Elastic Scattering of Protons from B^{11} and N^{14}†

GEORGE W. TAUTFEST, *Stanford Research Institute, Menlo Park, California and High-Energy Physics Laboratory, Stanford University, Stanford, California*

AND

SYLVAN RUBIN, *Stanford Research Institute, Menlo Park, California*

(Received March 23, 1956)

The absolute differential cross sections for the elastic scattering of protons by B^{11} and N^{14} have been measured with a probable error of 7%. The cross section for $B^{11}(p,p)$ was measured at a center-of-mass angle of 152° 36′ for proton energies from 600 to 2000 kev. A marked scattering anomaly is observed at a proton energy of 675 (2^-) kev. The cross section for $N^{14}(p,p)$ was measured at a center-of-mass angle of 152° for proton energies from 850 to 1900 kev. Scattering anomalies were observed at proton energies 1.060 ($\frac{1}{2}^+$), 1.555 ($\frac{1}{2}^+$), 1.740 ($3/2^-$ or $5/2^-$) and 1.803 ($3/2^-$ or $5/2^-$) Mev. The indicated spin and parity assignments for the corresponding levels in the compound nucleus are consistent with the results of this experiment. The off-resonance cross sections exhibit marked variations from the Rutherford cross sections over the entire range of energies studied.

I. INTRODUCTION

THE investigation reported here was undertaken in connection with the program of analysis of the composition of surface layers of solids by ion scattering[1] being carried on at Stanford Research Institute. Quantitative analysis of surface constituents requires that the absolute cross section for elastic scattering be accurately known. It is believed that the present work completes the large-angle proton scattering cross-section measurements for the abundant isotopes of the light elements ($Z<13$).

In addition to the rather specialized interest considered above, the study of elastic scattering yields information on the spins, parities, and partial widths of the levels in the compound nucleus. Proton scattering from N^{14} has previously been studied by Gove *et al.*[2] at a number of angles in the immediate vicinity of the scattering anomalies and more recently by Webb,[3] and a number of tentative assignments of spin and parity have been given to the states of O^{15}. Unfortunately, the present work is not sufficiently complete to resolve the ambiguities that still remain in these assignments.

This paper describes the experimental procedure and presents the results on the elastic scattering of protons by B^{11} and N^{14}. Preliminary results have been presented to the American Physical Society.[4]

II. EXPERIMENTAL PROCEDURE

The proton beam from a 2-Mev Van de Graaff accelerator located at Stanford Research Institute is analyzed and maintained homogeneous to better than 0.1% by a 90° magnetic analyzer of 15-in. radius and $\frac{1}{2}$-mm entrance and exit slits. The beam is focused by an electrostatic lens to a spot $\frac{1}{2}\times 2$ mm in size on a target placed at the "object" position of a 180°, point-focusing magnetic spectrometer previously described.[5] The spectrometer has an aperture of 2.52 millisteradians and was set for a resolving power of 1106 for these measurements. The scattered protons were detected by a scintillation counter placed at the exit slit of the spectrometer. The phototube is partly within the vacuum system and thus the protons have a continuous path in vacuum from analyzer to target to detector. The integrator for the proton beam is a modification of one described by Bouricious and Shoemaker[6] and is reproducible to 0.1% or better. The target is surrounded by an open-frame negative electrode to suppress second-

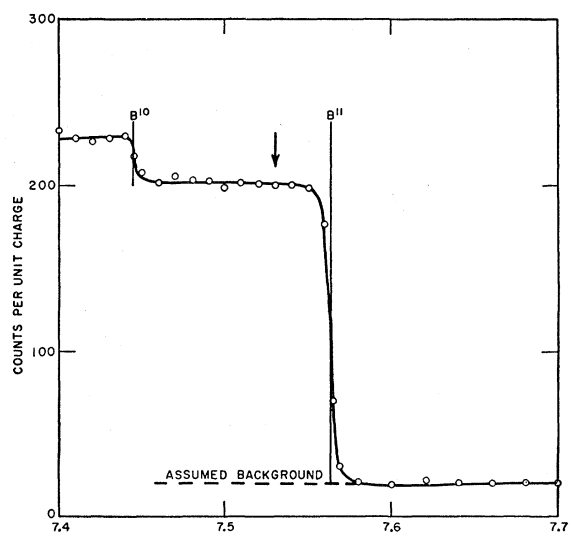

FIG. 1. Momentum profile of elastically-scattered protons from a pure boron target. The arrow indicates the spectrometer setting at which the excitation curve was taken.

