PHYSICAL REVIEW VOLUME 95, NUMBER 3 AUGUST 1, 1954

The Elastic Scattering of 18-Mev Protons by Al, Fe, Ni, and Cu†

IRVING E. DAYTON
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey

(Received February 2, 1954)

The absolute differential cross section for the elastic scattering of 18-Mev protons has been measured for Al, Fe, Ni, and Cu at 35 or more angles between 15 degrees and 172 degrees. The estimated standard deviation of each point is 3 percent. The scattered protons are detected by a sodium iodide crystal whose energy resolution is about 2.5 percent, and the resulting pulse spectrum is recorded on a 15-channel pulse-height analyzer. For all materials used, protons scattered inelastically to the lowest known level are completely resolved from the elastic group. The differential cross sections for the four elements are qualitatively similar, showing pronounced structure and low cross sections in the background direction. The experimental results are in disagreement with cross sections predicted by the optical model of the nucleus.

I. INTRODUCTION

THE measurement of the elastic scattering cross section of nucleons by nuclei provides a method for studying several properties of the nucleus. At low nucleon energy the scattering cross sections give information about single levels in the compound nucleus. This resonance scattering cannot be observed if the incident nucleon energy exceeds several Mev, since the levels of the compound nucleus become wide and overlapping. The scattering cross section should then show little variation with the energy of the incident nucleon.

This elastic scattering is often called potential or diffraction scattering because the differential cross sections show great similarity to optical diffraction patterns. This analogy has been used in constructing the optical model[1] of the nucleus. The optical model replaces the field of the nucleus by a complex potential in analogy to a complex refractive index for the scattering of light by a partly opaque body. The imaginary part of the potential is responsible for the absorption of a fraction of the incident beam by the nucleus.

The optical model has been successfully applied in the high energy region to neutron scattering[1,2] and to the analysis of meson reactions.[3,4] It has also been used successfully in predicting the energy and Z dependence of the total neutron cross sections up to 3 Mev.[5] However, these applications constitute a relatively weak test of the theory, since it was only necessary to fit total cross sections. Kessler and Lederman[6] recently report being able to fit total cross sections for high-energy mesons but not the angular dependence of the scattering cross sections.

The optical model was first used in the intermediate energy region by LeLevier and Saxon,[7] who succeeded in fitting the data of Burkig and Wright[8] on the elastic scattering of 18.6-Mev protons by Al. Gugelot[9] performed additional experiments at 18.3 Mev, the results of which were compared with those from optical model calculations by Chase and Rohrlich.[10] They confirmed the agreement between theoretical and experimental cross sections for the scattering of protons by Al. However, they were able to show that for heavier elements the backward scattering cross section was lower than the theoretical values for any square well potential. It now appears that the initial agreement in the case of Al was illusory, for in the earlier experiments[8,9] data were taken at such wide intervals that the sharp structure of the differential cross section was completely missed.[11]

The disagreement between theoretical and experimental results makes it impossible to obtain information about the nuclear radius, since the positions of the maxima of the diffraction pattern are a function not only of the nuclear radius but also of the other parameters of the potential (see Fig. 4). The usual calculations for diffraction scattering by a black nucleus,[12] in addition to leaving out Coulomb effects, contain small angle approximations which are not valid in the present case. The qualitative conclusions of Cohen and Neidigh[11] about the position of the diffraction maxima as a function of nuclear radius on the basis of simple diffraction theory would appear to be fortuitous.

Spin-orbit forces have been invoked by the shell model to explain the details of bound states in nuclei, and these forces may have to be added to the optical model to obtain complete agreement with experiment. The data presented in this paper may help to prove whether or not the interaction between a nucleon and the nucleus can be represented by a single potential independent of angular momentum and energy.

All of this information could also be obtained from neutron scattering data, and the absence of Coulomb

---

† Supported by the U. S. Atomic Energy Commission and The Higgins Scientific Trust Fund.

