber.

The scattering chamber used in these experiments was the same as that used by Heydenburg, Hafstad and Tuve in one of their proton-proton scattering experiments and has been described in detail by them.[7] A schematic diagram of the scattering chamber is given in Fig. 1. The magnetically analyzed proton beam from the electrostatic generator entered the scattering chamber through a thin aluminum window (0.0001-inch thick) and was defined by the indicated diaphragm system. The scattered protons entering slits S_2 and S_3 were detected by means of a parallel-plate ionization chamber C_1, connected to a linear amplifier and scale-of-eight counter. This chamber and attached defining diaphragms could be rotated from 0° to 140°. The guard shown in the diagram is to prevent protons scattered by the defining diaphragms from being counted. With the guard in, it was experimentally found that the number of counts in the absence of a scattering gas was negligible.

The beam was monitored by observing with the ionization chamber C_2 the number of protons

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[3] H. Staub and H. Tatel, Phys. Rev. **58**, 820–828 (1940).

[4] H. Primakoff and H. H. Goldsmith, Phys. Rev. **55** 1117 (1939).

[5] N. P. Heydenburg and R. B. Roberts, Phys. Rev. **56**, 1092–1095 (1939).

[6] J. Chadwick and E. S. Bieler, Phil. Mag. **42**, 923–940 (1921); C. B. O. Mohr and G. E. Pringle, Proc. Roy. Soc. **160**, 190–206 (1937)

[7] N. P. Heydenburg, L. R. Hafstad and M. A. Tuve. Phys. Rev. **56**, 1078–1091 (1939).

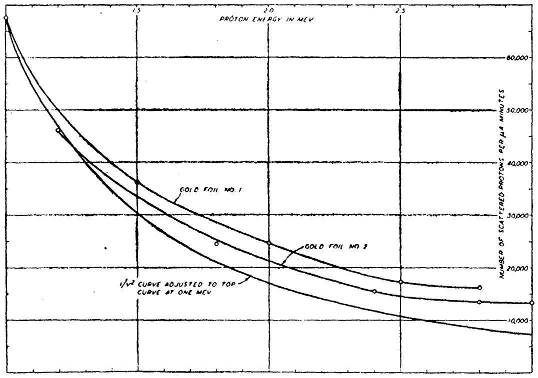

FIG. 2. Current calibration curve.

which were scattered from the gold leaf foil through an angle of about 135°. This gold foil count, however, was calibrated in microamperes of incident protons by simultaneously determining the average rate of counting of the monitor and measuring the current with an RCA amplifier microammeter when the scattering chamber was evacuated.

Most of the observations were made with helium of about ten-mm pressure in the scattering chamber. The helium pressure was measured with an Apiezon oil manometer. We used tank helium, purified by passing through a liquid-air-cooled charcoal trap. The helium in the chamber was tested for possible air impurity at the end of almost every run by a method which will be described in the next section.

PROCEDURE

At the beginning of the set of measurements, the scattering chamber was carefully aligned with respect to the beam direction. The generating voltmeter was calibrated in terms of the F and Al resonances at the beginning and end of the set of experiments.

During the observations the beam intensity was measured in terms of the number of protons scattered from the gold foil, but in a separate experiment this count was itself calibrated in terms of the number of microamperes of current entering the chamber when it was evacuated. This calibration was made for several proton energies between one and three Mev. The results are given in Fig. 2 for two different gold foils (foil No. 1 was damaged during the course of the experiments and was replaced by foil No. 2). While these two curves are similar in shape they are displaced, probably because of a difference in thickness and uniformity of the two foils. A Coulomb ($1/v^2$) curve, adjusted to fit the gold scattering curve No. 1 at one Mev, is also plotted. It is seen that the observed scattering is too large by about a factor of two at 2.8 Mev. This apparent anomalous scattering from gold was not expected and is probably not real. However, as the effect was reproducible and was repeated several different times in the course of the measurements, the curves of Fig. 2 were taken as a calibration of the number of microampere-minutes of current into the chamber corresponding to a given gold scattering count at different voltages. That this calibration was satisfactory was further verified by observing the proton scattering by argon at an angle of 30°. With the above calibration, the proton-argon scattering was found to be strictly Coulomb to within the experimental error of four percent for proton energies from 1.2 Mev to 2.8 Mev, the highest voltage for which these measurements were made.

As an additional check on the consistency of the apparatus, the angular distribution of protons scattered by He at one Mev was measured and found, in agreement with the earlier experiments of Heydenburg and Roberts,[5] to be purely Coulomb between 20° and 40°.

