Differential Cross Section Measurements for the Elastic Scattering of Protons by N^{14}†

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The differential cross section for the elastic scattering of protons by N^{14} has been measured in the energy range from 1.5 to 3.5 Mev at scattering angles of 39°14′, 54°44′, 90°, 125°16′, and 140°46′ in the center-of-mass coordinate system. The probable error in the values of the cross section is about 4 to 5%. Pronounced anomalies in the cross section occur at laboratory proton energies of 1.55, 1.74, 1.805, 2.36, 2.49, 3.20, and 3.40 Mev, with a probable error in these energies of 0.01 Mev. The anomaly at 3.40 Mev indicates a previously unreported level in O^{15*} at about 10.5 Mev. The magnitude of the off-resonance cross section at 140°46′ is about four times, at 125°16′ about three times, and at 90° about two times that which would result from pure Rutherford scattering. At 54°44′ the off-resonance cross section differs from the Rutherford cross section over most of the energy range by less than 5%, while at 39°14′ the cross section is generally 10 to 20% below the Rutherford cross section.

INTRODUCTION

THE elastic scattering of protons by N^{14} has been studied at three different angles in the energy range from 0.8 to 1.9 Mev by Webb *et al.*[1] and at a number of different angles in the energy range from 1.0 to 2.9 Mev by Ferguson *et al.*[2] Mozer,[3] who is engaged in an analysis of Webb's data, finds that he can fit the off-resonance cross section by assuming a reasonably energy varying *s*-wave potential phase shift. However, because the values of the absolute cross section obtained at Chalk River are about 10% higher than those measured by Webb,[3] Ferguson has found that *s* and *p* waves, and possibly more, are present in the nonresonant scattering below 2 Mev. Tautfest and Rubin[4] have recently reported a measurement of the absolute cross section at a single scattering angle over the energy range from 0.85 to 1.9 Mev. While their values for the cross section agree with those obtained by Webb, the accuracy of their measurement is not sufficient to resolve the discrepancy.

Bashkin *et al.*[5] have also observed protons elastically scattered by N^{14} in the energy range from 0.95 to 4.0 Mev and have reported an anomaly in the yield of scattered protons at an energy of 3.20±0.08 Mev corresponding to a level in O^{15*} at about 10.3 Mev. They have reported no determinations of the absolute cross section, however.

In addition to extending the measurement of the $N^{14}(p,p)N^{14}$ differential cross section to 3.5 Mev, an attempt has been made in the experiment described here to measure the cross section to a degree of accuracy sufficient to remove the existing discrepancy in the data below 2 Mev.

APPARATUS

The use of a gas target contained in a scattering chamber of well-known geometry, as was employed in this experiment, allows one to make a determination of the number of scattering centers seen by the counter to a somewhat greater degree of accuracy than with solid targets, since, in addition to the chamber geometry, the number of scattering centers depends only on the pressure and temperature of the gas, both of which are readily measured quantities. The addition of a differential pumping system between the chamber and the electrostatic generator eliminates the usual thin foil used to separate the chamber volume from the machine vacuum. This permits a more precise determination of the absolute energy of the incident protons and allows a continuous flushing of the chamber, thereby reducing the accumulation of contaminants.

The scattering chamber used is the same chamber described previously by Brown *et al.*[6] and by Claassen *et al.*[7], except that a new counter slit system has been installed. The protons scattered by the gas, before entering the proportional counter, pass through a defining slit of width $2b=0.1755$ cm, a round hole at the counter with a diameter of 0.2540 cm, and then a thin aluminum foil, which separates the counter volume containing a mixture of argon and CO_2 from the chamber volume. The amplifiers and 10-channel pulse height discriminator used in conjunction with the counter have been previously described.[6,7]

The differential pumping system is similar in design to that described by Jackson *et al.*[8] The existing chamber entrance slits, the final one of which has a diameter of 0.1187 cm, were used to restrict the gas

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[1] Webb, Li, and Fowler, Phys. Rev. **92**, 1084(A) (1953); T. S. Webb, Jr., Ph.D. thesis, California Institute of Technology, 1955 (unpublished).

[2] Ferguson, Clarke, Gove, and Sample, Preliminary Report PD-261, Atomic Energy of Canada Limited, Chalk River Project, 1956 (unpublished).

[3] Forrest Mozer, Kellogg Radiation Laboratory, California Institute of Technology (private communication).

[4] G. W. Tautfest and S. Rubin, Phys. Rev. **103**, 196 (1956).

[5] Bashkin, Carlson, and Jacobs, Bull. Am. Phys. Soc. Ser. II, **1**, 212 (1956).

[6] Brown, Freier, Holmgren, Stratton, and Yarnell, Phys. Rev. **88**, 253 (1952).

[7] Claassen, Brown, Freier, and Stratton, Phys. Rev. **82**, 589 (1951).

[8] Jackson, Galonsky, Eppling, Hill, Goldberg, and Cameron, Phys. Rev. **89** 365 (1953).