[1] Fernbach, Serber, and Taylor, Phys. Rev. **75**, 1352 (1949).
[2] J. DeJuren and N. Knable, Phys. Rev. **77**, 606 (1950).
[3] H. A. Bethe and R. R. Wilson, Phys. Rev. **83**, 690 (1951).
[4] Byfield, Kessler, and Lederman, Phys. Rev. **86**, 17 (1952).
[5] Feshbach, Porter, and Weisskopf, Phys. Rev. **90**, 166 (1953).
[6] J. O. Kessler and L. M. Lederman, Phys. Rev. **94**, 689 (1954).
[7] R. E. LeLevier and D. S. Saxon, Phys. Rev. **87**, 40 (1952).
[8] J. W. Burkig and B. T. Wright, Phys. Rev. **82**, 451 (1951).
[9] P. C. Gugelot, Phys. Rev. **87**, 525 (1952).
[10] D. M. Chase and F. Rohrlich, Phys. Rev. **94**, 81 (1954).
[11] B. L. Cohen and R. V. Neidigh, Phys. Rev. **93**, 282 (1954).
[12] B. T. Feld *et al.*, Atomic Energy Commission Report NYO-636 (unpublished).

effects would make the analysis considerably simpler. However, the experimental problems connected with intensity and energy resolution are formidable, and it may be some time before the neutron data will approach in accuracy what is now easily obtainable with protons.

II. EXPERIMENTAL TECHNIQUE

This experiment was carried out using the 60-in. precision scattering chamber and Faraday cup constructed by Yntema and White.[13] The center of the chamber, where the target was located, was about 8 meters from the cyclotron. The beam was collimated by two $\frac{1}{4}$-in. diameter apertures, one 1.32 meters from the center of the scattering chamber and the other 0.56 meter from the center. Each of these collimators was followed by baffles to remove slit-scattered protons from the beam.

The charge collected in the Faraday cup flowed through a calibrated resistance, developing across it a voltage which was integrated electronically. The integrator circuit could be checked by applying a known voltage to the input. It was found that the drift was less than one percent during running times of the order of five hours. The performance of the integrator circuit has also been checked by substituting for it an electrometer which measures the charge collected on a polystyrene capacitor. Cross sections obtained by the two methods checked to within the counting statistics of 2 percent.

The energy of the beam was determined from the range in Al of protons scattered at 90 degrees from C^{12}. The recent experimental range-energy data of Bichsel and Mozley[14] was used. The theoretical range-energy relation of Smith[15] would increase the quoted energies by about 140 kev. The beam energy was measured at the beginning of each run, and was adjusted so that it was the same for all runs with a given element. Tests have been made which indicate that the beam energy remains constant to ±50 kev over periods of 24 hours if operating conditions are not changed. The pulse height from the photomultiplier tube would have shown any short time changes in beam energy large enough to affect the measured cross sections.

The scattering foils were at an angle of 45 degrees to the incident beam for data taken between 50 degrees and 135 degrees, and normal to the beam for the other points. The Al foil was about 7 mg/cm^2 thick; for the other materials the thickness varied between 3 and 4 mg/cm^2. In the case of Fe, Ni, and Cu, the counting rate in the backward direction was so low that it was necessary to double the foil thickness there. With two foils it was always possible to repeat to within statistics data taken with a single foil. For this reason it is believed that effects due to multiple scattering were negligible.

Detector

The scattered protons were detected by a NaI(Tl) crystal mounted on the face of a 5819 photomultiplier tube. The counter was located at distances of 30 cm to 50 cm from the target. In general, the counter aperture subtended an angle of about 0.6 degree. However, for data taken on Al at angles less than 90 degrees this was reduced to one-third of a degree. Yntema and White[13] and Brockman[16] have made estimates which show that under these circumstances geometry corrections are quite small.

After amplification, the pulses from the photomultiplier were fed into a 15-channel differential discriminator of the Oak Ridge design.[17] The resolution of the crystal (full width at half-maximum) was generally about 2.5 percent. The gain of the system was adjusted so that the elastic peak was about three or four channels wide at half-maximum. This meant that in addition to the elastic peak the spectrum of all protons scattered inelastically with a loss of up to 1.0 or 1.5 Mev was also recorded. If one restricts his attention to isotopes whose natural abundance is more than a few percent, the lowest reported level in Al is at 0.84 Mev[18]; in Fe at 0.82 Mev[19]; Ni, 1.34 Mev[19,20]; and Cu, 0.96 Mev.[19] In all cases peaks were observed due to inelastic scattering to levels at about these energies, and these peaks were completely resolved from the elastic peak. Any existing unreported energy levels between 0.5 Mev and these levels would have been observed. Levels lower than about 0.25 Mev would have been missed since they would not be resolved from the elastic peak. The importance of the rejection of inelastically scattered protons will be discussed in the section on results.

