Elastic Scattering of 6.5-Mev Protons from Copper*

L. M. GOLDMAN†
Physics Department, University of Rochester, Rochester, New York
(Received September 29, 1952)

The 6.5-Mev protons from the 27-inch Rochester cyclotron have been used to determine the angular distribution of protons elastically scattered from copper. Significant differences from pure Coulomb scattering were observed. The results have been compared with the predictions of the Feshback-Weisskopf schematic theory and appear to disagree with these.

INTRODUCTION

MANY investigators[1–6] who have examined the angular distribution of energetic protons scattered from atomic nuclei have reported significant differences from pure Coulomb scattering. Since these differences must be attributed to a non-Coulomb interaction between the proton and the atomic nucleus, they are of interest in the study of nuclear forces.

Recently Shapiro[7] has applied the Feshbach-Weisskopf schematic theory[8] to the problem of elastic scattering of charged particles, and in particular he calculated an angular distribution for 7.3-Mev protons on copper. The measurement reported here of the angular distribution of the elastic scattering of 6.5-Mev protons from copper was undertaken as a check on the nuclear model used by Shapiro.

EXPERIMENTAL METHOD

The measurements were made with a 12-inch diameter circular scattering chamber containing a scintillation counter detector. A schematic diagram of the experimental arrangement is shown in Fig. 1. The 6.5-Mev protons from the Rochester cyclotron entered the scattering chamber through a set of three collimating apertures, traversed the target, and when undeflected stopped in the Faraday cup. The scattered particles were detected by the scintillation counter. The counter was supported inside the chamber in a mounting attached to a rotatable stainless steel arm. By rotating this arm from outside the chamber, the position of the counter could be adjusted to any angle from 0 to 160 degrees with respect to the incident beam. Since the axis of rotation of the counter coincided with the intersection of the beam with the target, the solid angle subtended by the detector at the target was the same for all angles of observation. Details of the construction of the chamber can be seen in Fig. 2.

A 1P21 photomultiplier and a NaI(Th) phosphor constituted the detector. The NaI crystal was mounted on a Lucite light pipe and covered with a 0.0002-inch aluminum foil. The clouding effect of water vapor on the surface of the crystals was no great problem as the crystals were in vacuum during the experiments.

Figure 3 is a block diagram of the electronic equipment used. All the instruments were of standard design with the exception of the 30-channel pulse-height analyzer which has been described elsewhere.[9] To insure that all the pulses entering the analyzer were of the same shape. The rise time and clipping time of the Model 500 amplifier were adjusted to 2 μsec and 8 μsec, respectively.

The copper foils bombarded in this research were obtained from the International Chromium Corporation of New Haven, Connecticut. Two different foils were used: one of thickness $(0.95\pm0.02)\times10^{-4}$ inch and the other $(2.07\pm0.03)\times10^{-4}$ inch.

The energy of the incident protons was ascertained from the range of the particles in aluminum. This range was found by observing the attenuation of the beam when successive thicknesses of aluminum foil were placed in front of the Faraday cup. The particles were found to have a mean range of 79.3 ± 1.0 mg/cm² of aluminum. This range corresponds to an energy of 6.50 ± 0.10 Mev.

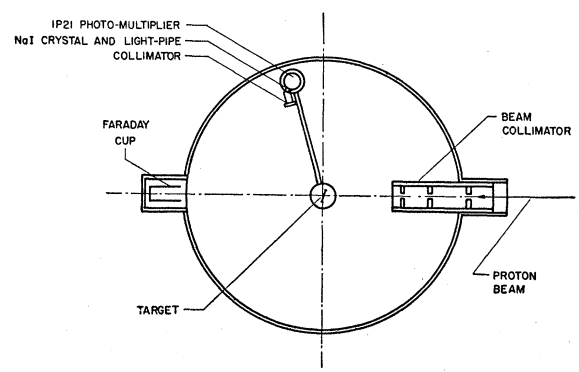

FIG. 1. Experimental arrangement.

* This research supported in part by the AEC.

† Now at Project Matterhorn, Forrestal Research Center, Princeton, New Jersey.

