PHYSICAL REVIEW VOLUME 101, NUMBER 5 MARCH 1, 1956

Elastic Scattering of 40-Mev Alpha Particles from Light Elements*

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(Received November 30, 1955)

The angular distribution for the elastic scattering of 40-Mev alpha particles from C, Al, Ti, Cu, Nb, Mo, and Ag has been measured. The angular distributions are characterized by strong diffraction patterns in contrast to the monotonically decreasing angular distributions of alpha particles scattered from Ta, Au, Pb, and Th. An analysis of the relative positions of the diffraction maxima yields a value for the interaction radius of $[(1.27\pm0.07)A^{\frac{1}{3}}+(1.60\pm0.23)]\times10^{-13}$ cm. A comparison is made of the angular distributions measured at the energies of 19, 22, 40, and 48 Mev.

INTRODUCTION

The angular dependence of the cross section for elastic scattering of alpha particles has been investigated recently for various elements at several bombarding energies. At 22 Mev for Ag, Pb, and Au, the ratio of the observed to Coulomb differential cross section, $(d\sigma/d\Omega)/(d\sigma/d\Omega)_C$, decreases exponentially with increasing angle beyond a critical angle.[1] At 40 Mev for Ta, Au, Pb, and Th,[2] $(d\sigma/d\Omega)/(d\sigma/d\Omega)_C$ increases slightly above one and then decreases exponentially with increasing angle. At 48 Mev for Ag, Au, and Pb,[3] a weak diffraction pattern superimposed on an exponential decrease is observed. Strong diffraction patterns maintaining an average value for this ratio of 0.7 and 0.5 are observed for Al at 19 Mev[4] and 40 Mev,[5] respectively. At 19 Mev, Cu exhibits a weak diffraction pattern superimposed on an exponential decrease similar to that observed for the heavy elements.[4]

The exponential decrease found in heavy-element cross sections has been interpreted[1,2,6,7] by using semiclassical models for the interaction of the alpha particle with the nucleus. The angular distributions of alpha particles scattered from the light elements have been interpreted as due to diffraction from a strongly absorbing nucleus, and the radii deduced from the diffraction patterns are compatible with the currently accepted values of nuclear radii.[4,5,8]

The purpose of the present work is to examine the angular dependence of $(d\sigma/d\Omega)/(d\sigma/d\Omega)_C$ at 40 Mev over a range of elements: C, Al, Ti, Cu, Nb, Mo, and Ag. A composite plot of the data shows the details of the gradual change from the diffraction to the exponential behavior. The interaction radius between the alpha particle and the nucleus, determined from the measurements, is $R=[(1.27\pm0.07)A^{\frac{1}{3}}+(1.60\pm0.23)]\times10^{-13}$ cm.

APPARATUS AND PROCEDURE

The scattering apparatus used in these experiments has been described in an earlier paper.[2] The following improvements and changes may be mentioned:

(a) The scattering chamber has been adapted to decrease the smallest angle for which measurements are possible from 21° to 8° for the experiment with C.

(b) The NaI scintillator used in the earlier measurements as a detector has been replaced in some of this work by an arrangement of counters which can separate the alpha particles from other reaction particles present in the form of a continuum.

(c) An absorber placed between the scatterer and detector effectively increased the over-all resolution of the detecting system so that inelastic contributions could be separated from the elastic data.

The detecting system described in item (b) consists of a counter telescope consisting of two thin proportional counters[9] followed by a NaI scintillator.[10] In this application of the method (described in detail in reference 10), the product of the smallest of two pulses from the proportional counters, which measure the specific ionization, and the pulse from the NaI scintillator, which measures the energy, was obtained from a multiplying circuit.[11] The output of the multiplying circuit is approximately proportional to MZ^2, where M and Z are respectively the mass and charge of the detected particle. The relative values of this quantity for a proton, deuteron, and alpha particle are 1:2:16, respectively. The voltage window of a single-channel pulse-height analyzer was set to accept only the output pulses corresponding to alpha particles. The output of the single-channel analyzer was used to gate on a 20-channel pulse-height analyzer into which the pulses from the NaI scintillator are also fed. By this method, the energy distribution of the alpha particles is obtained.

* Work performed under the auspices of the U. S. Atomic Energy Commission.
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[1] Wall, Rees, and Ford, Phys. Rev. **97**, 726 (1955).
[2] Wegner, Eisberg, and Igo, Phys. Rev. **99**, 825 (1955).
[3] L. Schechter and R. Ellis, Phys. Rev. **99**, 1044 (1955); R. Ellis and L. Schechter, **101**, 636 (1956).
[4] E. Bleuler and D. J. Tendam, Phys. Rev. **99**, 1605 (1955).
[5] Eisberg, Igo, and Wegner, Phys. Rev. **99**, 1606 (1955).
[6] J. S. Blair, Phys. Rev. **95**, 1218 (1954).
[7] C. E. Porter, Phys. Rev. **99**, 1400 (1955).
[8] A. Bratenhl *et al.*, Phys. Rev. **77**, 597 (1950).
[9] R. M. Eisberg and H. E. Wegner, Rev. Sci. Instr. **25**, 1129 (1954).
[10] G. Igo and R. M. Eisberg, Rev. Sci. Instr. **25**, 450 (1954).
[11] Massachusetts Institute of Technology Annual Progress Report, August 31, 1953 (unpublished).