The cross sections were determined from the area under the elastic scattering peak. The measured cross sections are corrected for the fact that about 1 percent of the beam at the target has an energy at least 300 kev less than the mean beam energy.[21] Because of the energy resolution of the detector, events produced by this low-energy tail will not be recorded.

This energy resolution also eliminated effects due to "slit scattering" from the detector collimator because any proton whose total path length in the brass collimator was more than about 0.0008 in. would be rejected. Calculations by Courant[22] bear out the

---

[13] J. L. Yntema and M. G. White, Atomic Energy Commission Report NYO-3478 (unpublished).

[14] H. Bichsel and R. F. Mozley, Phys. Rev. **94**, 764 (1954).

[15] J. H. Smith, Phys. Rev. **71**, 32 (1947).

[16] K. W. Brockman, Princeton University thesis, 1954 (unpublished).

[17] A. B. Van Rennes, Nucleonics **10**, No. 10, 50 (1952).

[18] Nuclear Science Abstracts **6**, No. 24*B*, 12–13 (1952).

[19] Hollander, Perlman, and Seaborg, Revs. Modern Phys. **25**, 469 (1953).

[20] Ely, Allen, Arthur, Bender, Hausman, and Reilley, Phys. Rev. **86**, 859 (1952).

[21] R. W. Peelle (unpublished measurements).

[22] E. D. Courant, Rev. Sci. Instr. **22**, 1003 (1951).

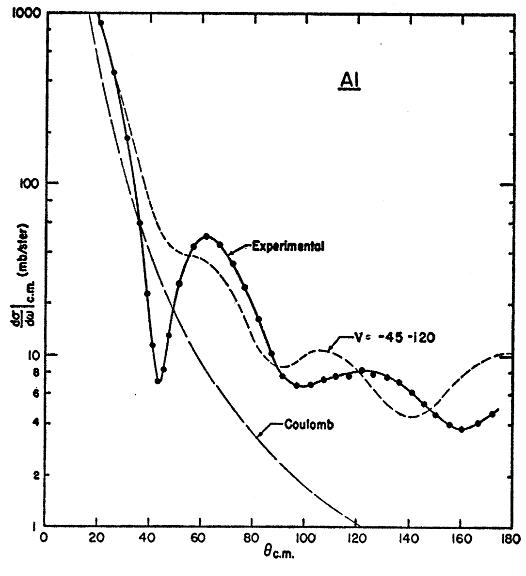

FIG. 1. Measured differential cross section for the elastic scattering of 18.4±0.1-Mev protons by Al. The estimated standard deviation is given by the size of the points. Included for comparison are curves calculated for Coulomb scattering from a point charge and for Coulomb plus a complex square well potential.

conclusion that the increase in effective solid angle in this case is negligible.

Errors

Data were taken every five degrees from 15 degrees to 172 degrees. Additional points were taken near the minima so that their true shape was resolved. At least 2500 counts were taken at each point. In addition to the statistical errors in counting there may also be random errors due to short-time drifts in the integrator (1 percent maximum) and random error in determining the area under the elastic scattering peak (2 percent). Errors in other parameters were negligible compared to these. These are combined to give a conservative estimated standard deviation of 3 percent for each point.

