The Energy Losses of Fast Electrons

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The energy losses experienced by electrons of energies from 1.5 to 4.5 Mev in traversing thin laminae of carbon and of lead were investigated with a hydrogen-filled cloud chamber. The carbon absorber had almost the same calculated stopping power as the lead and was used to provide a check on the method in regard to such factors as straggling, and scattering of the electrons by the gas of the chamber. As a source of electrons activated chlorine was used, the electrons being admitted through a thin mica window mounted on the periphery of the chamber. A comparison was made between the average energy loss per g/cm² of absorber found as the result of the measurements and the values for this quantity predicted on the basis of current theory. As the experimental rate of loss in lead was markedly greater than that theoretically expected, the attempt was made to account for this difference on the basis of the obliquity of the electron paths in the absorber; this attempt, however, was unsuccessful, so that the results indicate a higher rate of absorption in lead of electrons with the energies studied than is predicted by theory. A further comparison was made with theory in regard to the absolute probability of large energy losses—losses of approximately half the initial energy. Here a very large discrepancy was found, which indicates that the difference found in the computation of the average rate of energy loss is due to the probability of large (radiative?) losses being considerably greater in lead than is expected from theory.

INTRODUCTION

SEVERAL authors have investigated the energy losses which electrons with kinetic energies of a few million electron volts experience in traversing matter. The experiments have been performed with either heavy gases[1, 2] or thin laminae[2, 3] in a cloud chamber. In all cases, the losses have been found higher for *heavy* elements than expected on the basis of current theory, although the latest results of Turin and Crane[3] on the average energy loss for lead absorbers can be brought to near agreement with theory by making use of not unreasonable assumptions regarding the obliquity of the electron paths in the lead foil. If the frequency of large losses—of the order of half the initial kinetic energy—is compared with the theoretical value for radiative losses of this magnitude, the disagreement is much greater.

In view of this situation it was felt that some results which we have obtained, using electrons of energies between 1.5 and 4.5 Mev and thin (approximately 1/7 g/cm²) foils stretched across a cloud chamber, would be of interest. By using foils as thin as these, the measurement of *ionization* losses becomes necessarily inaccurate, but, under these conditions, large energy losses would be expected to arise only from other processes, presumably from single radiative processes which theoretically begin to become of importance for electrons of these energies in elements of high atomic number. Although our chief interest in this paper will be with the data obtained with a lead absorber, measurements were also made with a carbon absorber of thickness such that approximately the same ionization loss would be expected as in the lead; the scarcity of large energy losses in the carbon indicated that when they appeared in the lead absorber they could in general be ascribed to mechanisms other than ionization.

APPARATUS

The cloud chamber was of the pressure operated sylphon type, being, except for a few modifications, that used by Kurie, Richardson and Paxton[4] for studies of β-ray distributions. The sensitive volume was 16 cm in diameter and approximately 1 cm high. The chamber was in all cases filled with tank hydrogen at a pressure between 100 and 110 cm and with a mixture of ethyl alcohol and water to provide the con-

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[1] H. Klarmann and W. Bothe, Zeits. f. Physik **101**, 489 (1936).
[2] L. Leprince-Ringuet, Ann. de physique **7**, 5 (1937).
[3] J. J. Turin and H. R. Crane, Phys. Rev. **52**, 63 (1937).
[4] F. N. D. Kurie, J. R. Richardson, and H. C. Paxton, Phys. Rev. **49**, 368 (1936).

densable vapor. The selection of hydrogen as the permanent gas with which to fill the chamber is of importance because the distortions of electron tracks due to nuclear scattering become more serious in heavier gases.

Coils above and below the chamber provided a magnetic field of approximately 700 oersteds. To avoid overheating, current was passed through these only for short intervals during which the expansions took place; the value of the current was observed for each expansion.

The tracks were illuminated by a shorted carbon arc and photographed with a single Sept camera having a $f:2$ lens. Their curvatures were determined by reprojecting the photographs to their original size and fitting circles drawn on white Bristol board to the images of the tracks. The angles of incidence and deviation were found by first measuring the angles for chords of a fixed length (5 cm) and later correcting for the angles between the chords and tangents at the lamina.

Several series of expansions were taken, some with a carbon absorber and the rest with a lead absorber. The runs with carbon were interposed between two series of runs with lead. Pictures were measured in the same order as they were taken. The carbon absorber had a surface density of 0.130 g/cm^2 (volume density$=1.52$ g/cm^3); the lead had a surface density of 0.158 g/cm^2. From theory, losses of 0.44 mc^2 in the carbon and 0.33 mc^2 in the lead are to be expected. This value for lead does not include the expected mean radiation loss, which amounts to 0.09 mc^2.