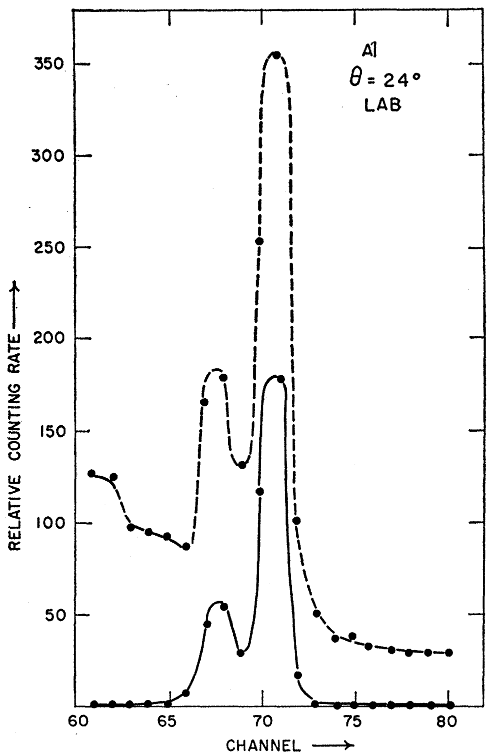

FIG. 1. Pulse-height spectrum of charged particles emitted by Al foil at 24° in the laboratory system. The dashed curve is measured with the NaI detector; the solid curve, with the counter telescope.

Figure 1 shows typical spectra taken with the NaI detector and also with the counter telescope which requires the coincidence gate. The two curves indicate that the continuum in the spectrum taken with the NaI detector is due primarily to protons and deuterons from nuclear reactions in the target. By utilizing the coincidence gate requirement, angular distributions could be measured at angles where the reaction continuum is larger in magnitude than the elastic scattering cross section, as is usually the case at larger scattering angles. In addition, a triple-coincidence requirement between pulses from the three counters eliminates counts from the crystal caused by induced radioactivity in the NaI and by gamma rays from the target. The Cu angular distribution was measured with both detectors and the two measurements were in good agreement.

In reference to item (c), inelastic scattering from the low-lying levels could contribute to the elastic peak. For example, Al has low-lying levels at 0.84 Mev and 1.01 Mev. In order to minimize the inelastic contributions, a 50-mg absorber (Al equivalent) was placed between the detector and target. At 23°, 39.2, 38.4, and 38.1-Mev alpha particles are emitted from the ground, first, and second excited states of Al with a separation of 0.8 Mev and 1.1 Mev between groups

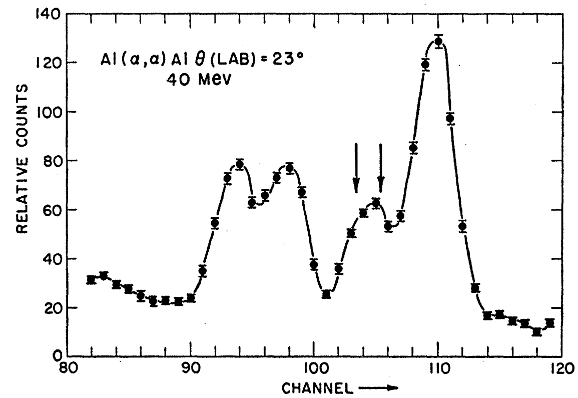

FIG. 2. Pulse-height spectrum of charged particles emitted by Al at 23° after passing through a 50-mg absorber. The arrows indicate the position of the inelastic groups from the first and second excited states of Al.

(2 percent and 3 percent, respectively). After passing through the 50-mg absorber, the energies calculated from the range-energy tables[12] are 29.9, 28.9, and 28.5 Mev, respectively. Because of the nonlinear response of NaI to alpha particles, the resultant pulse heights now correspond respectively to 25.4, 24.4, and 24.0. The calculated separation between groups is now 4 and 6 percent, respectively. Hence the introduction of an absorber has increased the over-all resolution.