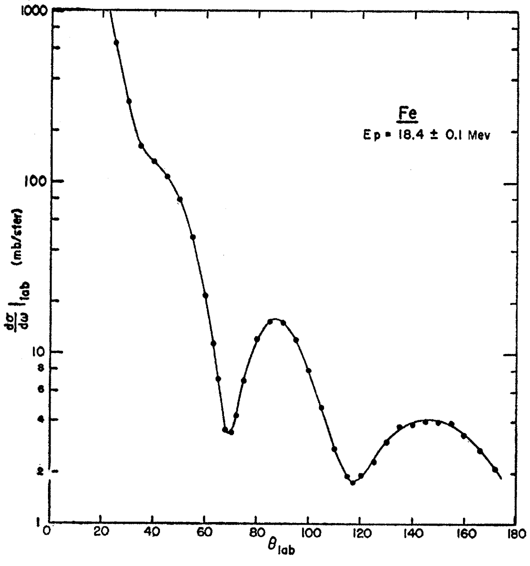

FIG. 2. Measured differential cross section for the elastic scattering of 18.4±0.1-Mev protons by Fe. The estimated standard deviation is given by the size of the points.

III. RESULTS

The measured differential cross sections are plotted in Figs. 1 through 4. The energy of the proton beam was 18.4±0.1 Mev for Al and Fe, 18.1±0.1 Mev for Ni, and 18.7±0.1 Mev for Cu. The estimated standard deviation is given by the size of the points. As a matter of convenience, smooth curves have been drawn through the points. The data for Al have been transformed to the center-of-mass system; for the other materials the correction is at most one degree in angle and 4 percent in solid angle and has not been included.

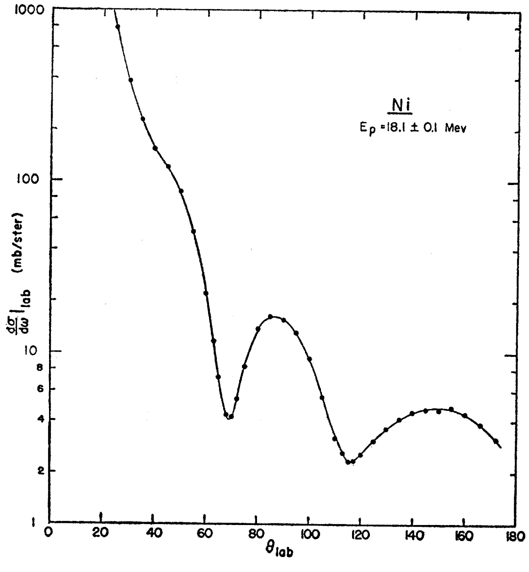

FIG. 3. Measured differential cross section for the elastic scattering of 18.1±0.1-Mev protons by Ni. The estimated standard deviation is given by the size of the points.

Inelastic Scattering

As mentioned in the preceding section, it was possible to observe the inelastic scattering to the lowest level in each target material. The angular distribution of the inelastic scattering is strikingly different from that of the elastic scattering, and appears to be smooth and peaked somewhat in the forward direction. Near minima in the elastic cross section the inelastic scattering is comparable with it, and near maxima the inelastic scattering is small compared with the elastic. This effect is most pronounced near the first minimum and smaller in the backward direction.

This fact would lead to serious consequences if one attempted to measure the differential cross section for elastic scattering with an energy resolution of several Mev. In the nuclei studied here, inelastic scattering from several levels would then be included, and as a result the cross section near the first minimum could be in error anywhere from 50 percent to a factor of three or four. In contrast, measurements in the forward direction and near the second peak would be virtually unchanged. Hence, the effect of poor energy resolution is to smooth out the structure in the curves. The available energy resolution may make it difficult to obtain reliable elastic scattering data for heavier elements, where in general the levels are more closely spaced and nearer to the ground state.

IV. DISCUSSION

Many of the features of the measured cross sections can be explained qualitatively by using the simple model of a plane wave diffracted by a spherical obstacle. The curves for Fe, Ni, and Cu are plotted together in Fig. 5 in order to facilitate comparison. At angles less than 30 degrees, the cross section increases with increasing Z. This fact agrees with expectations, since Coulomb scattering predominates in that region.

Since Cu is the largest nucleus of the three, and since the incident proton energy was highest in this case, its "diffraction pattern" should be the narrowest, which is in fact the case. In Fe and Ni the effects of nuclear size and beam energy go in the opposite direction and apparently approximately compensate each other. In the region around 40 degrees, one can see another minimum starting to form as the size of the nucleus decreases. The "diffraction pattern" argument also shows that the first minimum in the Fe, Ni, and Cu curves corresponds to the second minimum in the Al curve.