† This work was supported by the U. S. Office of Ordnance Research.

[1] S. Rubin and V. K. Rasmussen, Phys. Rev. **78**, 83 (1950).
[2] Gove, Ferguson, and Sample, Phys. Rev. **93**, 928(A) (1954).
[3] T. S. Webb, Jr., Ph.D. thesis, California Institute of Technology, 1955 (unpublished).
[4] Tautfest, Havil, and Rubin, Phys. Rev. **98**, 280(A) (1955).
[5] S. Rubin and D. C. Sachs, Rev. Sci. Instr. **26**, 1029 (1955).
[6] G. M. B. Bouricious and F. D. Shoemaker, Rev. Sci. Instr. **22**, 183 (1951).

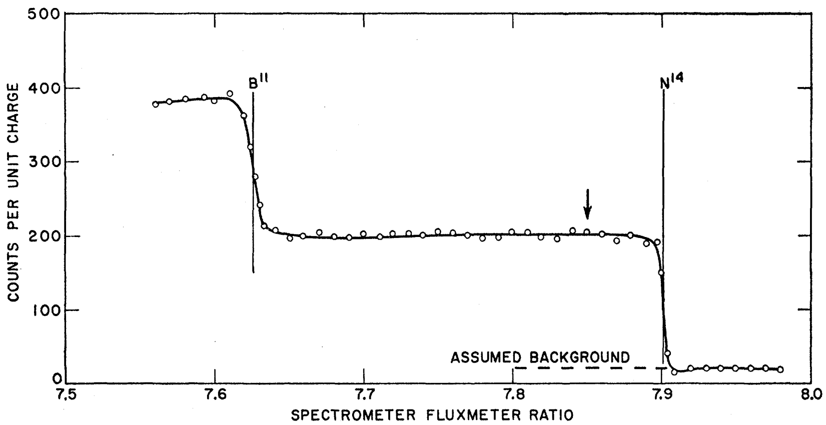

FIG. 2. Momentum profile of elastically-scattered protons from a boron nitride target. The arrow indicates the spectrometer setting at which the excitation curve was taken.

ary electron emission without obstructing either the incident or the scattered protons.

The magnetic fields of the analyzer and spectrometer are compared with each other or with a reference permanent magnet by means of a null balance flip coil.[7] It is possible to reproduce the magnetic field measurements to an accuracy of better than 0.05% over an extended period of time. The energy scale of the magnetic analyzer was calibrated by observing the gamma radiation from a thin aluminum target at the 993.3-kev $Al^{27}(p,\gamma)$ resonance.[8] The linearity of the analyzer fluxmeter has been checked by studying the excitation curves for $Al^{27}(p,\gamma)$ up to 1.3 Mev and the $C^{12}(p,p)$ resonance at 1.73 Mev.

Targets were prepared by pressing powdered boron nitride and high-purity boron of naturally-occurring isotopic abundance into a circular recess in an aluminum backing. The targets were generally satisfactory although polished fused boron targets were also used with some improvement in reproducibility. Carbon buildup on the target surface during bombardment was serious during the early phases of the work and required that the beam be shifted to a new area of the target after 50 microcoulombs of bombardment; this was greatly improved with more efficient cold trapping and pumping of the target chamber.

Momentum profiles of the targets are shown in Figs. 1 and 2. It is to be noted that at the large angles of this experiment there is no difficulty in resolving the protons scattered from the boron from those scattered from the nitrogen in the boron nitride target and no difficulty in separating the boron isotopes in the pure boron target. The excitation curve for the nitrogen cross section was obtained at a spectrometer-fluxmeter ratio of 7.850, which corresponds to protons scattered from a lamina 8 kev from the surface of the target. For the B^{11} excitation curve, the fluxmeter was set at a ratio of 7.530, which corresponds to protons scattered from a lamina 6-kev deep. The final data has of course been corrected for the energy loss in the target before scattering. The constant background ahead of the boron and nitrogen peaks is due to α-particles from the $B(p,\alpha)Be$ reactions in the targets.