Figure 2 shows a spectrum from a 1.5-mg/cm² Al target taken at 23° in the laboratory system where the elastic differential cross section is at a minimum. The secondary levels are relatively large only in the vicinity of the diffraction minima. The peak at channel 110 is the elastic peak and the arrows indicate the positions calculated for the inealstic groups from the first and second excited states. The peak observed at channel 105 probably contains contributions from both inelastic groups. It is concluded that the Al elastic data do not contain large contributions from inelastic scattering. By comparing spectra from 1.5 mg/cm² and 13 mg/cm² Al targets, the peaks located at channels 94 and 98 have been shown to be caused by scattering from oxide impurities on the surface of the targets.

With the exception of Mo and Ag, the first excited state of the other elements investigated lies approximately 1 Mev or more above the ground states and can be resolved. It is, therefore, concluded that the elastic peaks do not contain large contributions from inelastic events except possibly for Mo and Ag. Because of possible inelastic contributions, the position and shape of the maxima of the diffraction patterns are more reliable than those of the minima. The data, for all the elements except C, were taken with the 50-mg absorber in place. The first excited state in C is at 4.4 Mev; thus the additional resolution was not required.

[12] Aron, Hoffman, and Williams, U. S. Atomic Energy Commission Report AECU-663, May 28, 1951 (unpublished).

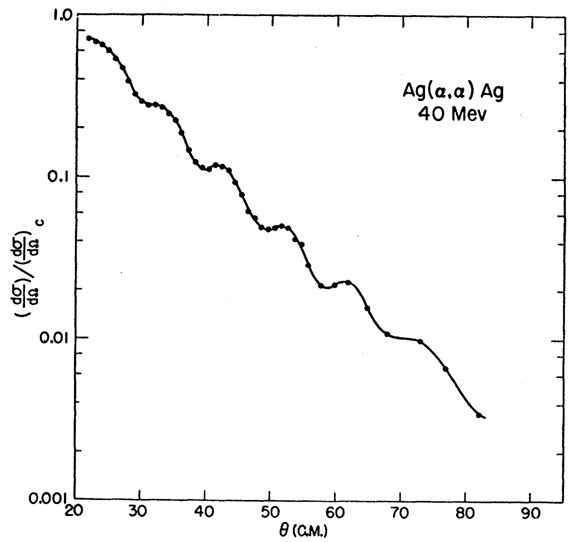

FIG. 3. Angular distribution of 40-Mev alpha particles elastically scattered from Ag.

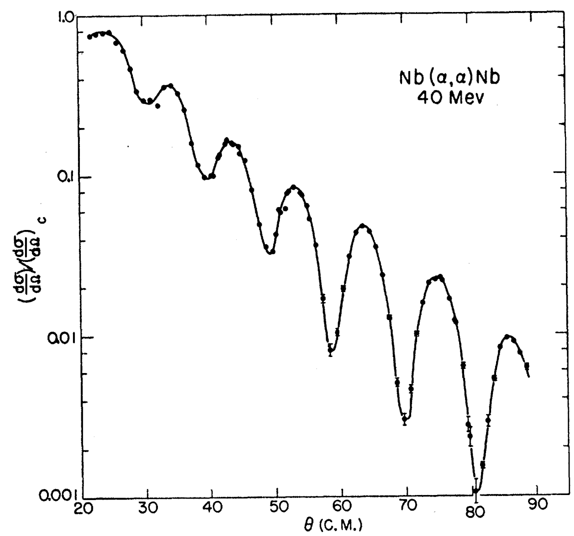

FIG. 5. Angular distribution of 40-Mev alpha particles elastically scattered from Nb.

EXPERIMENTAL RESULTS

The data for Ag are shown in Fig. 3. The ratio of the observed to the Coulomb cross section, $(d\sigma/d\Omega)/(d\sigma/d\Omega)_C$, is plotted as a function of the scattering angle in the center-of-mass system. The errors due to statistical fluctuations in the counting rate are equal to or less than the size of the dots. In addition, there is a ± 10 percent uncertainty in the position of the absolute cross section scale because of an instability in the beam current integrator. However, this does not affect the relative values for the cross section in a given element since the data were taken with respect to a monitor detector held at a constant angle. The statistical variation of the monitor was less than one percent. The data for Ag consist of a diffraction pattern of constant amplitude superimposed upon a rapidly decreasing cross section.

In Mo (Fig. 4), the amplitude of the diffraction pattern increases with angle. The average value decreases in a manner similar to that of the Ag angular distribution. The Nb angular distribution (Fig. 5) is similar to the Mo angular distribution; however, the amplitude of the diffraction oscillation is larger. The average value decreases similarly to that of the Ag and Mo angular distributions. It is interesting to note that the average slope of the Ag, Mo, and Nb angular distributions is approximately equal to the slope of