[1] E. G. Dymond, Proc. Roy. Soc. (London) **A157**, 30 (1936).
[2] Kanne, Taschek, and Ragen, Phys. Rev. **58**, 693 (1940).
[3] T. R. Wilkins, Phys. Rev. **60**, 365 (1941).
[4] Heitler, May, and Powell, Proc. Roy. Soc. (London) **A190**, 180 (1947).
[5] Baker, Dodd, and Simmons, Phys. Rev. **85**, 1051 (1952).
[6] J. W. Burkig and B. T. Wright, University of California at Los Angeles Technical Report No. 6 (1951) (unpublished).
[7] M. M. Shapiro, doctoral dissertation, Massachusetts Institute of Technology, 1950 (unpublished).
[8] H. Feshbach and V. Weisskopf, Phys. Rev. **76**, 1550 (1949).
[9] Fulbright, McCarthy, and McCutchen, Phys. Rev. **87**, 184 (1952).

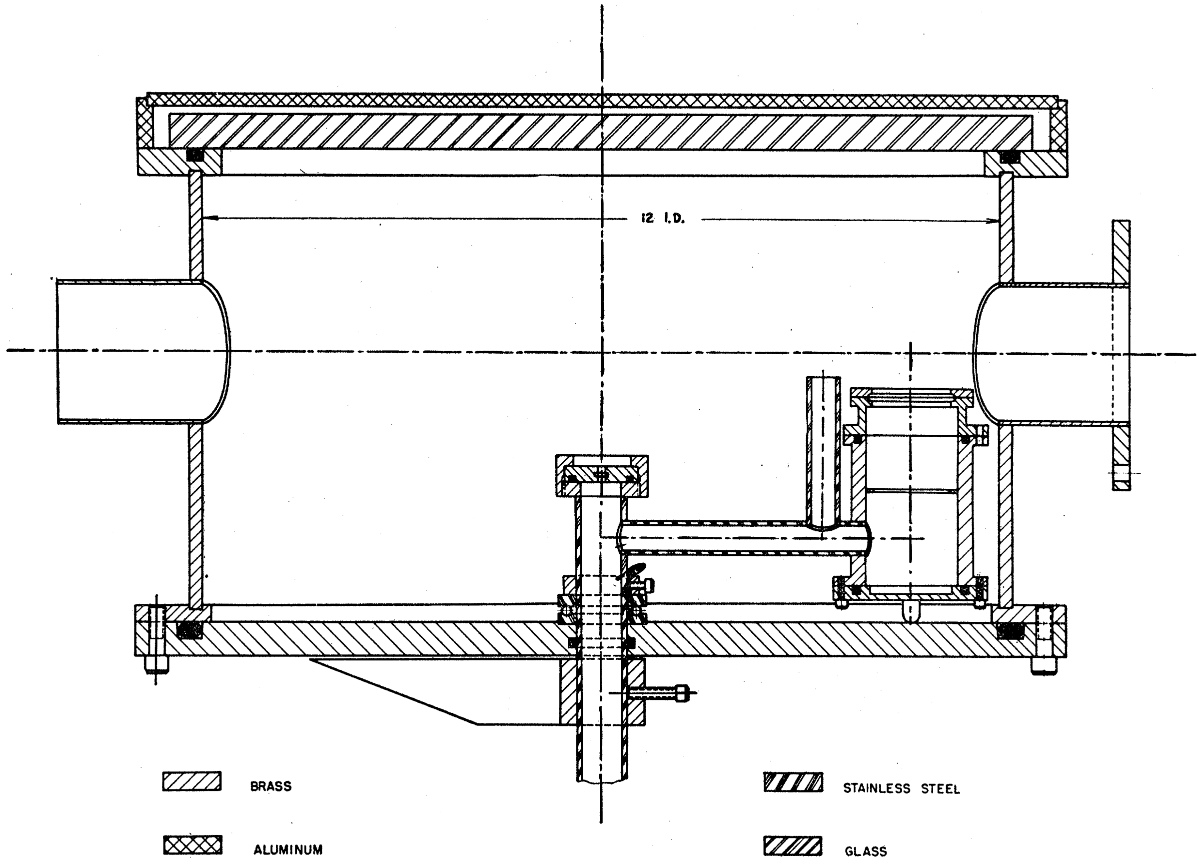

FIG. 2. Side view of the scattering chamber.

