Multiple Scattering of Fast Electrons

C. W. SHEPPARD
*Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California**
(Received July 23, 1942)

The multiple scattering of electrons from B^{12} has been studied by means of G-M coincidence counters in two scatterers of equal NTZ^2 where N is number of atoms per cc of scatterer, T and Z are the thickness and atomic number of scatterer. The scatterers were of Pb and C, respectively, and had a theoretical scattering power which differed by 20 percent. Comparison of the arithmetic mean angles of scattering showed that their ratio was nearly the same as given by the Williams theory.

INTRODUCTION

PREVIOUS measurements of multiple scattering of electrons of several Mev energy[1–3] indicated that a discrepancy existed between experiment and theory[4, 5] which was greater for lead than for elements of low atomic number such as carbon and aluminum. Since this discrepancy seemed difficult to account for theoretically, and since previous measurements were made with a Wilson cloud chamber, it seemed advisable to endeavor to detect it by a different method.

EXPERIMENTAL DETAILS

Since the theory of multiple scattering has been given in terms of the projection of the scattering angles upon a plane, a two-dimensional experiment was chosen in which G-M coincidence counters were used. The experimental arrangement can be seen in Fig. 1: A boron target was bombarded with deuterons accelerated by an a.c. tube operating at 350-kv peak voltage. A portion of the B^{12} electrons emerging from the front of the target was collimated by two lead slits after they traversed the 15-mil aluminum target cup. The electrons were then scattered and recorded by two cylindrical counters placed in a light wooden frame which could be moved about an axis through the scatterers. Behind the target was placed a single counter to be used as a monitor. This counter was heavily shielded but so situated that it received a part of the electrons which traversed the 10-mil copper target and emerged from the rear of the target cup. This arrangement gave a satisfactory check on the bombarding intensity during the experiment. The coincidence counters were of the tubular type. The glass walls had a surface density of 16 g/cm². The cylinders were $1\frac{1}{8}''$ in diameter, 9″ long, and were made of 8-mil copper oxidized with nitrogen peroxide. They were filled with argon and alcohol, their pulses were found to be fairly uniform, and their plateaus quite broad. The singles counter was similar in construction except that it had a cylinder only 2″ long. The natural background of the counters was measured before and after

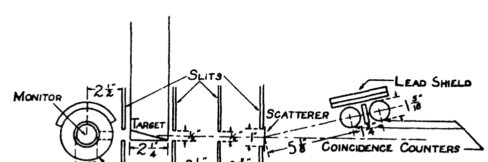

FIG. 1. Experimental arrangement employed.

the experiment. For the two large counters it was 111 and 163 counts per minute, respectively, at the beginning and 98 and 165 at the end. For the singles counter it was 59 before and 69 after. Since high voltage stabilization was not employed it was necessary to check the counter voltages every two minutes during operation. The coincidence counters were coupled by a Rossi coincidence circuit to a pulse-lengthener and recorder. The counters were shielded by $\frac{1}{8}''$

* Now at South Dakota State School of Mines, Rapid City, South Dakota.
1 W. A. Fowler, Phys. Rev. **54**, 773 (1938).
2 C. W. Sheppard and W. A. Fowler, Phys. Rev. **57**, 273 (1940).
3 Oleson, Chao, Halpern, and Crane, Phys. Rev. **56**, 482 and 1171 (1939).
4 E. J. Williams, Proc. Roy. Soc. **169**, 531 (1939).
5 S. Goudsmit and J. L. Saunderson, Phys. Rev. **57**, 24 (1940); **58**, 36 (1940).

of lead and had a relatively low coincidence background when the tube was in operation. In all cases the counting rate was slow enough to minimize skipping effects. The singles counter was coupled through a Neher-Harper stage to a scale-of-eight circuit. This was necessary because of the relatively high background to which it was exposed during operation which necessitated a proportionately higher counting rate.

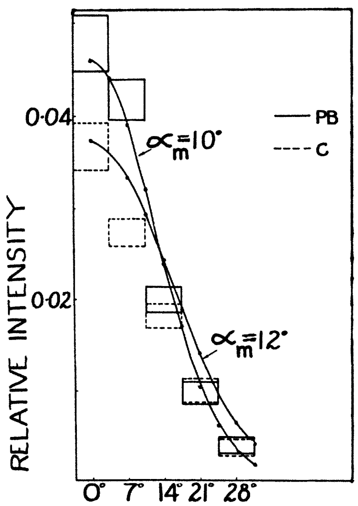

FIG. 2. Experimental results, arbitrary scale.