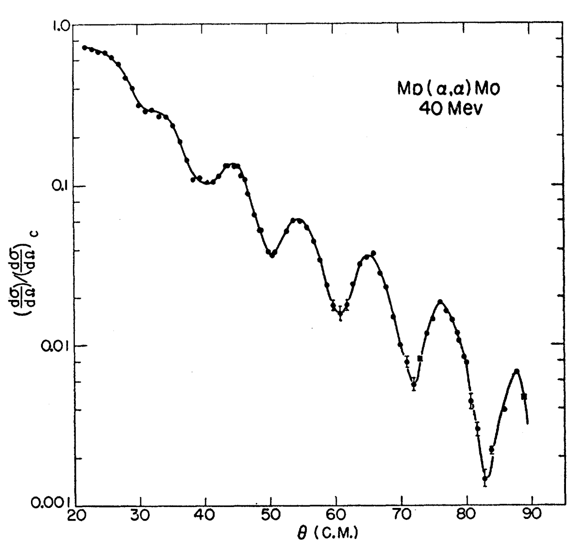

FIG. 4. Angular distribution of 40-Mev alpha particles elastically scattered from Mo.

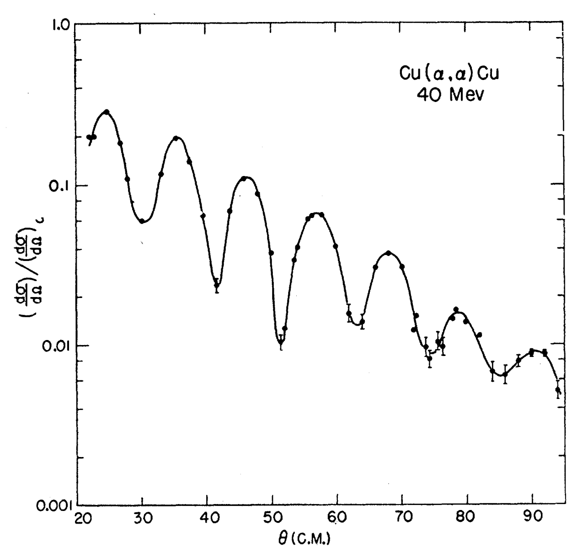

FIG. 6. Angular distribution of 40-Mev alpha particles elastically scattered from Cu.

the angular distribution of Ta which shows no diffraction pattern (Fig. 10).

In Cu (Fig. 6), the amplitude of the diffraction oscillation is large in the forward direction and decreases with angle. The average value does not decrease as rapidly as in the heavier elements. In Ti (Fig. 7), the diffraction oscillation is more pronounced in the forward direction and the average slope of the pattern is less than that of Cu. In Al (Fig. 8), the diffraction oscillation is large in the forward direction. In C (Fig. 9), the ratio is generally larger than one, and the average value increases slightly with angle. The distortion in the diffraction pattern noticeable in Al is reproduced in C.

A composite plot of the data is shown in Fig. 10. The gradual change in the pattern from the light elements to the heavier elements, the shift of the magnitude of the amplitude from the forward to the back angles, and the change of the average slope from positive to negative with increasing atomic weight are easily discernible.

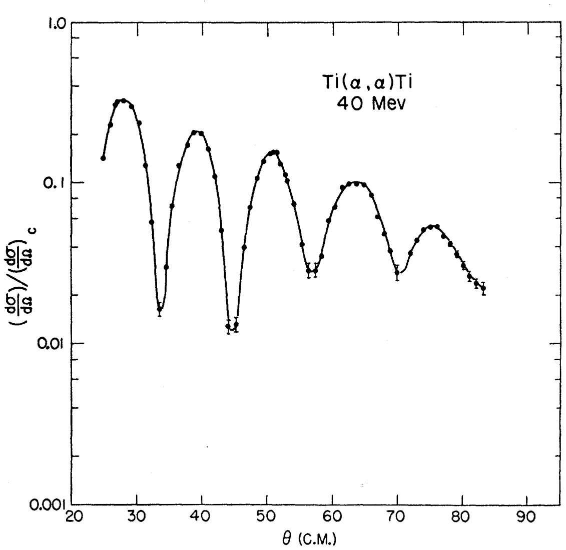

Fig. 7. Angular distribution of 40-Mev alpha particles elastically scattered from Ti.

DISCUSSION

The sharp diffraction patterns as well as the short mean free path of alpha particles in nuclear matter[7] suggests that the position of the maxima could determine the approximate nuclear radius through the diffraction formula for a strongly absorbing disk, $kR\Delta(\sin\frac{1}{2}\theta)=\pi/2$. The quantity, $\Delta(\sin\frac{1}{2}\theta)$, is the difference in $\sin\theta/2$ between the angular positions of adjacent maxima, k is the free space wave number of the alpha particle, and R is the interaction radius of the alpha particle with the nucleus. With the exception of Mo, the quantity, $\pi/2k\Delta(\sin\frac{1}{2}\theta)$, was a constant for each element, and the variation from the mean was never larger than 2 percent. From the data of all the elements, (excluding the Mo data), it was possible to measure $\Delta(\sin\frac{1}{2}\theta)$ accurately a total of 15 times and therefore 15 measurements of the various interaction radii were available for statistical analysis. The quantity, $\Delta(\sin\frac{1}{2}\theta)$, in the Mo diffraction pattern, showed larger variations. This is attributed to the existence of approximately equal abundances of isotopes between 92 to 100 in natural Mo. The other elements consist of single isotopes (Nb, Al, C), or two isotopes differing by two neutrons (Cu and Ag), or predominantly one isotope (Ti).