In determining the angular distribution of protons elastically scattered from copper, observations were made at 5-degree intervals from 20 to 135 degrees and at 10-degree intervals from 135 to 155 degrees. For each observation the detector angle and the target angle were set, the number of protons collected in the Faraday cup was measured, and the pulse-height spectrum of the detected particles was recorded by the 30-channel analyzer. Each of the pulse distributions showed a distinct peak which was attributed to the elastically scattered protons (see Fig. 4). This assignment was made for three reasons: one, the peak occurred at the same pulse height for the scattering from gold as it did for scattering from copper; two, there was only one peak; and three, the angular distribution that was determined for gold using this peak followed the expected Rutherford distribution to within 5 percent.

Thus the number of protons scattered into the angular region between θ and $\theta+d\theta$ was found by summing all the counts under the θ peak. $d\theta$ was determined by the finite size of the detector and was equal to 0.093° for this case.

EXPERIMENTAL RESULTS

Data from two separate runs were used to determine the angular distribution of the elastic scattering of 6.5-Mev protons from copper. The averaged results of these runs are shown in Fig. 5. The points plotted in Fig. 5 are the ratios of the observed relative differential cross sections to those predicted on the assumption of pure Coulomb scattering. The distribution was normalized by taking the ratio to be equal to 1 at 20 degrees. The error bars on the points are statistical standard deviations. With this normalization, appreciable differences from Rutherford scattering were found over the range between 30 and 150 degrees. The most prominent features of the distribution are the maxima at 45 and 125 degrees and the minimum at 75 degrees.

Different foils were used in the two runs to investigate the possibility of a systematic error due to target geometry. In addition, in one run the target was ad-

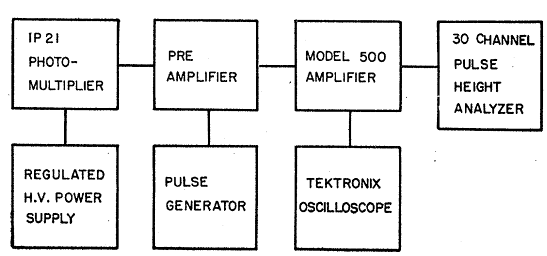

FIG. 3. Block diagram of the electronic apparatus.

justed so that the angle it made with the beam was just half the angle made by the counter, whereas in the second run the target was maintained at 45 degrees for all observations. The consistency of the two runs showed that no error caused by target geometry was detectable.

The accuracy of the whole experimental arrangement was determined by examining the angular distribution of protons elastically scattered by gold. As the Coulomb barrier for gold is more than 5 Mev above the energy of the incident protons, one would expect no nuclear scattering to contribute and therefore a pure Rutherford distribution should be observed. As can be seen in Fig. 6, the observed distribution for gold agrees with a pure Coulomb distribution to within 5 percent. An over-all accuracy of 5 percent is therefore claimed for the relative distribution presented here.

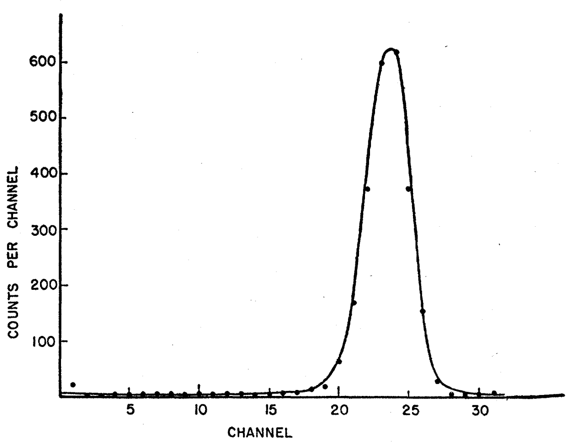

FIG. 4. Pulse-height spectrum observed at 30 degrees with a copper target.

