Proton Elastic Scattering Cross Sections of Si, Cl, K, Sc, Ti, and Mn

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The proton elastic scattering yields of silicon, chlorine, potassium, scandium, titanium, and manganese have been determined with respect to that from copper in the energy range 1.0–2.0 Mev at 150° laboratory angle. Two large resonances were found in silicon and two smaller ones in chlorine. The smooth regions of the curves do not vary significantly from the Rutherford values.

I. INTRODUCTION

THE investigation reported here was undertaken in connection with the program of analysis of the composition of surface layers of solids by proton scattering carried on at Stanford Research Institute. The quantitative analysis of surface constituents requires that the absolute cross section for elastic scattering be accurately known. In addition to this rather specialized interest, the complete study of elastic scattering yields reveals the existence of the levels in the compound nucleus as well as information on the spins, parities, and partial widths of these levels.

This group of elements was chosen to bridge the range between the very light elements which have been extensively studied, and the heavier elements, for which the proton scattering is essentially Coulombic up to 2 Mev. The principal purpose of these measurements was to determine the proton energies and the magnitudes of the deviations from Coulomb scattering.

Large-angle proton scattering cross-section measurements have been made by a number of investigators for the abundant isotopes of the light elements up to aluminum as a function of energy up to 2 Mev. Resonances due to the interference between the wave functions for Coulomb-potential or Rutherford scattering and the stationary states of the compound nucleus have been observed in these elements. Similar measurements by a number of investigators on copper show no detectable resonance effects in proton scattering up to 2-Mev energy, no doubt because 2-Mev protons are unable to approach the copper nucleus sufficiently close to interact with its nuclear fields. Elastic proton scattering on elements between aluminum and copper has been little studied. Ferguson and Gove[1] have investigated sulfur and have found resonances at 1.90 and 2.31 Mev. The scattering cross section was approximately Rutherford above and below these energies. Vorona, Olness, Haeberli, and Lewis report two resonances in silicon at 1.65 and 2.07 Mev.[2] To the authors' knowledge no data have been published for the remaining elements in this region.

This paper describes the experimental procedure and presents the results on the elastic scattering of protons by silicon, chlorine, potassium, scandium, titanium, and manganese.

II. EXPERIMENTAL PROCEDURE

The proton beam from a 2-Mev Van de Graaff accelerator is analyzed and maintained homogeneous in energy to better than 0.1% by a 90° magnetic analyzer of 14.85-inch 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.[3] The scattered protons were detected by a thin NaI(Tl) scintillation crystal cemented to the face of an RCA-6810 phototube placed at the exit slit of the spectrometer. The integrator for the proton beam current is a modification of one described by Bouricious and Shoemaker[4] and is reproducible to 0.1% or better. The target is surrounded by an open-frame negative electrode to suppress secondary electron emission without obstructing the incident or 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.[5] The energy scale of the analyzer magnet has been calibrated by observing the gamma radiation from a thin fluorine target (KF) at the 1.372-Mev resonance. The linearity of the analyzer fluxmeter has been checked by studying the excitation curves for $Al^{27}(p,\gamma)Si^{28}$ up to 1.3 Mev and the $C^{12}(p,p)C^{12}$ resonance at 1.73 Mev.

The principal problem in performing these investigations is the preparation of targets which are chemically and physically stable under proton beam bombardment. Pure elemental targets were used for the cross-section measurements on silicon, titanium, manganese, and copper. The compounds, NaCl, KF, and Sc_2O_3 were used for chlorine, potassium, and scandium cross sections, respectively. The elemental targets, having high heat conductivities, easily dissipated the heat generated by the stopping proton beam. The salts and oxides, being poor heat conductors, did not dissipate