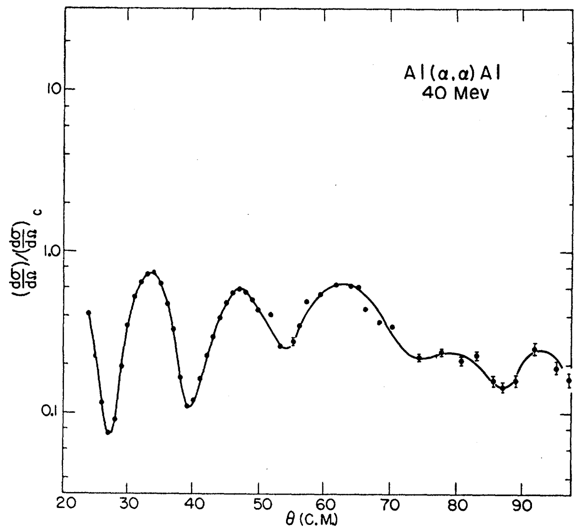

Fig. 8. Angular distribution of 40-Mev alpha particles elastically scattered from Al.

Figure 11 is a plot of $\pi/2k\Delta(\sin\frac{1}{2}\theta)$ *versus* $A^{\frac{1}{3}}$ for all but the Mo data. The method of least squares was used to obtain the parameters of a best straight line,

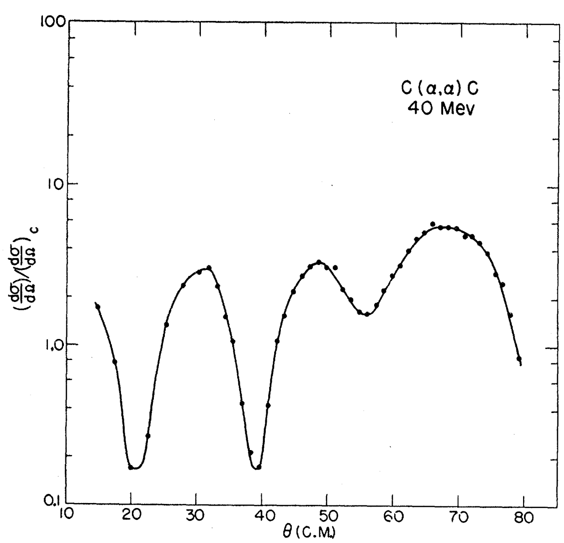

Fig. 9. Angular distribution of 40-Mev alpha particles elastically scattered from C.

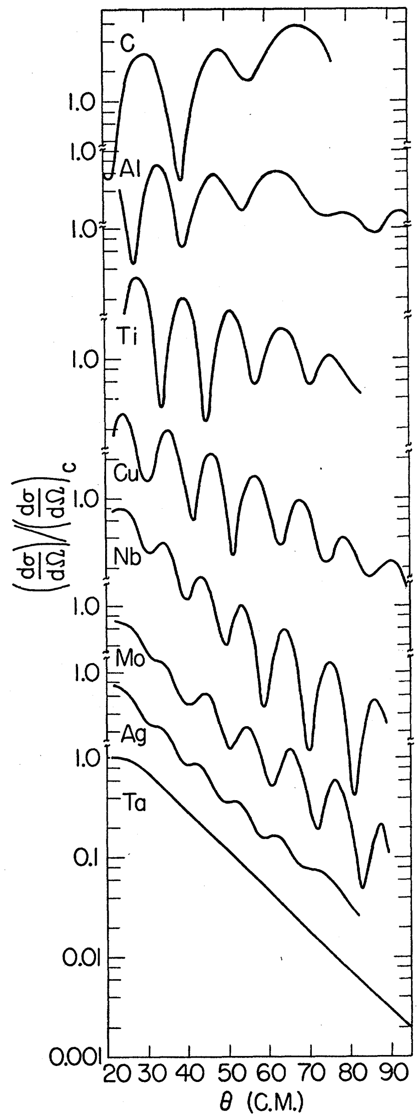

FIG. 10. The elastic scattering of alpha particles from Ag, Mo, Nb, Cu, Ti, Al, and C at 40 Mev.