DISCUSSION

The ratio of the differential cross section, including nuclear effects, to the Coulomb differential cross section can be written as

$$\frac{d\sigma}{d\sigma_c}=\frac{1}{\eta^2}\left|\sum_L\left\{(2L+1)\sin^2\frac{\theta}{2}e^{2i(\sigma_L-\sigma_0)}\times[e^{2i\Delta_L}-1]P_L(\cos\theta)+\eta\exp\left[-\left(\eta\sin^2\frac{\theta}{2}-\frac{\pi}{2}\right)\right]\right\}\right|^2, \quad (1)$$

where the only unknown quantities are the nuclear phase shifts Δ_L. The notation is the standard one used by Mott and Massey.[10]

An attempt was made to determine the unknown Δ_L's by fitting the observed distribution with real phase shifts alone. Only the first three phase shifts were con-

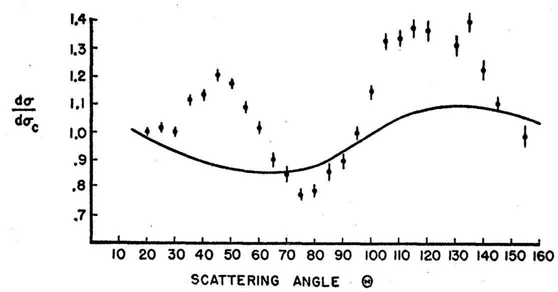

FIG. 5. The angular distribution of the elastic scattering of 6.5-Mev protons from copper. The points represent the relative differential cross section plotted as a ratio to Coulomb scattering. The solid curve is the prediction of the Feshbach-Weisskopf theory for $r_0=1.46$, and $V=20$ Mev.

sidered, as the Coulomb barrier is too high for $L=3$ waves to make any appreciable contributions. The method used was a graphical one suggested to the author by Dr. J. B. French. For this method Eq. (1) was expressed in terms of seven vectors, three of which contain the unknown phase shifts. One therefore looks for a set of Δ_L's such that the sum of the seven vectors is proportional to the observed $\{d\sigma/d\sigma_c\}^{\frac{1}{2}}$ for all angles. It was definitely found that the experimental results could not be described in terms of the real phase shifts alone.

It was therefore necessary to consider complex phase shifts, implying the presence of nuclear absorption. Nuclear absorption in this case would include all reactions other than elastic scattering.

The schematic theory of Feshbach and Weisskopf which was used by Shapiro to describe this problem assumes nuclear absorption and thus predicts complex phase shifts. This theory describes the interaction of the incident proton and the nucleus in terms of the nuclear radius R and the average effective potential V_0 which the nucleon sees inside the nucleus. The theory assumes that a nucleon entering the nuclear surface will not emerge in the same state in which it entered, i.e., that the target nucleus acts as a "sink" for the incident particles. This assumption determines

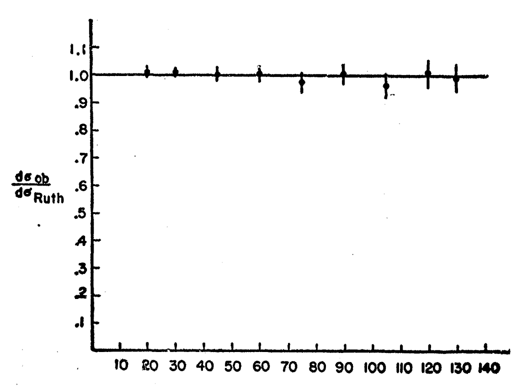

FIG. 6. Angular distribution of elastic scattering of 6.5-Mev protons from gold.

---

[10] N. F. Mott and H. S. W. Massey, *Theory of Atomic Collisions* (Clarendon Press, Oxford, 1949), second edition.

the logarithmic derivative at the nuclear surface and thus the phase shifts. Assuming the radius $R=r_0A^{\frac{1}{3}}$, $r_0=1.48\times10^{-13}$ cm, and $V_0=20$ Mev the phase shifts given by this theory are

$$\Delta0=(-0.367+0.178i),$$
$$\Delta1=(-0.209+0.128i),$$
$$\Delta2=(-0.069+0.062i).$$

By introducting the above values into Eq. (1), a theoretical angular distribution for the elastic scattering of 6.5-Mev protons from copper was determined. This distribution is shown by the solid curve in Fig. 5. The distribution does not differ appreciably from those calculated by Shapiro[7] for 7.35 Mev using the same parameters. Decreasing r_0 to 1.35 or increasing V_0 to 28 Mev does not greatly alter the shape of the distribution.