When the energy loss of the scattered protons in the target is greater than the energy interval accepted by the spectrometer the target is said to be "thick" and the differential cross section in the center-of-mass system at the angle $\theta_{\text{c.m.}}$ is given by[9]

$$\frac{d\sigma(\theta_{\text{c.m.}})}{d\Omega}=\frac{Y}{q\Omega_{\text{c.m.}}}\left(\frac{R_s}{2E_2}\epsilon_{\text{eff}}\right)\times1.6\times10^{-13}\ \text{cm}^2/\text{sterad},\quad(1)$$

where Y is the number of scattered protons observed for q microcoulombs of protons incident on the target; $\Omega_{\text{c.m.}}$ is the solid angle of the spectrometer in the center-of-mass system; R_s is the resolution of the spectrometer $p/\Delta p$; E_2 is the energy of the scattered protons; and ϵ_{eff} is the over-all stopping cross section of the target material. The quantity $2E_2/R_s\epsilon_{\text{eff}}$ is the effective number of target nuclei per cm² perpendicular to the beam. If one ignores chemical binding effects on the stopping cross section and the increase of the stopping cross section along the path of the proton, then for a target containing a homogeneous mixture of atoms of types a_i with atomic concentrations n_i, the number of target nuclei of type a_j per cm² perpendicular to the beam can be written as

$$\frac{2E_2}{R_s\epsilon_{\text{eff}}}=\frac{2E_1}{R_s}\left[\sum_i\frac{n_i}{n_j}\left(\epsilon_{i1}+\frac{\epsilon_{i2}}{k_j}\right)\right]^{-1},\quad(2)$$

where ϵ_{i1} and ϵ_{i2} are the stopping cross sections of atoms of type a_i for protons of energy E_1 (initial proton energy) and E_2 (energy of proton after scattering), respectively. It is assumed that the normal to the target surface bisects the angle between the incident and scattered protons; $k_j=\partial E_2/\partial E_1$ is calculated from the expression $E_2=E_2(E_1,\theta_{\text{c.m.}},M_j)$ derived from the usual conservation laws.

The effective resolution widths, R_s, for three spec-

[7] H. R. Fechter and S. Rubin, Rev. Sci. Instr. **26**, 1108 (1955).
[8] Herb, Snowden, and Sala, Phys. Rev. **75**, 246 (1949).
[9] Brown, Snyder, Fowler, and Lauritsen, Phys. Rev. **82**, 159 (1951).

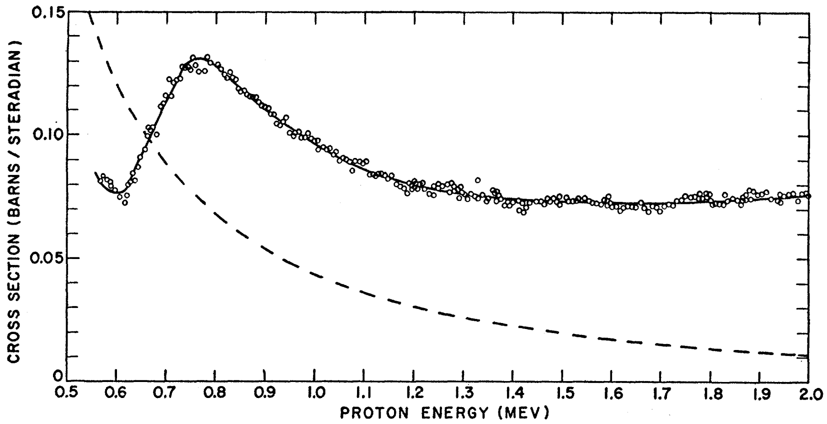

FIG. 3. Differential cross section for the elastic scattering of protons from B^{11}. The dashed curve is the Rutherford cross section for reference.