$R=aA^{\frac{1}{3}}+b$, through the weighted points. The values of the parameters were determined to be $a=1.27\pm0.07$ and $b=1.60\pm0.23$, where the uncertainties of ±0.07 and ±0.23, respectively, represent the changes in each parameter, keeping the other parameter fixed, which makes the sum of the squares of the residuals twice as large as the minimum value.

If the slope of the line in Fig. 11 is assumed to be r_0, where $R=r_0A^{\frac{1}{3}}$ (the intercept is assumed to be related to the alpha-particle radius), it is in agreement with the values determined by excitation function measurements,[13] by 90-Mev neutron total cross-section measurements,[14] and by elastic scattering of protons.[15] It is in disagreement with the 14- and 25-Mev neutron total cross-section data which yield larger nuclear radii.[12]

Comparisons of $(d\sigma/d\Omega)/(d\sigma/d\Omega)_C$ for Al and Cu at 19 and 40 Mev are shown in Figs. 12 and 13. The patterns are qualitatively similar; however, the diffraction maxima are more widely separated at the lower energy as expected. At 19 Mev, R is approximately 5.5×10^{-13} cm, in good agreement with the value, $(5.41\pm0.23)\times10^{-13}$ cm, obtained at 40 Mev. As pointed out by Bleuler,[4] the maxima of the Cu angular distribution at 19 Mev are far from equidistant in $\sin\frac{1}{2}\theta$. Therefore, no attempt was made to compare these data with the 40-Mev data. More precise measurements are now in progress at 19 Mev[4] and it will be interesting to compare these with the 40-Mev data.

A comparison of $(d\sigma/d\Omega)/(d\sigma/d\Omega)_C$ for Ag at the bombarding energies of 22, 40, and 48 Mev is shown in Fig. 14. The 22-Mev data show no diffraction pattern and are similar to the Ta angular distribution at 40 Mev. A slight diffraction pattern is observed in the Ag angular distribution at 40 Mev and it exhibits a larger amplitude at 48 Mev. The value of $R(\sim7.2\times10^{-13}$ cm) obtained from a measurement of the position of the maxima of the 48-Mev angular distribution agrees with the value $(7.65\pm0.23)\times10^{-13}$ cm obtained at 40 Mev for Ag. Pb and Au show a monotonic behavior for both 19 and 40 Mev, while at 48 Mev a slight diffraction pattern is observed in both angular distributions.

As pointed out by Blair,[6] a semiclassical description of the scattering of 40-Mev alpha particles is probably adequate. Consequently the apsidal distance plots of Fig. 15 qualitatively indicate why the angular distributions of the light elements do not show an exponential decrease as is observed, for instance, in Ag. The expo-

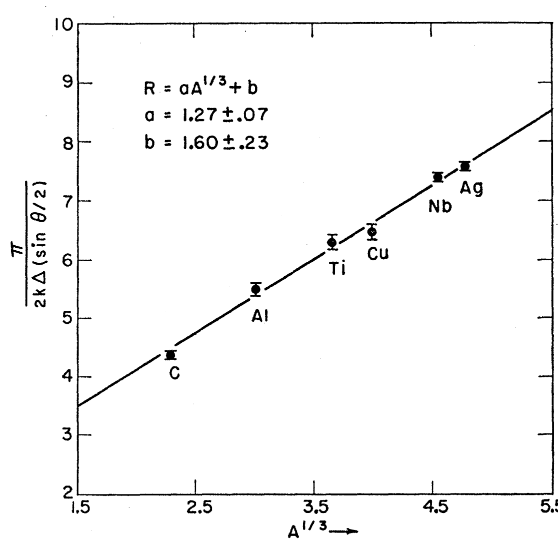

FIG. 11. A plot of $\pi/[2k\Delta(\sin\frac{1}{2}\theta)]$ *vs* $A^{\frac{1}{3}}$. The straight line is $R=[(1.27\pm0.07)A^{\frac{1}{3}}+(1.60\pm0.23)]\times10^{-13}$ cm.

[13] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952), p. 482.
[14] Fernbach, Serber, and Taylor, Phys. Rev. 75, 1352 (1949).
[15] Brookhaven National Laboratory Report BNL-331 (C-21), 1955 (unpublished), p. 37.

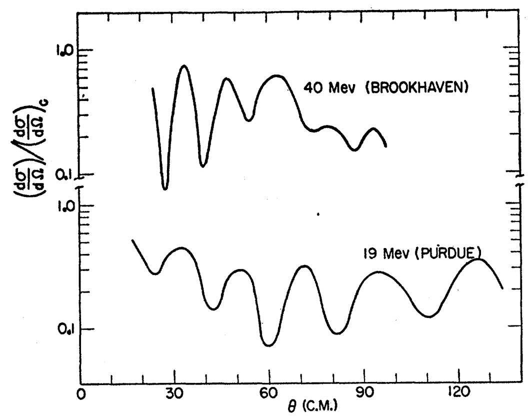

FIG. 12. Comparison of elastic scattering of alpha particles from Al at 19 Mev and at 40 Mev.