[1] A. J. Ferguson and H. E. Gove, Phys. Rev. **91**, 439(A) (1953).
[2] Vorona, Olness, Haeberli, and Lewis, Bull. Am. Phys. Soc. Ser. II, **2**, 34 (1957).
[3] S. Rubin and D. C. Sachs, Rev. Sci. Instr. **26**, 1029–1034 (1955).
[4] G. M. B. Bouricious and F. C. Shoemaker, Rev. Sci. Instr. **22**, 183–184 (1951).
[5] H. R. Fechter and S. Rubin, Rev. Sci. Instr. **26**, 1108–1111 (1955).

this heat readily. This can cause vaporization or phase changes of target material, which in turn produces unwanted fluctuations in the scattered proton yields. The effect is not serious for KF, NaCl, and Sc_2O_3 for the beam intensities used in these experiments. However, data taken on K_2CO_3 and CaO, for example, are not reported here for the above reasons. The erratic behavior of CaO was probably due to solid-state phase changes since little vaporization can occur below 2570°C, a temperature probably not attained.

The protons accepted by the spectrometer are scattered from a lamina located below the surface of the target, and therefore are of lower energy than the primary proton energy. The fractional energy loss is determined from the ratio of the spectrometer field to the analyzer field, which ratio was maintained constant for all primary energies for a given element. The fraction of the incident proton energy lost before scattering varied from 0.066 for copper to 0.022 for chlorine.

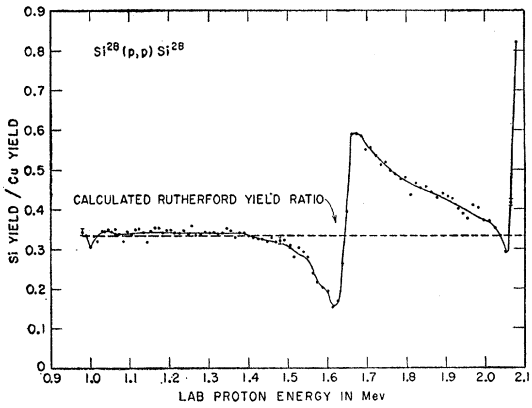

FIG. 1. The ratio of the thick-target elastic proton scattering yield of elemental silicon to that of elemental copper at 150° laboratory scattering angle.

The solid angle, Ω, and the resolution, R_s, of the spectrometer can be calibrated by proton scattering from a polished copper target. It has been shown that this cross section has an E^{-2} dependence between 1 and 2 Mev, i.e., the cross section is given by the Rutherford formula. We have found that a lateral displacement of the beam may occur when the beam energy and electrostatic focus are changed. This displacement produces a change in the solid angle of the spectrometer. The most reliable method of eliminating an error from this cause is to compute Ω at each setting of the analyzer magnet by running copper concurrently with each other element. The various targets investigated are mounted such that by raising, lowering, or rotating the target holder, the orientation of all targets with respect to the beam and spectrometer is very nearly the same. In this manner, any error arising from a displacement of the beam on each target is avoided.

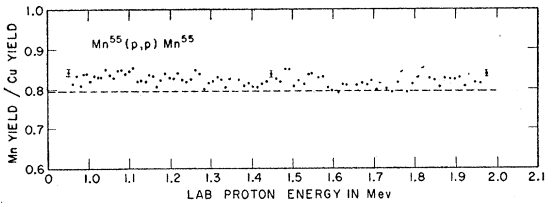

FIG. 2. The yield ratio between metallic manganese and metallic copper for elastic scattering of protons at a laboratory angle of 150°.

III. CALCULATIONS

The data obtained in this work are presented in plots whose ordinates are the yield from element j divided by the yield from copper, and whose abscissa are the proton energy in the laboratory system at the lamina of scattering in the lighter element (j). On this type of plot, the yield ratio is a horizontal straight line if both differential cross sections are exactly Rutherford. Copper was chosen as a reference material because (a) its elastic scattering cross section for protons is well known to be resonance-free and Rutherford for protons from 1 to 2 Mev, (b) this material can be prepared in a highly polished, stable form for targets, and (c) its stopping power for protons is accurately known.