trometer exit slits were measured by means of proton scattering from a polished copper target. The scattering cross section is assumed to be given by the Rutherford formula. This was confirmed by observing that the cross section varied with energy over the range from 1 to 2 Mev exactly as E^{-2}. The stopping cross section for copper is taken from the compilation of Fuchs and Whaling.[10] The resolution measurements were made at a proton energy of 1.44 Mev and at 150° scattering angle. The results are shown in Table I in which the effective resolution widths are compared with those calculated from the spectrometer formulas given by Judd.[11]

The determination of the absolute elastic-scattering cross sections thus involves directly the absolute stopping cross sections of boron and nitrogen. No direct experimental measurements of these quantities were attempted. The absolute stopping cross section for protons in nitrogen gas has been measured by Chilton *et al.*[12] for energies up to 1 Mev and yields a value of 90 ev for the mean ionization potential. These data were extrapolated to 2 Mev by calculations using the Bethe stopping cross-section formula with K-shell correction.[13] A smooth fit to the experimental data was obtained, but the result may be in error by several percent. No measurements of the stopping cross section of boron are available. Huus and Day[14] have reported a calculation done by R. G. Thomas which gave an average ionization potential for boron equal to that for beryllium. The stopping cross section for boron was accordingly calculated using a mean ionization potential of 65 ev. An estimate of the relative errors in the stopping cross-section calculations can be made by comparison of the absolute cross section for $N^{14}(p,p)$ obtained by Webb[3] and the results of this experiment. Webb used targets of ammonia and beryllium nitride for which constituent elements the stopping cross sections have been measured. Agreement on the value of the nonresonant cross section is well within the statistics of the two measurements. We therefore conclude that the uncertainty in the calculated value of the boron stopping cross section is not appreciably greater than the uncertainty in the measured stopping cross sections involved.

We assign a probable error of 5% to the $N^{14}(p,p)$ cross section due to the uncertainty in the stopping cross section of boron nitride. To this must be added an additional 5% uncertainty due to target behavior and reproducibility of results. The uncertainty in the absolute value of the $B^{11}(p,p)$ cross section is almost entirely due to the uncertainty in the stopping cross-section calculation. Reproducibility of results with different targets was excellent and difficulties due to carbon buildup were negligible. We assign a probable error of 7% to this measurement.

TABLE I. Comparison of measured and calculated resolution widths.

Exit slit width	Calculated R_e	Measured R_e (from Cu scattering)
0.0140-in.	3350	3300
0.0420-in.	1120	1106
0.0837-in.	560	560

III. EXPERIMENTAL RESULTS

1. $B^{11}(p,p)$

Figure 3 shows, as a function of incident proton energy, the differential cross section for the elastic scattering of protons from B^{11} at a center-of-mass angle of 152° 36′. The pronounced scattering anomaly occurs at a proton energy of 675 kev in agreement with previous results[14,15] and is identified with the 16.57-Mev level in C^{12}.[16] The increase in the cross section from 700 to 2000 kev may be attributed to the influence of the

[10] R. Fuchs and W. Whaling, "Stopping Cross Sections," California Institute of Technology (unpublished).
[11] D. L. Judd, Rev. Sci. Instr. **21**, 213 (1950).
[12] Chilton, Cooper, and Harris, Phys. Rev. **93**, 413 (1953).
[13] H. Bethe and J. Ashkin in *Experimental Nuclear Physics*, edited by E. Segrè (John Wiley and Sons, Inc., New York, 1953), Vol. I, Chap. 2.
[14] T. Huus and R. B. Day, Phys. Rev. **91**, 599 (1953).
[15] Beckman, Huus, and Zupančič, Phys. Rev. **91**, 606 (1953).
[16] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).