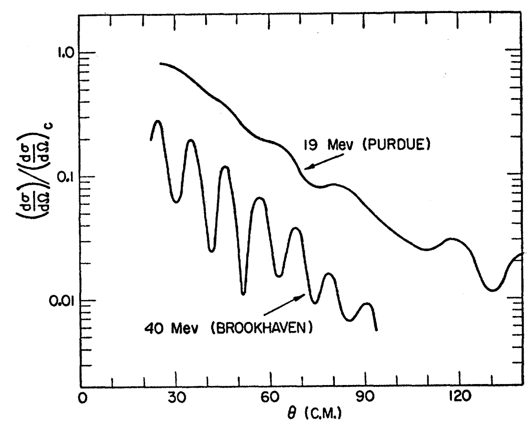

FIG. 13. Comparison of elastic scattering of alpha particles from Cu at 19 Mev and at 40 Mev.

nential decrease in $(d\sigma/d\Omega)/d\sigma/(d\Omega)_C$ for heavy elements results from the attenuation of the alpha-particle beam in grazing the nuclear surface.[16] In the plot for Ag, the heaviest element under investigation, the apsidal distance is 5.7 in units of 10^{-13} cm and corresponds to the largest scattering angle observed. As the classical diagram shows, the alpha particle penetrates only into the rim of the nucleus at this extreme scattering angle and remains outside the charge distribution.[17] Consequently the exponential drop in the Ag data is probably due to this attenuation effect.

In the apsidal distance plot for C, the charge has been assumed to be concentrated at the center for simplicity. The diagram is drawn for the smallest deflection angle observed experimentally. Even at this small scattering angle, the alpha particle would penetrate almost to the center of the nucleus and would be strongly absorbed. Consequently the attenuation effect which accounts for the exponential decrease observed in heavy elements would not be observed since it is a surface effect. Experimentally, an exponential decrease is not observed. The differential cross section changes gradually with atomic number; being predominantly due to attenuation in the diffuse rim in Ag, and predominantly due to diffraction in the lightest element investigated, C.

It is not surprising that diffraction effects are observed in light and not in heavy elements. The incident Coulomb wave describing the alpha particle becomes less like a plane wave as the charge on the nucleus increases. Consequently the diffraction scattering, which is pictured as resulting from the absorption of a plane wave incident on an opaque disk, disappears. At lower energies, the incident Coulomb wave deviates more strongly from a plane wave. Hence, for Cu (Fig. 13) at 19 Mev, the diffraction pattern is smoothed out in a manner similar to that observed for Mo and Ag at 40 Mev.

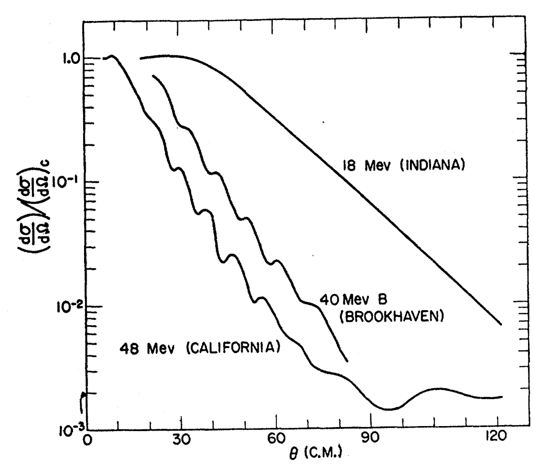

FIG. 14. Comparison of elastic scattering of alpha particles from Ag at 22, 40, and 48 Mec. The Indiana energy is incorrectly written as 18 Mev.

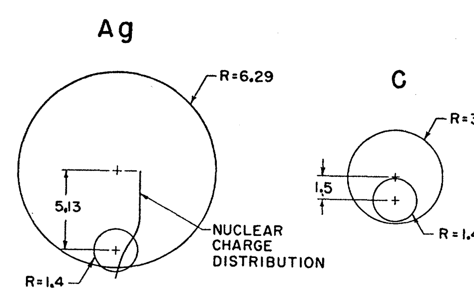

FIG. 15. Apsidal distance plots for alpha particles elastically scattered from Ag and C. In Ag, the apsidal distance corresponding to the largest angle of observation exceeds the mean radius of the charge distribution. In C, the apsidal distance corresponding to the angle of the first maximum in the diffraction pattern is small compared to the nuclear radius. The dimensions are in units of 10^{-13} cm.

[16] The model proposed by Porter has been used in this qualitative discussion of the data. It should be pointed out that the Blair model as well as the Ford-Wheeler model could be substituted for the Porter model to explain the attenuation effect.