The Fe and Ni nuclei have spin 0, Cu has spin 3/2, and Al has spin 5/2. However, it is not possible to observe any qualitative change in the curves which might be ascribed to any spin interaction. It will be necessary to have detailed calculations available in order to decide to what degree the nuclear spin may have an effect on the scattering cross section.

Comparison with Optical Model Calculations

Chase and Rohrlich[10] have made calculations on the elastic scattering of 18.3-Mev protons using the optical model with a square well potential. Some of their curves are compared with the experimental results for Al and Cu in Figs. 1 and 4. The curves labeled "Coulomb" refer to pure Rutherford scattering from a point charge. For Cu the curve $V=-45\ -31i$ Mev is almost identical with that for $V=-45-20i$ Mev and has not been plotted.

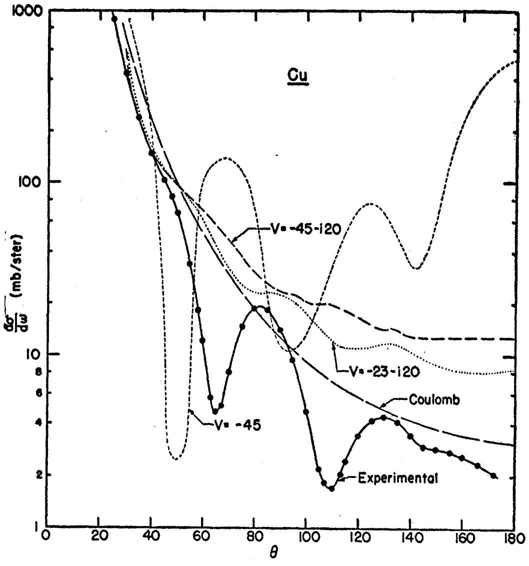

FIG. 4. Measured differential cross section for the elastic scattering of 18.7±0.1-Mev protons by Cu. The estimated standard deviation is given by the size of the points. Included for comparison are curves calculated for Coulomb scattering from a point charge and for Coulomb plus different complex square well potentials.

It can be seen that the results of the calculations presented are in disagreement with the experimental results. Over a wide variation in parameters the complex square well potential will not yield both the pronounced structure and the low cross section in the backward direction found by experiment. It is possible to decrease the backward cross section somewhat by increasing the imaginary (absorptive) part of the potential. On the other hand, in order to reproduce the structure of the curves, a small absorptive potential is necessary. When the absorption is reduced, the backward cross section increases rapidly due to reflection scattering. All of these features are exhibited in the graphs of Fig. 4.

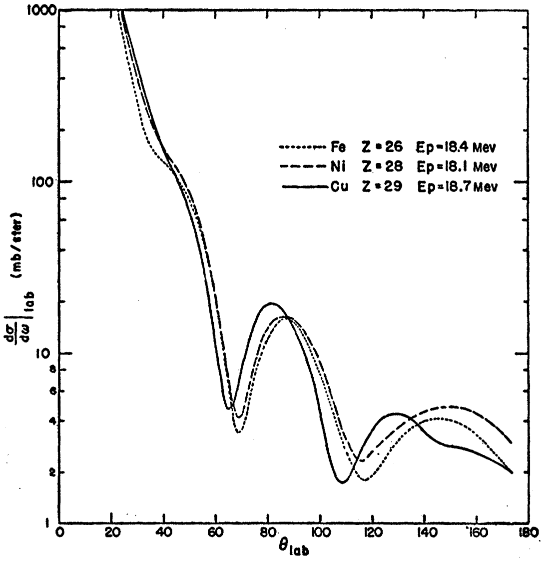

FIG. 5. Comparison of the measured differential cross sections for Fe, Ni, and Cu.

Chase and Rohrlich[10] point out that this unsatisfactory state of affairs may stem from the use of a square well potential whose sharp boundary produces large reflection scattering when the absorption is small. They suggest that a long-tail potential with a small (about 5 Mev) imaginary part might prove more satisfactory. However, a small absorptive potential is in disagreement with the known reaction cross sections, which are approximately geometric. If a long-tail potential were sufficiently "soft" to reduce reflection scattering, it is hard to see how it could at the same time produce a sharp diffraction pattern in the forward direction.