After these preliminary and consistency tests had been completed the actual observations were made by counting the number n_1 of protons scattered by the gas while another number n_2 was scattered from the gold. From these two numbers, from the measured voltage, from the gold scattering calibration, and from the geometry of the apparatus, the number N_S of protons scattered from the chamber per microampere per minute could be calculated. The method of calculation is the same as that of Heydenburg, Hafstad and Tuve[8] and, since the same scattering chamber was used, the geometrical constants are identical.

At the end of almost every run, the purity of the gas was tested by a simple scattering experiment. Since one-Mev protons scattered by He

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[8] M. A. Tuve, L. R. Hafstad and N. P. Heydenburg, Phys. Rev. **50**, 806–825 (1936).

through 140° lost so much energy that they could not be counted, the only countable protons of such an energy scattered in this direction were necessarily due to the presence of a heavier scattering gas such as air. Hence, by determining the number of countable protons so scattered, the amount of impurity of the gas could be determined. All observations were rejected if the amount of impurity was sufficiently great for any scattering observations at an angle greater than 39° to be appreciably affected by the Coulomb scattering of the impurity.

TABLE I. *Results of the scattering experiments.*

θ	Energy Mev	Ratio He/Au Scat. $\times 10^3$	Obs. N_S per μA Min.	Coulomb N_S per μA Min.	Ratio N_S Obs. to N_S Coulomb
76°	1.2	3.49	16.3	5.60	2.91
	1.8	9.70	24.3	2.49	9.75
	2.4	21.6	33.5	1.40	23.9
	3.0	25.1	33.9	0.896	37.8
140	1.2	5.45	25.6	1.44	17.8
	1.4	10.7	40.0	1.06	37.7
	1.6	17.8	54.8	0.809	67.8
	1.8	28.4	71.1	0.639	111
	2.0	35.6	75.7	0.518	146
	2.2	39.8	71.5	0.428	167
	2.4	42.0	65.1	0.359	181
	2.6	35.3	49.5	0.306	162
	2.8	33.8	45.6	0.264	173
	3.0	30.3	40.8	0.230	177
20	1.5	315.0	1065	1640	0.65
40		12.53	42.4	57.9	0.73
60		6.47	21.9	9.34	2.34
80		8.70	29.4	2.97	9.90
100		11.0	37.1	1.44	25.8
120		9.90	33.5	0.974	34.4
140		13.2	44.6	0.921	48.5
20	2.0	236	500	923	0.54
40		52.7	112	32.5	3.45
60		18.7	39.7	5.26	7.55
80		13.1	27.8	1.67	16.6
100		14.9	31.6	0.808	39.1
120		19.2	40.7	0.548	74.2
140		32.7	69.4	0.502	138
20	2.5	612	1055	590	1.79
40		11.9	204	20.8	9.81
60		35.9	61.9	3.36	18.4
80		18.8	32.4	1.07	30.6
100		16.9	29.2	0.517	56.5
120		23.8	40.9	0.351	116.5
140		34.7	59.8	0.331	180.7
20	3.0	899	1215	410	2.96
40		145.4	196.4	14.5	13.5
60		53.8	72.7	2.34	31.1
80		21.1	28.4	0.743	38.2
100		16.5	22.3	0.359	62.1
120		21.5	29.1	0.244	119
140		33.7	45.4	0.230	197

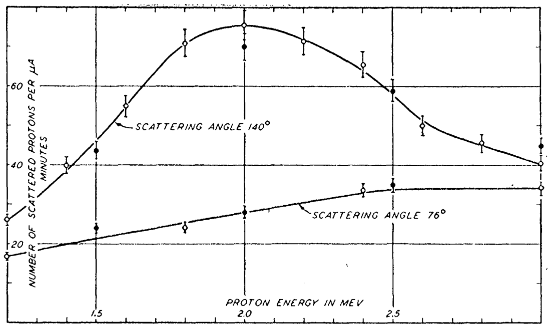


FIG. 3. Dependence of the amount of scattering upon voltage at fixed angles (points shown by solid circles are taken from curves in Figs. 4, 5 and 6).

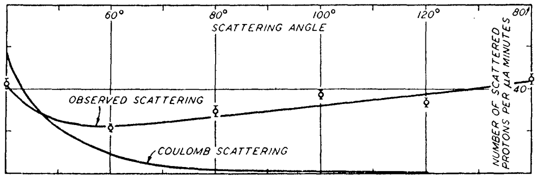
RESULTS

The results of these experiments are given in Table I. In column (4) the observed N_S has been obtained from the ratios in column (3) by use of the gold foil calibration curves of Fig. 2. The calculated N_S gives the number of scattered protons to be expected from the Coulomb scattering law of Rutherford and Darwin for our scattering chamber dimensions. These results are plotted in Figs. 3, 4, 5 and 6, both the experimentally observed scattering and the theoretical Coulomb scattering being plotted. The calculated Coulomb scattering values given in column (5) and plotted in the figures have been multiplied by a $(1/\sin\theta)$ factor to take into account the change in the effective scattering volume with angle.[8]

Measurements were taken both at fixed angles as the voltage was varied and at fixed voltages as the scattering angle was varied. The results of the former type are shown in Fig. 3. These curves are at 140° and 76° in the laboratory system or at 149° and 90° in the center-of-gravity system. These angles are such that a pure p wave should show 75 percent of its maximum effect at 149° and none at 90°. The curves at fixed voltages as the scattering angle was varied are shown in Figs. 4, 5 and 6. Although these two sets of observations were made independently, they obviously overlap. Therefore, points obtained from Figs. 4, 5 and 6 have also been plotted on Fig. 3 to make clear the extent of the agreement between the two types of observations.