The form of the Rutherford formula used in the calculation is

$$\left(\frac{d\sigma}{d\Omega}\right)_R = \frac{1.296\times10^{-27}}{E_p^2} Z^2 \left(\frac{A+1}{A}\right)^2 \csc^4\left(\frac{\theta}{2}\right), \quad (1)$$

where $(d\sigma/d\Omega)_R$ is the Rutherford differential cross section in cm² per atom per steradian, E_p is the laboratory proton energy in Mev at the lamina where scattering takes place, Z is the atomic number of the target material, A is the mass number of the target material, and θ is the scattering angle in the center-of-mass coordinate system.

Having obtained the Rutherford cross sections for each element of interest, the thick-target (any target in which the energy loss in the target is greater than the energy interval accepted by the spectrometer) yield (Y_j) to be expected can be obtained from

$$Y_j = \left(\frac{d\sigma}{d\Omega}\right)\frac{2\Omega N E_0}{R_s \epsilon_{\text{eff}}}, \quad (2)$$

where

$$\epsilon_{\text{eff}} = \sum_i \frac{n_i}{n_j}\left(\epsilon_{i1} + \frac{1}{k_j}\epsilon_{i2}\right),$$

Y_j is the yield observed by the spectrometer counter, Ω is the spectrometer solid angle in steradians (center-of-mass system), $d\sigma/d\Omega$ is the differential scattering cross section in the center-of-mass system, E_0 is the incident proton energy in the laboratory system, ϵ_{i1} and ϵ_{i2} are the stopping cross sections of atoms of type i

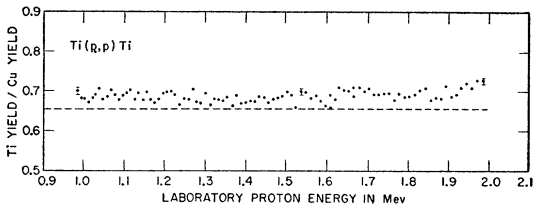

FIG. 3. Proton elastic scattering yield ratio between elemental titanium and elemental copper at 150° laboratory angle.

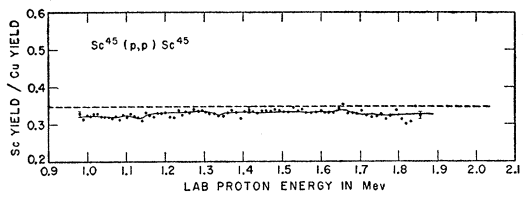

FIG. 4. The proton elastic scattering yield ratio between scandium in Sc_2O_3 and elemental copper at 150° laboratory scattering angle.

for protons of energy E_1 (energy before scattering) and energy E_2 (energy after scattering), respectively, k_j is the ratio of the proton energy after scattering to that before scattering, N is the number of protons incident upon the target, R_s is the momentum resolution of the spectrometer, $p/\Delta p$, $n_{i(j)}$ is the atomic fraction of element $i(j)$ in the thick target. Atomic stopping cross sections for calculating ϵ_{eff} were obtained from the compilation of Fuchs and Whaling.[6]

Equations (1) and (2) were used to calculate the expected yield ratio for each element j with respect to copper, assuming both had Rutherford scattering cross sections. This calculated Rutherford yield ratio is shown as a dotted line in each yield curve (Figs. 1 through 6).

IV. EXPERIMENTAL RESULTS

Figures 1 through 6 show, as a function of incident proton energy, the ratio of the thick target yield of each of six elements relative to that from copper, respectively, at 150° laboratory scattering angle.

Observations were made at intervals increasing from 9.5 kev at 1 Mev to 14 kev at 2 Mev for the majority of the points, and in intervals $\frac{1}{3}$ this size in the neighborhood of the narrow resonances. The resolving power $p/\Delta p$ of the spectrometer was 560 for all these experiments.