It is important to repeat these experiments with neutrons, for the absence of the Coulomb scattering may reveal whether these discrepancies are due to specific nuclear effects or to the interplay of nuclear and Coulomb scattering.

V. ACKNOWLEDGMENTS

The author wishes to thank Professor P. C. Gugelot for suggesting this experiment and for many helpful discussions during it. Dr. John McIntosh and Dr. W. A. Aron provided illuminating discussions of the theory. The author is deeply indebted to Mr. R. W. Peelle and Mr. J. B. Reynolds for their patient introduction to the lore of the Princeton cyclotron.

PHYSICAL REVIEW VOLUME 95, NUMBER 3 AUGUST 1, 1954

Activities Produced in Gold by Proton Bombardment*

C. H. Braden, L. D. Wyly, and E. T. Patronis, Jr.
School of Physics, Georgia Institute of Technology, Atlanta, Georgia

(Received April 15, 1954)

We have investigated activities produced in gold by bombardment with 12- and 20-Mev protons. Gamma rays of 1.17, 0.81, 0.58, and 0.255 Mev energy are found in the Hg fraction from the target bombarded at 20 Mev. These gamma rays all decay with a half-life of 42±3 hours and we ascribe them to Hg^{195} produced by the Au(p,3n)Hg reaction. Our data concerning the decay of Hg^{197}, Au^{196}, and Au^{195} are, in most cases, consistent with previous work.

INTRODUCTION AND EXPERIMENTAL PROCEDURE

We have studied the gamma-ray spectra of activities produced by the bombardment of gold with 12- and 20-Mev protons in the Oak Ridge 86-inch cyclotron. Bombardments at about 12 Mev were accomplished by inserting slowing down foils in front of the target. Mercury and gold were separated using iso-amyl acetate by a chemical procedure similar to that of Fink and Wiig.[1] In one 20-Mev sample a platinum separation was made six days after bombardment; no change in the spectrum of the mercury fraction was detected.

The gamma-ray spectra were investigated using standard scintillation counter methods. Gamma rays were detected by use of a $1\frac{1}{2}$-in. diameter by 1 in. NaI(Tl) crystal affixed to a DuMont type 6292 photomultiplier tube. The pulses were amplified by an Atomic Instrument Company amplifier and applied to either an Atomic Instrument or a locally built single-channel pulse-height analyzer. A resolution of about 12 percent was obtained for the Cs^{137} 0.662-Mev gamma line. Some gamma-gamma coincidence work was done using two such gamma-ray counters and a coincidence circuit based on the fast-slow method.[2] The resolving time of our fast-coincidence circuit was limited by the rise time of the amplifier to about 0.25×10^{-6} sec. The coincidence circuits are a modification of one described by Elmore.[3] The associated trigger, delay, and pulse-shaping circuits are modifications of standard designs. A block diagram of the coincidence counting setup is given in Fig. 1. A section of delay line was inserted in one of the fast-coincidence channels in order to determine the accidental counting rate.

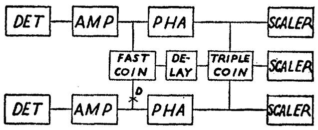

FIG. 1. Block diagram of the experimental arrangement used for gamma-gamma coincidence measurements. The detectors are NaI(Tl) crystals mounted in DuMont type 6292 photomultiplier tubes. The resolving time of the fast coincidence circuit is about 0.25×10^{-6} sec. A delay may be inserted at D in order to determine the accidental rate.

MERCURY DECAY ACTIVITIES

Figure 2 is a gamma-ray spectrum of Hg^{197} produced by the Au(12-Mev$p$,n)Hg reaction. Some gamma rays found by other investigators in conversion electron

---

* Supported in part by the National Science Foundation.

[1] R. W. Fink and E. O. Wiig, J. Am. Chem. Soc. **74**, 2457 (1952).

[2] F. K. McGowan, Phys. Rev. **79**, 404 (1950); **93**, 163 (1954).

[3] W. C. Elmore, Rev. Sci. Instr. **21**, 649 (1950).