SCATTERERS

Two scatterers were measured of equal NTZ^2 (No. of atoms per cc, thickness and atomic number of scatterer), one of rolled lead and the other of Acheson graphite. The surface densities were determined by weighing before and after the scattering measurements were made. Both scatterers were 1″ wide and 5″ long. The important theoretical quantities for them are given in Table I. After correction of Z for extranuclear electron scattering and inclusion of the logarithmic factor the theoretical scattering differs by 20 percent. The notation which has been used in Table I is the same as has been used elsewhere.[2]

EXPERIMENTAL PROCEDURE

The counting equipment was arranged so that it could be stopped and started by means of a master switch. In addition a magnetic shutter was provided with which the bombarding beam could be interrupted in order to obtain background counting rates. The scatterers were interchanged constantly during the experiment. An estimate of the angle subtended by the sensitive region of the counters is rather difficult. In practice five angular intervals of 7° were taken in the region from 0° to 28°. Any overlapping effect which might occur will affect both scatterers by the same factor. In order to compensate for the rather large difference in energy loss in the two scatterers end pieces were attached to them and each was placed between the counters during the measurements on the companion scatterer. The total number of coincidence counts recorded in any angular interval varied from 500 to 100 depending upon the scattered intensity. The monitor counts averaged about 15,000. The data were averaged and background rates subtracted. Mean errors were calculated and combined to obtain the mean error in the result. These errors were obtained both from the total number of counts in each case and also from the computed residuals, thus affording a good indication of consistent counter behavior. In only two cases was the latter error greater than the former. The final results were expressed as ratios of coincidence counter intensity to that of the monitor counter. These results are plotted in Fig. 2. A measure of the resolving power of the experiment was obtained by measuring the counting rates with no scatterer present. These data are shown in Fig. 3.

TABLE I. Theoretical quantities for scatterers used.

	Surface density σ	Z_{eff}	$W\delta$ in Mev-deg.	M	$W\bar{\alpha}$ in Mev-deg.	$W\varphi_2$ in Mev-deg.	$W\alpha_m$ in Mev-deg.
Pb	0.177 g/cm^2	82.3	24.7	375	84	210	76
C	1.28 g/cm^2	6.49	27.0	2390	99	270	92

RESULTS

In Fig. 2 Gaussian curves, normalized to the same arbitrary scale, have been fitted to the data. The mean angle for lead is seen to be 10° and for carbon 12°. The mean angle for the curve in Fig. 3 is approximately 7°, so it is necessary to compensate for the effect of poor resolving power. Since the mean angle for the resulting distribution obtained by measuring a Gaussian distribution with an instrument having a Gaussian error is the square root of the sum of the squares of the mean angle of the distribution and of the error of the instrument, this compensation can be made. The resulting values of α_m are therefore closer to 10° and 7°, respectively. Their ratio is thus 0.7 whereas the theoretical quantities have a ratio of 0.8.

DISCUSSION

Energy loss effects are important in the experiment, and the question arises as to whether the placing of the carbon scatterer between the counters when the lead is scattering, and vice versa actually produces proper compensation for the reduction in intensity by the carbon due to energy loss when it is scattering. A consideration of the energy loss of electrons in the region above 5 Mev shows that the variation with energy loss by ionization is quite slow. Radiative losses in the carbon are still negligible. Straggling effects due to multiple scattering in the carbon must be considered. The best justification for the method of compensation used can be obtained by considering the total reduction in forward intensity from 0° to 28° when the carbon is scattering compared to that when the lead is scattering. This reduction was found to be a factor of 0.54. If we compare this with the reduction in intensity in the case of the scattering of lead effected by placing the carbon scatterer between the counters we find that the latter reduction is by a factor of 0.53.

The fitting of a Gaussian curve to the measured scattering distribution might appear to ignore the fact that the electrons from B^{12} have a wide energy distribution. In considering this effect it is necessary to make an estimate of the minimum energy with which electrons can traverse the system and be recorded in the last counter. This estimate is complicated by the effects of multiple scattering of the diffusion type and cannot be made with precision. For purposes of discussion an estimate of 5 Mev can be made for this cut-off energy. With this value, the electron spectrum[6] of B^{12} was approximated by a polynomial. Figure 4 shows the distribution for carbon obtained by integrating according to this method. Since the mean angle is inversely proportional to the energy in the Williams theory the α_m for the approximate Gaussian curve should be the r.m.s. value which can be obtained by computing a mean energy for the incident electrons. This can be obtained by integrating the mean square reciprocal of the energy. In the case at hand this was found to be 6.2 Mev. A Gaussian curve for carbon having a value of α_m computed from this mean energy is also shown in Fig. 4 and can be seen to fit within the accuracy of this experiment. The inclusion of the second term in a Gram-Charlier series expansion was found to give a very close fit indeed, but its use was not considered necessary in this case.

The estimate of 6.2 Mev for the mean energy of the electrons is subject to too much uncertainty, and so the values of α_m calculated from

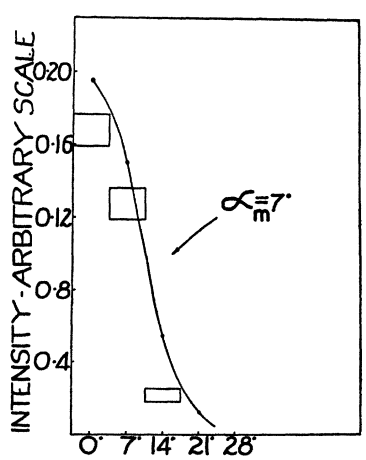

FIG. 3. Intensity distribution of electrons with no scatterer present.