Because of the way in which the data were taken, the laboratory proton energy at which scattering took place in copper is some constant fraction lower than the corresponding energy before scattering in the other element. Therefore, the yield curve as plotted is lower by the fraction (E_{Cu}/E_j) than would have been the case for exactly equal proton energies in the two elements before scattering. However, the calculated Rutherford yield ratio shown in each curve was corrected for the above effect. Therefore, the curves in Figs. 1 through 6 show accurately (within experimental error) the departure of each element's differential elastic scattering cross section from Rutherford.

1. Si^{28}

Figure 1 shows the results from proton scattering on a polished surface of elemental silicon (semiconductor grade).[7] The two pronounced resonances arise from the Si^{28} nucleus (abundance 92.14%) because the dip below the Rutherford yield level is far too great (to 42% and 83% of Rutherford cross section, respectively) to be the result of scattering on Si^{29} (abundance 4.73%) or Si^{30} (abundance 3.13%). This is not to say that Si^{29} and/or Si^{30} are not possibly contributing to each resonance by the accidental coincidence of excitation levels in P^{30} and P^{31} with those in P^{29}. However, the probability of such a coincidence is small.

Table I gives the various parameters associated with each resonance. The practical upper energy limit of our accelerator at the time the experiments were performed prevented our delineating the high-energy side of the resonance at 2.07 Mev. However, we assume that the peak was reached and are basing the level width estimation on that assumption.

The work of Vorona, Olness, Haeberli, and Lewis[2] reported recently is in good agreement with the present work in the overlapping energy region. Their experiments extend from 1.40 to 3.80 Mev whereas ours include the region between 0.980 and 2.08 Mev. A very

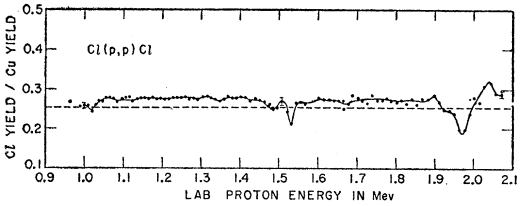

FIG. 5. The ratio of proton elastic scattering by chlorine to that by copper for NaCl and elemental copper targets, respectively. The laboratory scattering angle is 150°.

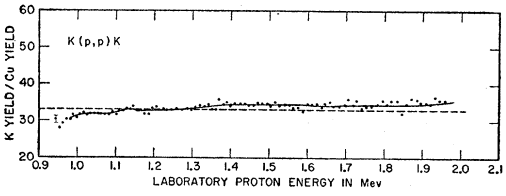

FIG. 6. The yield of potassium in KF divided by the yield of copper in copper metal for elastic scattering of protons at 150° in the laboratory frame.

[6] R. Fuchs and W. Whaling. "Stopping Cross Sections," Kellogg Radiation Laboratory, California Institute of Technology (unpublished compilation of stopping power data from published literature up to October, 1953).

[7] This material was very kindly supplied by Shockley Semiconductor Laboratories of Mountain View, California.

small resonance may exist at 1.00 Mev but it was not possible to reproduce it consistently.

2. Mn^{55}, Ti, and Sc^{45}

The results of proton scattering from polished metallic manganese, polished metallic titanium, and a pressed disk of Sc_2O_3 (all targets of greater than 99% purity) are shown in Figs. 2, 3, and 4. These reactions are grouped together because none of them show any pronounced resonances and all of them exhibit cross sections very close to Rutherford. The statistical uncertainties for each target are shown at the center and both extremities in the energy scale. It is apparent that many weak resonances are possibly present, at least in titanium and manganese. However, experiments at much greater resolution and at smaller energy intervals will be necessary to quantitatively observe these resonances. Some of the variations (in excess of the statistical variation) were possibly due to the nonreproducible operation of experimental apparatus. However, the well-behaved nature of portions of the scandium, potassium, silicon, and chlorine curves indicate that the fluctuations of manganese and titanium are probably real.