The electrons were those emitted by active chlorine (half-life 37.5 min.) produced by deuteron bombardment of silver chloride in the Berkeley cyclotron. The active sample was placed outside the chamber at a distance of from 20 to 40 cm from a thin (0.008 cm) mica window on the periphery through which the electrons were admitted. A brass tube limited the beam of electrons outside the window in such a way that the magnetic field excluded from the chamber many of the low energy electrons. The distribution as to initial kinetic energy of the tracks studied is that indicated in Table I, from which it will be seen that the measurements were confined to electrons with initial kinetic energies above 3 mc^2.

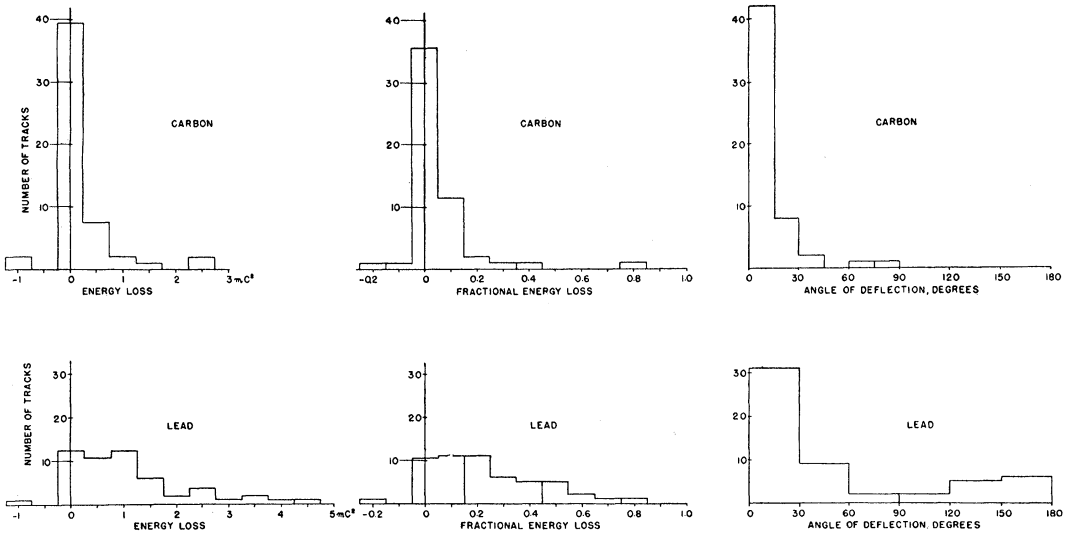
Besides rejecting tracks which apparently suffered deflections in the gas, tracks whose lengths for some reason (such as obliquity to the sensitive plane of the chamber) were less than 5 cm were not measured, it being felt that the absence of some such criterion would impair the accuracy of the curvature measurements. In comparing energies on both sides of the absorber, it is, of course, essential that one be as sure as possible that the tracks measured are really associated, i.e, belong to the same electron. Even when all tracks whose identities are rendered uncertain by virtue of the presence of other tracks are rejected from consideration, there remains the possibility that a Compton electron be ejected from the absorber close to the point at which another electron enters and is somehow scattered from view. From the number of apparently unaccompanied measurable electron tracks emerging from the absorber, we calculated that accidental coincidences would be expected to account for one-half of one per cent of the total number of "traversals." The number of pairs projected backward from the plate, which might be mistaken for reflected electrons, is altogether negligible.

Results

The results are shown in the histograms of Figs. 1 and 2. The scale of ordinates is such that in all the diagrams equal heights represent equal numbers of electrons *per measurable incident track*—the numbers appended at the side are, however, the true number of electrons. It will be noticed that a few negative energy losses are recorded. These may be the result of errors of measurement or of undetected deflections; in either case they should be included in the histogram, as they will tend to cancel similar positive errors when the average energy loss is calculated and so make the latter quantity more reliable.

Table I. *Distribution in initial kinetic energy of those tracks whose energy losses were measured.*

Initial kinetic energy	0–3	3–4	4–5	5–6	6–7	7–8	8–9	>9 mc^2
Number of tracks	0	30	29	21	19	6	3	0



FIGS 1. AND 2. Histograms showing the energy losses, the fractional energy losses, and the angles of deflection in carbon and in lead of the electrons studied in this investigation. It is to be noted that, in the plots showing the distribution with respect to the angle of deflection, the histogram interval in carbon was taken as half that used in the case of lead. The total number of *incident* tracks in carbon = 210; in lead, 301.