DISCUSSION OF RESULTS

From Fig. 3 it appears that the amount of scattering does pass through a maximum at



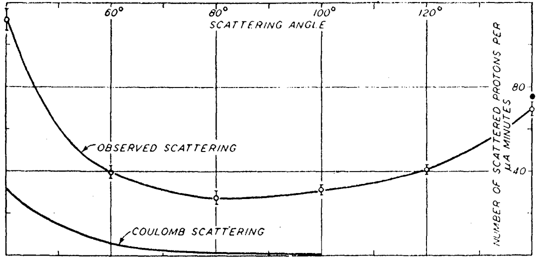


FIG. 4. (above) Angular distribution of 1.5-Mev protons scattered by helium.

FIG. 5. (below) Angular distribution of 2.0-Mev protons scattered by helium.

about two Mev as expected theoretically on the basis of the neutron-helium scattering results and the assumption of the equality of n-n and p-p forces. However, the height and narrowness of the maximum are much less than in the neutron-helium case, being only a factor of 2 instead of 5 in intensity, while the half-width is more than one Mev instead of about 0.5 Mev. Nevertheless, as Dr. Fano, Dr. Breit, and others have indicated, it is quite reasonable that the Li^5 resonance should be broader and less intense than the He^5.

This increased breadth of the resonance makes the interpretation of these results more difficult. In the first place it is more difficult to be certain that the maximum of the curve really is a resonance, since the amount of scattering could pass through a slight maximum merely due to the fact that the scattering cross section for a given type of scattering decreases with the increasing energy of the scattered particles. However, the maximum is probably sufficiently intense to justify at least the tentative assumption that the observed maximum is due to a resonance.

A second difficulty arising from the increased breadth of the curve is the difficulty in determining if there is a doublet structure to the curves. In the neutron-helium scattering experiments there has been disagreement among the observers as to whether there is a single or doublet structure of the resonance.[1,2] However, the more recent work of Staub and Tatel[3] seems to show conclusively that the resonance is a doublet. They have analyzed their data in terms of the theoretical equations given by Bloch[9] and find that their resonance curve can be fitted by assuming the $P_{3/2}$ and $P_{1/2}$ levels to be either an inverted or a normal level system depending on the values assigned to the constants occurring in the theoretical equation. They prefer the latter as being the correct interpretation when other considerations are taken into account. As proton experiments are in general less difficult than neutron ones, it was hoped for a time that it would be easier to determine the existence of a doublet structure in proton-helium scattering experiments than in n-He experiments. However, the greater width of the maximum in the p-He scattering makes it more, rather than less, difficult to detect a slight doublet structure in the curve. However, as far as our results yield information on the multiplicity of the resonance, there is no evidence for the existence of a resolvable doublet structure to the maximum in proton-helium scattering.

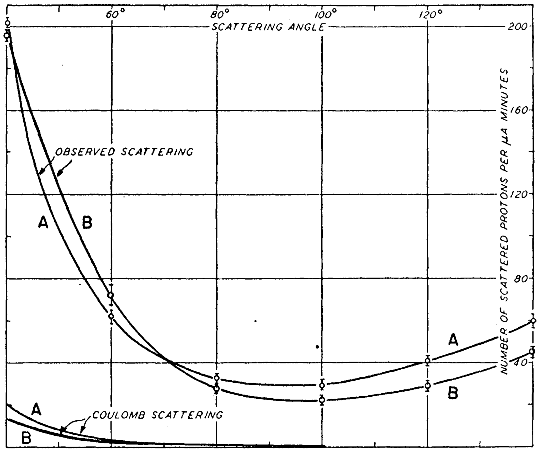


FIG. 6. Angular distribution of protons scattered by helium. Curve A, 2.5-Mev protons; curve B, 3.0-Mev protons.

The authors wish to thank Dr. J. A. Fleming, Dr. M. A. Tuve, Dr. L. R. Hafstad, R. C. Meyer, and others of the Department of Terrestrial Magnetism staff for their friendly cooperation and assistance in this work.

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[9] F. Bloch, Phys. Rev. 58, 829–836 (1940).