3. Cl

Two peaks appear in the intensity of protons elastically scattered from chlorine in sodium chloride targets (Fig. 5). There is no evidence as to which of the two chlorine isotopes are responsible for the resonance in each case. The numerical parameters for each resonance are shown in Table I.

4. K

Figure 6 shows the scattering yield data for potassium *versus* copper. Although two possible resonances exist at 0.96 and 1.85-Mev proton energy, they are indistinct and one can say that the potassium scattering cross section is essentially nonresonant for an experiment of this resolving power.

V. DISCUSSION

The energy scale upon which the values in Table I are based was found to be about 0.5% lower than one later determined using the 1372-kev resonance in the $F^{19}(p,\alpha\gamma)O^{16}$ reaction. Therefore, the proton energies at resonance are probably low by 0.5%. However, since the energy scale inaccuracy is of the same order of magnitude as the momentum window of the spectrometer no correction was applied to the data.

TABLE I. Parameters for four resonances observed in silicon and chlorine elastic proton scattering yields at 150° laboratory angle.

Target	Proton energy at resonance	Excited nucleus	Excitation energy	Binding energy of last proton in excited nucleus	Level width in kev (approx)
Si^{28}	1.65	P^{29}	4.314	2.724	60
Si^{28}	2.07	P^{29}	4.721	2.724	30
Cl	1.496	?			20
Cl	1.96	?			70

TABLE II. Theoretical values of the expression $(J+\frac{1}{2})P_l(\cos 151°)$ for several energy-level types.

Energy-level type	$(J+\frac{1}{2})P_l(\cos 151°)$
$S_{1/2}$	1.00
$P_{1/2}$	0.83
$P_{3/2}$	1.77
$D_{3/2}$	1.08
$D_{5/2}$	1.62
$F_{5/2}$	0.58
$F_{7/2}$	0.78
$G_{7/2}$	0.48
$G_{9/2}$	0.59

There are certain conclusions which can be drawn from the scattering data on the 1.65-Mev resonance in Si^{28}. Laubenstein and Laubenstein[8] describe the analysis of elastic scattering of protons with O^{16} which applies to proton scattering on all spin zero nuclei. We use Eq. 6 in reference 8, namely

$$\lambda\bar{}[(\sigma_{\max})^{\frac{1}{2}}\pm(\sigma_{\min})^{\frac{1}{2}}]=(J+\tfrac{1}{2})P_l(\cos\theta), \qquad (3)$$

where $\lambda\bar{}$ is the DeBroglie wavelength of the proton of energy equal to the resonance energy, $\sigma_{\max}$ and $\sigma_{\min}$ are the maximum and minimum differential cross sections observed in the resonance fluctuation, J is the total angular momentum of the energy state exhibiting resonance, $P_l(\cos\theta)$ is the appropriate Legendre polynomial, and θ is the scattering angle in the center-of-mass system.

The right side of this equation gives theoretical values to be matched with experimentally observed values of $\sigma_{\max}$, $\sigma_{\min}$, and $\lambda\bar{}$. Table II gives theoretical values for various possible energy level types under the experimental conditions of this work (151°, 1.65 Mev). The experimental values are 1.88 using the plus sign and 0.63 using the minus sign in the left side of Eq. (3).

Since the higher momentum states are less likely to be excited at these proton energies, we take the state with the lowest momentum which gives agreement with 1.88 or 0.63. This is obviously $P_{\frac{3}{2}}$. This is the same assignment given this level by Newton in studies of resonances in the reaction $Si^{28}(p,\gamma)P^{29}$ (reported by Endt and Braams[9]).

VI. SUMMARY

The only unambiguous data on nuclear energy levels obtained in this work was for silicon-28. All the other elements except chlorine show no definite structure at

[8] R. A. Laubenstein and M. J. W. Laubenstein, Phys. Rev. **84**, 18 (1951).