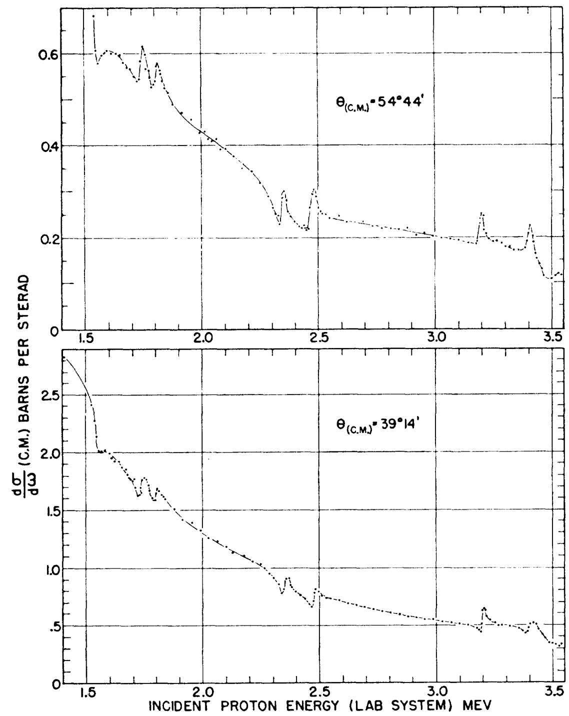

FIG. 1. The differential cross section for the elastic scattering of protons by N^{14} as a function of incident proton energy at scattering angles of 39°14′ and 54°44′. The scattering angles as well as the absolute values of the cross section are given in the center-of-mass coordinate system, while the incident proton energy is given in the laboratory system of coordinates.

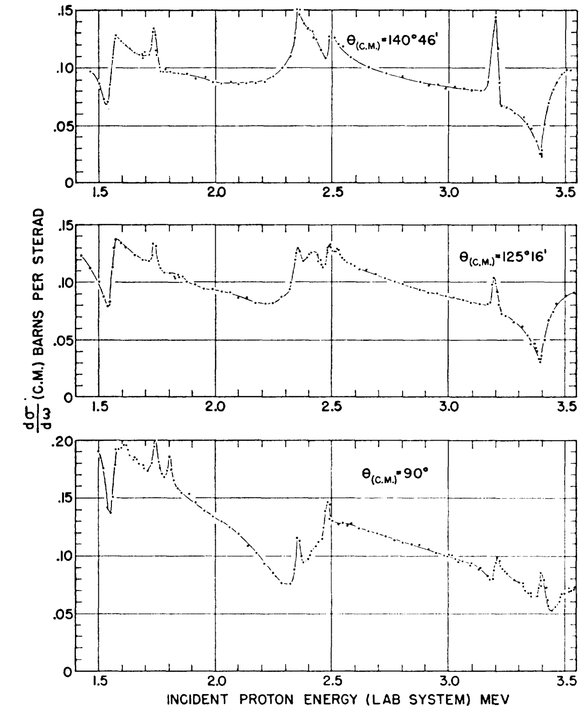

FIG. 2. The differential cross section for the elastic scattering of protons by N^{14} as a function of incident proton energy at scattering angles of 90°, 125°16′, and 140°46′. The scattering angles as well as the absolute values of the cross section are given in the center-of-mass coordinate system, while the incident proton energy is given in the laboratory system of coordinates.

flow between the chamber and the first pumping stage, where a 12-liter/second capacity forepump maintained a pressure of about 0.5 mm Hg with a normal operating pressure of 5 cm Hg in the chamber. Twenty apertures, each consisting of a 2-mm hole drilled in a 5-mil Ta disk, separated the first and second and also the second and third pumping stages. The second and third pumping stages were exhausted by a 1.5-liter/second forepump and a 300-liter/second oil diffusion pump respectively, maintaining corresponding pressures of 10^{-2} and 5×10^{-6} mm Hg. Two additional apertures separated the third pumping stage from the machine vacuum, which was not noticeably affected by the presence of the gas in the chamber. Since the first slit of the pumping system and the final chamber slit are 65 cm apart, the maximum half-angle spread in the incident beam upon entering the chamber is about 8 min.

After the incident protons have passed through the scattering chamber, they enter a Faraday collector cup through a 0.25-mil Mylar[9] exit window, which allows the collector cup to be evacuated to 2×10^{-6} mm Hg. The well-centered position of a small charred spot, which appears on the Mylar after a period of use, indicates that the beam passes through the chamber symmetrically and that all of the beam is entering the collector cup properly. Secondary electrons are prevented from leaving the collector cup by means of a transverse magnetic field and an electrostatic bias. The collector cup is connected to a current integrator which throws a shutter into the path of the beam and disconnects the 10-channel discriminator from the counter as soon as a specified quantity of charge has been collected.