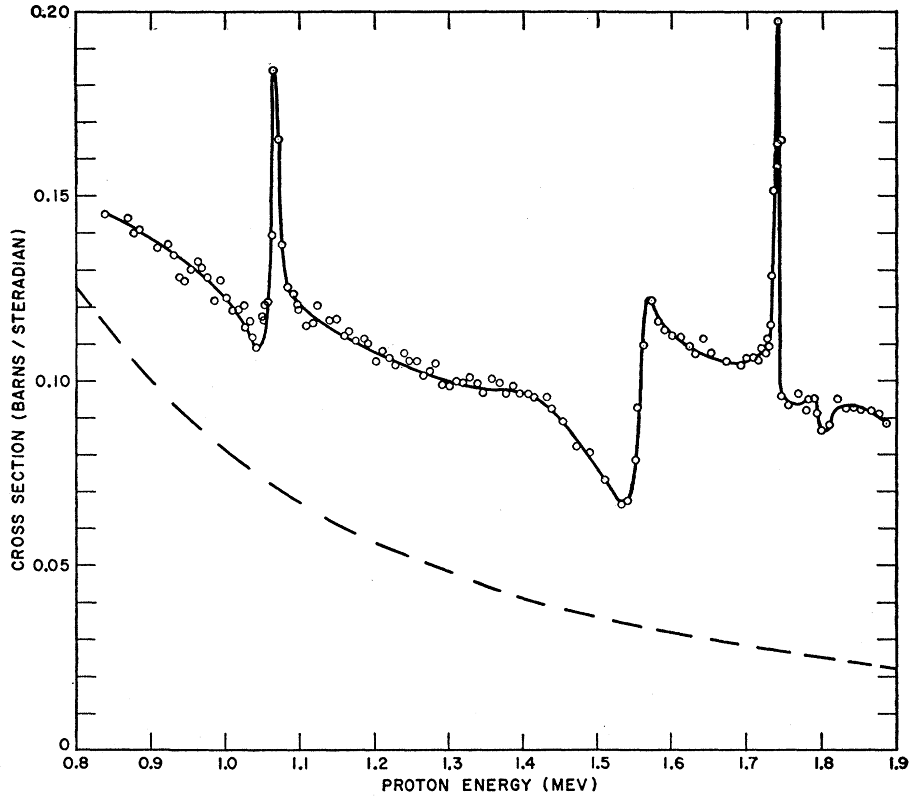

FIG. 4. Differential cross section for the elastic scattering of protons from N^{14}. The dashed curve is the Rutherford cross section for reference.

very broad (1.3-Mev) resonance observed at 1.4 Mev in the $B^{11}(p,\gamma)$ and $B^{11}(p,\alpha)$ reactions.[14,15,17,18] No rapid variation in cross section was observed in the neighborhood of the 2.0-Mev resonance which has been reported.[17,18] The assignment of 2^- to the 16.57-Mev level which has been suggested by Beckman *et al.*[15] is consistent with the value of $\sigma_{\max}-\sigma_{\min}$ observed if we assume that there is no overlapping with the 1.4-Mev resonance. In view of the dubious nature of this assumption it would be important to observe the behavior of the resonance at a number of angles in order to definitely confirm s-wave formation.

2. $N^{14}(p,p)$

The differential cross section obtained for the elastic scattering of protons by nitrogen at a center-of-mass angle of 152° is shown in Fig. 4. Observations were made at 8-kev intervals for the majority of the points and in 2-kev intervals in the neighborhood of the narrow resonances. Each point represents about 10 microcoulombs of protons incident on the target.

[17] E. B. Paul and R. L. Clarke, Phys. Rev. **91**, 463(A) (1953).
[18] H. E. Gove and E. B. Paul, Phys. Rev. **91**, 463(A) (1953).

The scattering anomalies observed at 1.060, 1.555, 1.740, and 1.803 Mev are in agreement with the resonances observed in the $N^{14}(p,\gamma)$ reaction by Duncan and Perry[19] and in the $N^{14}(p,p)$ reaction by Gove *et al.*[2] and Webb.[3] Both Gove *et al.* and Webb suggest s-wave formation of the 1.060- and 1.555-Mev states with the assignment of $1/2^+$ to these levels, although the latter does not rule out $3/2^+$ for the 1.060-Mev resonance. The value of $\sigma_{\max}-\sigma_{\min}$ obtained for this resonance are in very good agreement with the $1/2^+$ assignment. The two resonances at 1.740 and 1.803 Mev are believed to be due to p-wave formation with assignments of $3/2^-$ or $5/2^-$ to both levels.[2,3] The results presented here are not sufficient to decide between these possible assignments. The values of the absolute cross section are in excellent agreement with those obtained by Webb[3] over the entire range of energies studied.

ACKNOWLEDGMENTS

We wish to thank the members of the Ion Scattering Group for their generous assistance in target preparation and data collection.

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