[9] P. M. Endt and C. M. Braams, Revs. Modern Phys. **29**, 683 (1957).

the resolution of these experiments (~10 kev). No decision could be made as to which isotope of chlorine is responsible for the two resonances observed. It appears worthwhile to investigate manganese, titanium, and potassium at high resolution inasmuch as resonance structure is very likely present in these elements.

ACKNOWLEDGMENTS

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Energy Levels of B^9 and O^{15}†

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Energy levels of B^9 have been investigated by the $B^{10}(He^3,\alpha)B^9$ reaction. Alpha-particle groups leading to the ground, 2.37-Mev and 2.83-Mev states of B^9 have been found. There is no evidence for any well-defined state between the ground state and 2.37-Mev state of B^9. The $O^{16}(He^3,\alpha)O^{15}$ reaction has been studied in the neighborhood of 5-Mev excitation in O^{15} and excited states have been found at 5.247- and 5.195-Mev energy in O^{15}.

INTRODUCTION

THE energy levels of Be^9 have been the subject of many recent studies.[1] It is of interest to compare the level structure of the mirror nuclei Be^9 and B^9, especially because of the unusual properties of the 1.75-Mev state in Be^9. Prior to the present investigation, the ground state and a state near 2.33 Mev in B^9 had been firmly established,[2–5] while a state in the vicinity of 1.4 Mev had been suggested.[4]

The energy level scheme of N^{15} is well known from precise measurements of the $N^{14}(d,p)N^{15}$ reaction,[1] while the O^{15} levels below the threshold for $N^{14}+p$ have been studied only by $N^{14}(d,n)O^{15}$ and by gamma-ray cascades[1] which do not provide resolution comparable to the (d,p) work. From a comparison of the N^{15} and O^{15} energy-level schemes it would be expected that there should be two levels in O^{15} just above 5 Mev corresponding to the 5.276- and 5.305-Mev states in N^{15}. The $O^{16}(He^3,\alpha)O^{15}$ reaction was employed in order to resolve these levels.

THE B^9 MEASUREMENTS

For both experiments singly charged He^3 ions were accelerated by the Kellogg Radiation Laboratory 3-Mv electrostatic accelerator and were selected in energy by an electrostatic analyzer. The reaction products were analyzed by a 16-inch double-focusing 180° magnetic spectrometer and detected by a 0.003-inch thick CsI (Tl) scintillator.

In the B^9 experiment a 96% enriched B^{10} target approximately 20 $\mu g/cm^2$ thick, evaporated on a tantalum backing, was used. An observation angle of 131° in the laboratory system was chosen in order to reduce the alpha-particle energy below the 10-Mev limit of the magnetic spectrometer. Alpha-particle spectra were taken at 2, 2.5, and 3 Mev He^3 energy, of which the 3-Mev spectrum shows the most pronounced structure (Fig. 1). Alpha-particle groups were found leading to the ground state and to excited states of B^9 at 2.37 ± 0.02-Mev and 2.83 ± 0.03 Mev (based on the assumed ground-state calibration). The shift of these excited-state groups with angle is consistent with their assignment to a level in B^9. A possible contribution of alpha particles in the region of the 2.83-Mev state from the $B^{11}(He^3,\alpha)B^{10}$ reaction due to B^{11} contamination of the target was excluded by the measurement of an alpha spectrum with a B^{11} target. The B^{11} reaction does not show any yield in this region. The width of the 2.37-Mev state was measured separately with improved resolution and was found to be 80 ± 15 kev, while the 2.83-Mev state width is about 300 kev. There is no indication of a level between the ground and 2.37-Mev states. To investigate excitation energies of B^9 between 4 and 7 Mev, the alpha spectrum was taken with the spectrometer at 90°. No sharp level was observed in this region.

The 2.37-Mev energy value for the state in B^9 established in this experiment is in agreement with the 2.33-Mev value[4] for the threshold of the same state, assuming the measured 80-kev width for this state. To

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