In carbon one out of 3.9 measurable incoming tracks came out in such a way as to be measurable; in lead, one out of 5.5. These ratios do not differ greatly from what one might expect from the scattering of the incident electrons out of the sensitive region of the chamber, since it was required that an emerging track have a length of 5 cm to be "measurable."

The average energy losses were formed for those electrons whose curvatures could be measured on both sides of the absorber (or, in the case of reflections, whose curvatures could be measured before and after reflection.) These were then divided by what might be considered the *effective* thickness of the absorber when the obliquity of incidence and emergence is taken into account; for this quantity the attempt was made to find what might be regarded as upper and lower limits. As an estimate of the upper limit for the effective thickness, the average was taken of the thickness times the secant of the larger of the angles of incidence and emergence (for the few cases of reflections, the *sum* of the secants of the two angles was taken); as an estimate of the lower limit, the average was taken of the thickness times the secant of the smaller of the angles (in the case of reflections, *zero* was taken as the minimum thickness). The estimate of the mean effective thickness was simply the thickness times the average of the secants of all the angles of incidence and emergence. The spread in the energy loss per gram per square centimeter as calculated with these various values for the thickness of the absorber was not very great, as can be seen from Table II. The losses to be expected from inelastic collisions are 30 percent greater in the carbon than in the lead, the values, as given above, being 0.33 mc^2 and 0.44 mc^2 for the lead and carbon respectively. The expected radiative loss increases the theoretical average loss in the lead to 0.42 mc^2. Referring to Table II one sees that

TABLE II. *Average energy loss and fractional energy loss in carbon and lead. The figures give the average measured energy loss and fractional energy loss per gram per square centimeter calculated from the following figures: Av. energy loss in C = 0.233 mc^2, average fractional loss in C = 0.0515; Av. energy loss in Pb = 1.09 mc^2, average fractional loss in Pb = 0.225. The various columns have the following significance: a, from directly measured thickness; b, from estimate of lower limit of effective thickness; c, from estimate of upper limit of effective thickness; d, from estimate of the mean effective thickness.*

	Av. Energy Loss (mc^2/g·cm^{-2})				Av. Frac. Energy Loss (per g·cm^{-2})			
Element	*a*	*b*	*c*	*d*	*a*	*b*	*c*	*d*
Carbon 0.130 g·cm^2	1.79	1.74	1.64	1.69	0.396	0.384	0.363	0.374
Lead 0.158 g·cm^2	6.9	8.4	5.1	6.3	1.42	1.72	1.05	1.30

the carbon results are below the theoretical by 0.2 mc^2; a calculation of the probable error, taking into account fluctuations and errors of measurement leads to values close to 0.2 mc^2 for both the carbon and the lead. Hence the disagreement in the carbon can be explained on this basis, but if we apply a similar probable error to the energy loss found in lead, so that we have in the average *rate* of loss (expressed per $g \cdot cm^{-2}$) a probable error of 1.2 $mc^2/g \cdot cm^{-2}$, the experimental values (see Table II) indicate losses significantly greater than predicted by theory (2.7 $mc^2/g \cdot cm^{-2}$), even when the estimate of the upper limit for the effective thickness is used.[5]

A second comparison with theory—one which concerns itself with the *large* (radiative?) energy losses—may be made by calculating, for example, the theoretical probability of an incident electron experiencing in the lead strip a radiative loss between 0.45 and 0.55 of its initial kinetic energy. With the following notation:

$\mu = mc^2$ = the rest energy of the electron,
E_0 = initial total energy of the electron in units of mc^2,
k = energy of emitted quantum,
Ndl = number of atoms per cm^2 of the absorber,

Heitler[6] defines the probability of the emission of k in the range $dk/(E_0-\mu)$ by

$$\text{probability} = Ndl\phi_k dk/(E_0-\mu).$$

Substituting in the above $Ndl = 4.65 \times 10^{20}$, $dk/(E_0-\mu) = 0.1$, and the value of ϕ_k appropriate[7] to $k = 0.5(E_0-\mu)$ and $E_0 = 6\ mc^2$, one has for this probability the value 0.003. Thus the theory indicates the probability of a fractional (radiative) energy loss in the interval 0.45–0.55 to be 3 : 1000 for the thickness of lead used; actually, as can be obtained from the histogram shown in Fig. 2, we find experimentally that of the total 55 measured tracks, 5, or 91/1000, lost a fraction of their energy lying in this range. Since electrons which have suffered large losses should in any case not be less likely to be scattered, nor more likely to be "measurable," than those with small losses, our experimental value for the probability of practical losses in the range 0.45–0.55 is thirty times the theoretical.