The chamber pressure was measured with a Wallace and Tiernan differential manometer which was calibrated periodically with a Hg manometer. In order to be certain that the flow of gas through the small volume chamber was not causing an incorrect pressure reading, He^4 and O^{16} were used as scattering gases in the chamber. The cross sections measured using these gases agreed very well with those reported by Freier *et al.*[10] for He^4 and with those reported for O^{16} by Eppling,[11] indicating that the manometer was reading the true pressure. A change in pressure of as much as 0.4 mm Hg was noted when the proton beam was admitted into the chamber. In order to minimize the effect of this change of pressure with beam intensity,

[9] DuPont's trade name for its polyester film.

[10] Freier, Lampi, Sleator, and Williams, Phys. Rev. **75**, 1345 (1949).

[11] Eppling, Cameron, Davis, Divatia, Galonsky, Goldberg, and Hill, Phys. Rev. **91**, 438(A) (1953); F. J. Eppling, Ph.D. thesis, University of Wisconsin (unpublished).

the intensity was maintained as constant as possible during a run, and, whenever possible, the manometer was observed continuously to determine the average pressure during a run.

The temperature was measured by means of a thermometer in contact with the wall of the chamber. It was thought that a heating effect in the vicinity of the scattering volume, due to the dissipation of energy by the incident protons in passing through the gas, might be taking place, causing an increase in the temperature of the gas which was not detected by the thermometer. Since this effect would be a function of the beam intensity, several runs were taken at the same scattering angle and the same energy but with varying beam intensities. Differences in intensity of several orders of magnitude, however, failed to produce any noticeable change in the number of scattered protons counted, indicating that this was not a serious effect.

EXPERIMENTAL RESULTS

The differential cross sections for the elastic scattering of protons by N^{14} are shown as a function of incident proton energy in the range from 1.5 to 3.5 Mev at scattering angles of 39°14′ and 54°44′ in Fig. 1, and at 90°, 125°16′, and 140°46′ in Fig. 2. The scattering angles as well as the absolute values of the cross section are given in the center-of-mass coordinate system, while the incident proton energy is given in the laboratory system of coordinates. The angles chosen are those which cause the first, second, and third degree Legendre polynomials ($l=1$, 2, 3, respectively) to vanish.

The values of the off-resonance cross section presented here are generally in better agreement with those obtained by Ferguson *et al.*[2] than with those reported by Webb.[1] An energy spread, due to straggling introduced in the beam in passing through the gas and the insufficient energy resolution of the machine, caused a broadening of the resonances and decreased their height. However, the shapes of the resonances seem to have been well established by Webb, so that no effort was made to improve the energy resolution.

The positions of the scattering anomalies occurring at proton energies of 1.55, 1.74, 1.805, 2.36, and 2.49 Mev agree well with those reported by Ferguson *et al.* and by Webb, and also with the positions of the resonances reported by Duncan and Perry[12] from a study of the $N^{14}(p,\gamma)$ reaction. The scattering anomaly at a proton energy of 3.20 Mev agrees with that reported by Bashkin *et al.*,[5] while the anomaly at 3.40 Mev has not been previously reported. The anomalies occurring at 2.36 and 2.49 Mev appear to be superimposed on a very broad resonance in the neighborhood of 2.55 Mev corresponding to the resonance reported by Duncan and Perry at 2.60 Mev. Additional structure is present at 2.43 Mev, although the nature of this anomaly is difficult to ascertain without a detailed analysis of the data.

The factors which contributed to the error in the cross section at each angle and energy are: counting statistics, 1.0 to 2.0%; charge collection and integration, 1.0%; chamber geometry, 0.5%; gas pressure, 1.0%; and gas temperature, 0.5%. The sum of these errors gives a total probable error in the values of the absolute cross section of four to five percent.

The target gas used in this experiment was ordinary tank nitrogen obtained from the Air Reduction Company. A mass spectrometric analysis of the gas showed it to contain better than 99.5% N^{14}, with about 0.4% N^{15} and less than 0.1% O^{16}. It was considered that the effect of these contaminants was negligible, and so no correction to the data was made to allow for their presence.

The energy of the incident protons was measured and controlled by an electrostatic analyzer, which operated on the molecular hydrogen beam. The analyzer was calibrated by determining the point at which the 1.882-Mev threshold for the $Li^7(p,n)$ reaction occurred. The error in determining the absolute energy is due to two causes. First of all, a long time drift in the analyzer calibration introduced an error of 5 to 7 kev. In plotting the data, this drift was taken into account so that the error in the relative energy due to this effect is probably somewhat less than 5 kev. The second source of error, amounting to about 5 kev, was introduced in determining the energy lost by the incident protons in passing through the gas before reaching the volume seen by the counter. This energy loss was measured by noting the shifts produced in the positions of several scattering anomalies when different chamber pressures were used.

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[12] D. B. Duncan and J. E. Perry, Phys. Rev. 82, 809 (1951).