[17] Hahn, Ravenhall, and Hofstadter, High-Energy Physics Laboratory, Stanford University Report HEPL-28 (unpublished).

CONCLUSIONS

The diffraction patterns which are found in the angular distributions of alpha particles scattered elastically from light and intermediate elements determine approximately the alpha-particle interaction radius. A complete understanding of the details of the diffraction patterns awaits a detailed calculation based on a model for the nucleus which incorporates the properties which are indicated by a superficial treatment of the data, namely, opacity of the central part of the nucleus and diffuseness of the edge.[7]

The trend with increasing energy indicates that at sufficiently high energies, the angular distributions of elastically scattered alpha particles will probably exhibit strong diffraction patterns over the entire range of the periodic table and, therefore, should provide a good measure of nuclear parameters. Heavier ions, such as C or N, which presumably interact even more strongly with nucleons, should also give diffraction patterns at sufficiently high bombarding energies and could possibly give a better measure of nuclear radii. Finally, angular distributions of 20-Mev deuterons elastically scattered from Al and Au also show similar phenomena.[18] It would be of interest to compare the interaction radius of the deuteron and the alpha particle.

ACKNOWLEDGMENTS

The authors would like to express their thanks to the operating staff of the Brookhaven 60-in. cyclotron.

[18] In addition to the unpublished work at 20 Mev by the authors, H. E. Gove [Massachusetts Institute of Technology Progress Report, July 1, 1950 (unpublished), pp. 139–144] has observed similar distributions at 17 Mev.

PHYSICAL REVIEW VOLUME 101, NUMBER 5 MARCH 1, 1956

Energy of the Delayed Neutrons from the Fission of U^{235}

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(Received November 2, 1955)

The energy distribution of neutrons from the short-lived neutron emitters produced in the thermal fission of U^{235} has been determined with a cloud chamber. A continuous energy distribution was obtained with a maximum number of neutrons at the lowest energies and a few neutrons with energies of at least 2.4 Mev. A linear plot of (number of neutrons)$^{1/5}$ *versus* the neutron energy is obtained indicating an extrapolated neutron energy of 3.5 Mev.

DELAYED neutrons which follow the fission of U^{235} have been extensively studied[1] and the latest experiments[2] find six neutron emitters with half-lives of 54, 20, 5.5, 2.1, 0.44, and 0.11 sec. The three emitters with the longest periods[3] have been shown to be Br^{87}, I^{137}, and Br^{89} or Br^{90}; the three emitters of shorter period have not been definitely identified. Experiments of Hughes, Dabbs, Cahn, and Hall[1] on the diffusion of delayed neutrons through paraffin showed that the average energy of these delayed neutrons varied from 0.25 to 0.62 Mev. The purpose of the present experiments was to obtain more detailed information about the energy distribution of the delayed neutrons. Since it is not possible to separate completely the effects of the different neutron emitters, the method employed was to operate so as to maximize the effects of the 2.1-sec emitter which gives the largest yield of neutrons[2] and also has the highest average neutron energy.[1]

Experiments were carried out by sending a "rabbit"

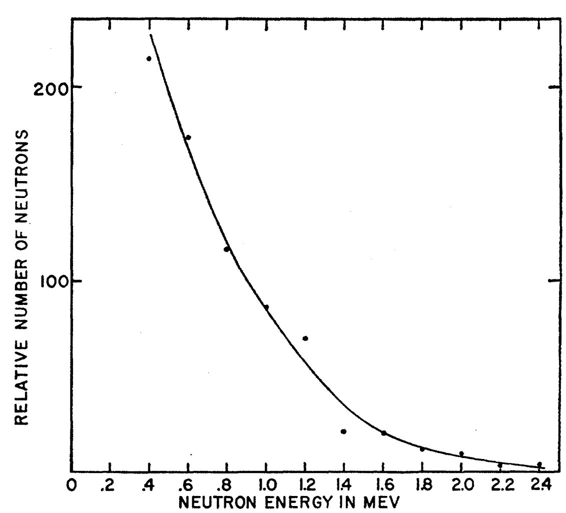

FIG. 1. The energy distribution of the delayed neutrons.

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[1] Brostrom, Koch, and Lauritsen, Nature **144**, 830 (1939); Roberts, Meyer, and Wang, Phys. Rev. **55**, 664 (1939); Snell, Nedzel, Ibser, Levinger, Wilkinson, and Sampson, Phys. Rev. **72**, 541 (1947); Hughes, Dabbs, Cahn, and Hall, Phys. Rev. **73**, 111 (1948); de Hoffmann, Feld, and Stein, Phys. Rev. **74**, 1330 (1948).
[2] G. R. Keepin and T. F. Wimmett, Proceedings of Geneva Conference on the Peaceful Uses of Atomic Energy, August, 1955 (to be published).
[3] N. Sugarman, J. Chem. Phys. **17**, 11 (1949).