Although the number of tracks in the histogram interval from which this experimental value was obtained is small, the fact that the distribution is fairly smooth in this region suggests that statistical fluctuations cannot account for a significant part of the discrepancy. Further, the marked difference between the distribution found for lead and that for the carbon absorber demonstrates that the large losses in the lead arise from processes other than those ascribable to electrons, i.e., they are due to interaction with nuclei. A possible resolution of the difficulty is to suppose that the path taken by the electron in the lead is very tortuous, and in some cases is so long that the resulting loss is many times that due to a straight traversal. Such deviations as are required to account for the long paths are caused by elastic scattering by nuclei. (The alternative of electronic scattering has been shown above to be untenable, while inelastic nuclear scatterings are, on current theory, almost exclusively radiative and these do not concern us at the moment.) A formula by Mott[8] gives the fraction of tracks deflected through an angle greater than some angle θ in terms of absorber, energy, etc. Employing this formula and Wentzel's criterion as stated by Rasetti,[9, 10] we find that single scattering only is effective for angles of deviation greater than 50°. This shows that elastic scattering cannot greatly increase the path.

Conclusion

As a result of this investigation, we feel that there are serious difficulties in fitting the energy losses—specifically, the large energy losses—observed for electrons traversing lead absorbers to those predicted on the basis of present theory. This difficulty has been encountered by the investigators,[1, 2] working with heavy gases in a cloud chamber; those results of Leprince-

[5] If electrons which have undergone reflection are excluded from the average, this latter quantity is reduced by 17 percent. However, there appears to be no convincing reason for excluding reflections, as is sometimes done.

[6] W. Heitler, *The Quantum Theory of Radiation* (Oxford, 1936), p. 165.

[7] Obtained from curves given by Heitler, reference 6, p. 170.

[8] F. C. Champion, Proc. Roy. Soc. **A153**, 353 (1936).

[9] G. Wentzel, Ann. d. Physik **69**, 335 (1922).

[10] F. Rasetti, *Elements of Nuclear Physics* (Prentice-Hall, 1936), p. 74.

Ringuet[2] which were concerned with the traversal of a lead lamina by electrons in the energy range we have investigated also indicate that the losses are above the theoretical. Similar discrepancies have been reported by Skobeltzyn and Stepanowa.[11]

In this connection it might be pointed out that a recent note by Jaeger[12] reports the result of calculating the theoretical radiative losses without having recourse to a Born approximation. For electrons of 1.5 Mev initial energy, Jaeger finds that the probability for a fractional loss of 0.5 is roughly thirty percent greater, in Pb, than that given by the approximate values we have used. For electrons of higher initial energy the corrections are presumably even smaller, except in those cases where the electron loses nearly the whole of its energy. These corrections therefore do not help to clear up the discrepancies that we have found.

Because of the difficulties mentioned above, it is planned that the experimental investigation of the subject will be continued by others in this laboratory.

[11] D. Skobeltzyn and E. Stepanowa, Nature **137**, 234, 456 (1936).
[12] J. C. Jaeger, Nature **140**, 108 (1937).

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The Normal Energy Distribution of Photoelectrons from Sodium

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The theory of the normal energy distribution of photoelectrons has been reformulated by including the effect of contact potential; if photoelectric currents are plotted against applied retarding potentials, the apparent stopping potential at 0°K is shown to be independent of the cathode work function. Apparatus has been constructed for the precise determination of the normal energy distributions of photoelectrons from sodium. Photoelectric currents emitted by monochromatic light were measured after passage through a retarding field. The results of such measurements were found to vary with changes of the anode potential barrier. Energy distribution curves taken at different frequencies exhibit satisfactory mutual consistency; when plotted logarithmically they are of identical shape. This shape does not agree with the theoretically predicted normal energy distribution. An explanation for this discrepancy is given in terms of the structure of the anode potential barrier. A method for the determination of h/e is suggested, which is based on the consistency in shape of the empirically determined curves.

INTRODUCTION

ON the basis of Fowler's[1] theory of photoelectric emission, the energy distribution of photoelectrons in the temperature dependent high energy region has first been discussed by DuBridge,[2,3] who developed theoretical expressions for the distribution in "normal energy," i.e., in the energy associated with the momentum component normal to the surface, and for the total energy distribution. Shortly afterwards, DuBridge and Hergenrother[4] published the results of experimental work on the normal energy distribution of photoelectrons from molybdenum,

[1] R. H. Fowler, Phys. Rev. **38**, 45 (1931).
[2] L. A. DuBridge, Phys. Rev. **43**, 727 (1933).
[3] L. A. DuBridge, *New Theories of the Photoelectric Effect*, (Paris, 1935).
[4] L. A. DuBridge and R. C. Hergenrother, Phys. Rev. **44**, 861 (1933).