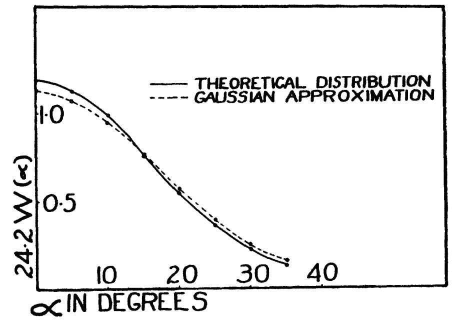

FIG. 4. Distribution in scattered intensity to be expected on the basis of a sharp energy cut-off in the B^{12} spectrum at 5 Mev. Dotted curve is Gaussian having a computed mean energy of 6.2 Mev.

[6] D. S. Bayley and H. R. Crane, Phys. Rev. 52, 604 (1937).

this cannot be depended upon. However, the ratio of α_m for carbon and for lead should be correct within 10 percent at least. On the basis of this result it seems doubtful that any large systematic deviation from the Williams theory can occur with increasing atomic number. Recent measurements by others also support this conclusion.[7,8] However, in order to examine the seeming discrepancy between the cloud-chamber and counter results it should be possible to perform an experiment in which measurements by the two methods could be made simultaneously.

The author wishes to express his appreciation to Mr. Sylvan Rubin, Mr. Eldred Hough, and Mr. R. E. Logan for assistance with the experimental work, and to Professor W. A. Fowler and Professor C. C. Lauritsen for advice and assistance.

[7] Oleson, Chao, and Crane, Phys. Rev. **60**, 378 (1941).
[8] L. A. Kulchitzky and G. D. Latyshev, Phys. Rev. **61**, 254 (1942).

OCTOBER 1 AND 15, 1942 PHYSICAL REVIEW VOLUME 62

Inefficiency and Other Sources of Error in Cosmic-Ray Measurements with Self-Quenching Counters

KENNETH GREISEN AND NORRIS NERESON
Cornell University, Ithaca, New York
(Received May 25, 1942)

The errors in coincidence measurements with self-quenching counters, due to inefficiency inherent in the counters and due to apparent inefficiency arising from showers and scattering, have been measured. The inefficiency inherent in the counters has been found to be almost entirely due to the dead time. The dead time, for the counters investigated and with the recording circuit employed, was 4×10^{-4} second. This gives rise to an inefficiency of 0.2 percent in counters with a normal counting rate of 300 per minute. The apparent inefficiency of the counters and the error in coincidence measurements, for most of the experimental arrangements used were found to be almost entirely due to showers. From the data presented below, we estimate that near sea level, with the counter telescope in the vertical direction and with 35 cm between the extreme counters, the coincidences due to side showers were about 15 percent of the normal coincidence rate when two counters were in coincidence, 7 percent when three counters were in coincidence, and 3 or 4 percent when the telescope contained five counters in coincidence. These percentages increased by a factor of 2 when the apparatus was taken from 259- to 4300-m elevation.

INTRODUCTION

As sources of error in coincidence measurements with a conventional cosmic-ray telescope we wish to consider the following effects: (1) *chance coincidences*, (2) *inefficiency* of the counters, (3) *scattering* in the absorber or in the counter walls, and (4) cosmic-ray *showers*. All four of these effects contribute to the "apparent inefficiency" of a counter; i.e., to the decrease in the counting rate when an additional counter is put into a cosmic-ray telescope.

The existence of these sources of error has been recognized for many years. The inefficiency of a counter was determined with an anticoincidence method by Rossi in 1930,[1] and a counter measurement of cosmic-ray showers was made by the same author in 1932.[2] In the years since then, there have been very numerous reports of measurements of these effects.[3] However, in the determinations of the influence of cosmic-ray showers on telescope measurements, some effects have been included which have made the determination of the error inexact; and the measurements of the inefficiency of counters have been influenced by the recording of showers so

[1] B. Rossi, Rend. Acc. dei Lincei [6] **11**, 831 (1930).
[2] B. Rossi, Physik. Zeits. **33**, 304 (1932).
[3] See, for example, T. H. Johnson, Rev. Mod. Phys. **10**, 193 (1938); Phys. Rev. **40**, 638 (1932); D. K. Froman and J. C. Stearns, Can. J. Research **A16**, 29 (1938); M. E. Rose and W. E. Ramsey, Phys. Rev. **59**, 616 (1941); M. Cosyns, Bull. Tech. de'l Assoc. Ing. sortis del Ecole Polytech. Brux. (1936); W. E. Danforth and W. E. Ramsey, Phys. Rev. **49**, 854 (1936).