The counting of so large a number was accomplished by rotating in the path of the direct pencil a wheel containing a slit. By adjusting the ratio of the width of the slit to the circumference of the wheel, the number of particles falling on the screen could be reduced to the desired extent. Thus the direct and scattered particles were counted on the same zinc-sulphide screen under similar conditions, and the accuracy of the measurement of the nuclear charge depended chiefly on the total number of $\alpha$ particles counted in the experiments.

The apparatus used in these experiments is shown in Fig. 51. The diaphragm $D$ served to define the angular limits of the beam of $\alpha$ particles striking the scattering foil held on the support $A$. It was arranged by suitable disposition of $D$ and $A$ that no particles could be scattered directly to the screen $S$ from the edges of the diaphragm. The direct pencil of $\alpha$ particles passed through holes in the central discs of $D$ and $A$, and could be cut off at will by the lead screen $L$ carried by a glass joint $G$. The wheel containing the slit was rotated between the end of the box and the screen $S$. The source of $\alpha$ particles, $R$, was a disc of 2 to 3 mm. diameter coated on its face with radium ($B+C$).

Three series of experiments were carried out in which foils of copper, silver and platinum were used as scattering materials. The results of the measurements gave for the values of the nuclear charge 29.3e, 46.5e and 77.4e, for copper, silver and platinum respectively,
COLLISIONS OF $\alpha$ PARTICLES IN HYDROGEN

A more direct method Chadwick and Bieler* made a very
y of the collisions of $\alpha$ particles with hydrogen nuclei, and
d the angular distribution of the projected H particles for
various velocities. The arrangement was similar to that
hadwick for the scattering of $\alpha$ particles, the foil in Fig. 50
seed by a thin sheet of paraffin wax to provide the source
en particles. Let the number of H particles projected
angle $\theta$ by a single $\alpha$ particle in passing through 1 cm. of
gas at N.T.P. be $q = F(\theta)$. Then it is easy to show that
of H particles falling per second on unit area of a zinc
creen at $S$ will be

$$Q \frac{i}{16\pi^2} [F(\theta^2) - F(\theta)]$$

s the number of $\alpha$ particles emitted per second by the
is the mean value of $r^2$ and $i$ is the mean value of $t \sec \frac{1}{2} \theta$,
e thickness of the paraffin wax sheet expressed as the
of hydrogen gas containing the same number of atoms of
araffin wax is in the form of a circular sheet, the number
icles observed on the screen is directly proportional to
the simplest method of experiment is to use circular
erent angular limits $\frac{1}{4} \theta^2$, $\frac{1}{4} \theta$, etc. The observations then
 on the curve $q = F(\theta)$ corresponding to the different
$\frac{1}{2}$, etc. This method was used for smaller angles only.
 greater than 20°, annular rings of wax of suitable angular
c used. Scattered $\alpha$ particles were prevented from reaching
by means of suitable absorbing screens.
als obtained in these experiments are shown in Fig. 70,
is plotted against $\theta$ for various velocities of the $\alpha$ particle,
the diagram as ranges in air.
erved numbers of H particles at small angles were greatly
of those given by the theory of point charges and Coulomb's
this theory the value of $q$ for $\theta = 30^\circ$ and an $\alpha$ particle of
is 4.4 x $10^{-7}$, and for an $\alpha$ particle of 2.9 cm. range it
. The corresponding observed values were 4.3 x $10^{-5}$
9; in the first case 100 times as great as the inverse
ber, in the second not quite 4 times as great.
thus a rapid approach to inverse square conditions as the

* Chadwick and Bieler, Phil. Mag. 42, 923, 1921.

range of the $\alpha$ particle is reduced, that is, for large distances of
collision. Further experiments, the results of which are not shown
in Fig. 70, showed that with $\alpha$ particles of 2 cm. range the number
and distribution of the projected H particles were in fair agreement
with the simple theory.

A comparison of the experimental curve $B$ with the curve $B'$
calculated on the inverse square law shows the approach to normal

![Graph showing number of H particles per $\alpha$ vs. angle of projection $\theta$.]

Fig. 70.

collisions as the value of $\theta$, and with it the distance of collision,
increases. It would appear that inverse square conditions would be
reached with $\alpha$ particles of 6.6 cm. range at a distance of collision
responding to a value of $\theta$ of about 80°, i.e. at about $7 \times 10^{-13}$ cm.