Comparing the theoretical distribution with the experimental, one finds very little agreement. The maximum at 45 degrees and the rapid decrease in the cross section at large angles which appear in the experimental distribution are not present in the theoretical one. The appearance of a minimum in both curves constitutes the only real agreement.

One may therefore conclude that: (1) definite nuclear effects are present in the elastic scattering of 6.5-Mev protons by copper; (2) the observed distribution cannot be fitted using only real phase shifts, implying that appreciable nuclear absorption takes place; and (3) the Feshbach-Weisskopf theory does not appear to describe adequately the interaction of a 6.5-Mev proton with a copper nucleus.

The author would like to express his indebtedness to Professors H. W. Fulbright and J. B. Platt for their continued interest and valuable advice. He wishes to thank Dr. J. B. French for many enlightening discussions. The complete cooperation and assistance of Dr. D. A. Bromley contributed largely to the conduct of this research.

PHYSICAL REVIEW VOLUME 89, NUMBER 2 JANUARY 15, 1953

Transition Probability for Photoelectric Emission from Semiconductors*

H. B. HUNTINGTON† AND L. APKER
General Electric Research Laboratory, Schenectady, New York
(Received October 6, 1952)

An adaptation of Makinson's theory of photoelectric emission from metals is used to treat simple one- and three-dimensional semiconductor models. The probability of excitation from a state of initial energy ϵ lying near ϵ_0, the top of an occupied band, is found proportional to $\epsilon_0-\epsilon$. Thus, the transition probability vanishes at the top of the band. For a density of states having the normal form, $n\sim(\epsilon_0-\epsilon)^{\frac{1}{2}}$, the energy distribution of the emitted electrons contains a factor $(\epsilon_0-\epsilon)^{\frac{3}{2}}$ and is thus concave upward near the band edge.

For certain simple surfaces, the photoelectric threshold may be high because transitions requiring low energy are forbidden. It is pointed out that this feature is an idealization probably not found for real surfaces having the usual inevitable irregularities. In a qualitative discussion, more realistic cases are mentioned. It is suggested that the results retain the form derived above, although the high threshold energy disappears.

An energy distribution proportional to $(\epsilon_0-\epsilon)^{\frac{3}{2}}$ near the band edge is in good agreement with previous experimental results on Te and other monatomic semiconductors. With the graphical methods of analysis previously applied to data on these materials, the point of view taken above permits more definite location of the edges of occupied bands. Improved estimates of upper limits to the density of occupied surface levels are then possible.

I. INTRODUCTION

RECENT experiments indicate that the external photoelectric effect can give useful information on the electronic energy structure of solids.[1] There is interest in certain monatomic semiconductors and semimetals, for which photoelectric data are available in the form of a product $n(\epsilon)\cdot s(\nu,\epsilon)$. Here the quantity of interest is n, the density of electronic energy states expressed as a function of the energy ϵ; s is a photoelectric excitation probability which may be a function of both ϵ and the frequency ν.[2] In the absence of theoretical information, it has not been possible to isolate n without making questionable assumptions about the form of s. This paper attempts to improve this situation by showing that in certain idealized cases s is proportional to $\epsilon_0-\epsilon$ in the vicinity of ϵ_0, the top of the occupied energy band. These restricted conclusions are then qualitatively extended to more complicated and realistic situations.

There have been many attempts to develop a satisfactory theory of the external photoelectric effect at surfaces of simple metals.[3] A recent and elegant treatment of the problem has been given by Makinson.[4] His

* Presented in part at the Chicago meeting of the American Physical Society, November, 1950 [see Phys. Rev. 81, 321 (1951)].

† On summer leave (1949) from Rensselaer Polytechnic Institute, Troy, New York.

[1] Apker, Taft, and Dickey, Phys. Rev. 76, 270 (1949), and foregoing papers.

[2] Apker, Taft, and Dickey, Phys. Rev. 74, 1462 (1948).

[3] For a review and recent theory, see K. Mitchell, Proc. Roy. Soc. (London) 146, 442 (1934).

[4] R. E. B. Makinson, Phys. Rev. 75, 1908 (1949).