These results confirmed the general conclusions reached by
Rutherford, that within a certain distance of approach of the par	icles the force between them varied much more rapidly than on
Coulomb's law and that no system of central forces between two
point charges would explain the observations. A closer analysis led
to an estimate of the dimensions of the region over which the forces
between the $\alpha$ particle and the H nucleus became abnormal. This
COLLISIONS OF $\alpha$ PARTICLES IN HELIUM

has a plate-like shape. This indication is confirmed by a consideration of experiments performed at small angles of scattering. These again can be interpreted without ambiguity, for at small angles the number of projected particles is, if Coulomb’s law holds, very small compared with the number of scattered particles. It can therefore be assumed without serious error that, except in the collisions of very fast $\alpha$ particles, the particles observed are scattered $\alpha$ particles only.

The experiments at small angles showed that, as the velocity of the $\alpha$ particle is reduced, the ratio of the number of scattered particles observed to the number calculated on inverse square forces falls, sometimes to as low as one-third, and then rises to roughly unity.

\[
\left(\frac{V_p}{V}\right)^2
\]

Fig. 74.

§ 61. Scatter

The natural interpretation of the number—literally the further evidence in the interpretation in close of the light experiments the critical distance are major, in the form of evidence that the experimental very accurate and mainly to the (or magnesium and helium to the $\alpha$ particle. The closest positive to an aluminium. While we may with aluminium more than with the distance of approach, so great that

A further... proton from
to be expected on inverse square forces were deduced by measuring the scattering produced by a gold foil under the same conditions. The results of the experiments on the scattering by aluminium at 135° are shown in Fig. 76, where the ratio of the observed number of particles to the inverse square number is plotted against $1/V^2$. Since for a given angle of scattering the closest distance of approach of an $\alpha$ particle to the nucleus is proportional to $1/V^2$, the abscissae also represent the distances of collision, calculated on the assumption of inverse square forces. The dotted line gives the number of particles calculated from the simple theory. It is seen that for low energies of the incident $\alpha$ particles the scattering is approximately normal. As the energy of the particles is increased, the scattering diminishes to a minimum corresponding to $\alpha$ particles of 5 cm. range, and then rises sharply.

We may compare these results with those obtained in the collisions with helium which have been given in Fig. 74. The aluminium curve corresponds to the small portion of the helium curve which lies below the dotted line representing the inverse square numbers. The comparison suggests that if $\alpha$ particles of greater energy were available the scattering by aluminium at 135° would increase perhaps to several times the normal amount.

The experiments at an average angle of scattering of 90° showed only a diminution in scattering as the energy of the particles was increased and notions are represented in scattering at 135°.

In both Bielefeld and the departure from the scattering of $\alpha$ particles is less than normal over all the particles within 40° and 180° not provided only than 10°. Over the whole observed scattering must be compared with the curve of a larger than 135° view, for they show that inverse square excess in this region. If not, less than 20° of the aluminum (and it is probable that involves the case) is, however, not excluded by such a comparison of the data given.

The data given allow a definite conclusion in which increases in the scattering the nucleus and this ever, of interest, very different hydrogen and square law is...
If a nucleus acts as a black disk of radius \( R \) (i.e., for all particles of impact parameter \( b < R \)), the partial waves for which \( R > \hbar/p = \lambda l_{\max} \) will give \( \eta_l = 0 \) and Eq. (11.5.11) gives

\[
\sigma_l = 2\pi \lambda^2 \sum_{l=0}^{l_{\max}} (2l+1) = 2\pi \lambda^2 (l_{\max} + 1)^2 = 2\pi \lambda^2 \frac{R^2}{\lambda^2} = 2\pi R^2 \tag{11.5.17}
\]

which is twice the geometric cross section. At first one would expect, thinking macroscopically, that a reaction cross section equal to \( \pi R^2 \) should not be

![Graph showing differential elastic scattering cross sections for 7-MeV neutrons. The qualitative behavior is that of a diffraction curve from a sphere of radius \( R = 1.4 A^{1/3} \) F, but to obtain the detailed fit the sphere has been assumed not to be completely opaque and to have a fuzzy edge. [From S. Fernbach, Rev. Mod. Phys., 30, 414 (1958).]
and the asymptotic forms

\[ J_1(x) \to \left( \frac{2}{\pi x} \right)^{1/2} \sin \left( x - \frac{x^3}{3} \right) \quad \text{and} \quad J_1(x) = \frac{x}{2} \left( 1 - \frac{x^2}{8} + \cdots \right) \quad (6.3.5) \]

for large and small \( x \), respectively. The first minimum of scattering thus occurs for an angle such that

\[ \sin \theta = 0.610 \times 2\pi (\bar{x}/R) \quad (6.3.6) \]

and from its measurement we have another method of obtaining \( R \) (Fig. 6.7).

**Figure 6.7** Experimental and theoretical differential cross sections for 14-MeV neutrons scattered from Sn, Cu, Fe, and Al. The experimental data presented are not completely corrected for multiple scattering, nor have angular and energy resolutions been taken into account. [S. Fernbach, *Rev. Mod. Phys.*, 30, 414 (1958).]