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The Absorption of High Energy Electrons, Part I

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The recoil electrons produced by the 6 Mev gamma-radiation from fluorine bombarded with protons were allowed to pass through 5 mm carbon and 0.5 mm lead absorbers placed across the center of a cloud chamber. The curvatures of the incident and emergent tracks in the magnetic field were measured, the difference giving the loss in passing through the absorber. The losses in carbon are in good agreement with the theoretical losses due to electron collisions alone, and this is satisfactory, since practically no radiative losses are expected in a substance of such low atomic number. In the case of lead, the data show clearly that radiative losses play a large part, and increase with increasing energy of incident particle. The losses in lead are slightly greater than those predicted by theory.

INTRODUCTION

THE abundant gamma-radiation emitted when fluorine is bombarded with protons[1] can be used conveniently to produce recoil electrons with energies extending up to approximately 6 Mev. We have made a study of the energy loss of these particles in passing through carbon and lead absorbers. The results which we propose to report constitute the first data which have been obtained in the region between 3 and 6 Mev, although several authors have reported upon experiments performed with electrons in the region of energy available with natural radioactive substances.

Skobeltzyn and Stepanowa,[2] using the beta-rays from radium in an expansion chamber reported that the stopping of these particles in air took place much too frequently to be accounted for by the present radiation theory. They observed that about 100 times as many particles suffered sudden large losses of energy as theoretically predicted, and they were led to conclude that there must be some other totally independent process by which beta-rays lose energy. Leprince-Ringuet,[3] using the gamma-rays from radio-thorium and its products to produce recoil electrons, studied their passage through thin foils of lead and various gases by means of a cloud chamber. He also came to the conclusion that the average energy loss observed was much too large to be explained on the basis of the present theory. He observed from 5 to 10 times as much energy loss supposedly due to radiation as predicted by theory. Klarmann and Bothe,[4] studied the passage of recoil electrons from the gamma-rays of thorium C$''$ through xenon and krypton. They observed tracks in the expansion chamber which suffered a sudden deviation and energy loss without the presence of another ionizing particle visibly connected with the process. They assumed that these processes were radiative collisions of the electrons with the nuclei of the atoms in the gas. Their conclusion was that the number of large energy losses observed for the total length of track measured in both xenon and krypton was about 3.5 times as great as that predicted by theory. They also expressed the opinion that there must exist a process by which an electron can lose energy which is not included in the quantum theory of radiation. As a result of observations of cosmic-ray particles in a cloud chamber Anderson and Neddermeyer[5] gave a value for the average energy loss of electrons which seemed to indicate that there was no appreciable departure from the theory at extremely high energies.

Thus for electrons of energies of the order of 2 Mev we are confronted with a radiative loss which seems to be too large, while in the region of cosmic-ray energies the observed radiative loss is in agreement with theory. The suggestion has been made that because the contribution which radiation makes to the total energy loss is small

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[1] Crane, Delsasso, Fowler and Lauritsen, Phys. Rev. **46**, 531 (1934); Delsasso, Fowler and Lauritsen, Phys. Rev. **51**, 527 (1937).

[2] Skobeltzyn and Stepanowa, Nature **137**, 234 (1935).

[3] Leprince-Ringuet, Comptes rendus **201**, 712 (1935); Ann. de physique **11**, 5 (1937).

[4] Klarmann and Bothe, Zeits. f. Physik **101**, 489 (1936).

[5] Anderson and Neddermeyer, Phys. Rev. **50**, 263 (1936).

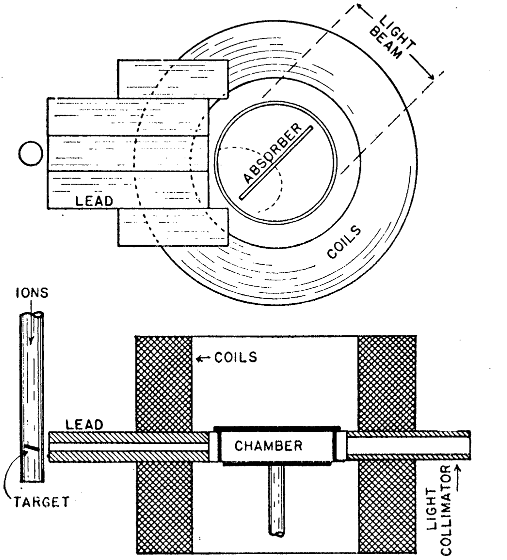

FIG. 1. Experimental arrangement of cloud chamber and gamma-ray collimator.

at energies of 2 Mev and less, the errors in the values obtained for the radiative loss may be quite large. The advantage of the experiments to be reported in this paper over the previous ones is that in the neighborhood of 6 Mev the energy loss in lead due to radiation is comparable to that due to mechanical collisions. A more accurate test of the theory should therefore be possible.

EXPERIMENTAL ARRANGEMENT

The cloud chamber employed (see Fig. 1) was 15 cm in diameter and 4 cm deep, filled with air and ethyl alcohol vapor at atmospheric pressure. It was equipped with an air core solenoid arranged so as to bend the electron tracks in the plane of the chamber. A collimated beam of parallel light from a carbon arc illuminated a portion of the chamber 1.5 cm in depth, located centrally between the top and bottom. The gamma-rays from the fluorine target were collimated into a beam the same height as the light beam, by means of a lead channel 5 cm wide and 1.5 cm in height. The absorber was placed across the center of the chamber in such a position that most of the recoil electrons ejected from the wall of the chamber were incident normally upon the absorber. By measuring the radii of curvature of the incident and emergent tracks both the primary energy and the energy loss of each electron which passed through the absorber was determined.

RESULTS

A total of 448 measurable tracks were observed which passed through 5 mm carbon and 0.5 mm lead absorbers. The energies of the incident particles ranged from 2 to 6 Mev, and the data for each absorber were separated into two groups according to incident energy, 2 to 4 Mev and 4 to 6 Mev. Plots of the change in energy against the number of electrons for the two absorbers and the two energy groups are shown in Figs. 2, 3 and 4. The average energy loss, calculated by using the points themselves, rather than the smooth curve, and the most probable energy loss, which is indicated by the highest point of the curve, are given for each of the four groups in Table I.

DISCUSSION OF POSSIBLE ERRORS

Measurement of tracks

Because the absorber was placed at the center of the chamber there was a maximum of 7 cm from the absorber to the side wall of the chamber. This placed a limit upon the length of visible track on each side of the absorber. A length of at least 5 cm of sharp and distinct track on each side

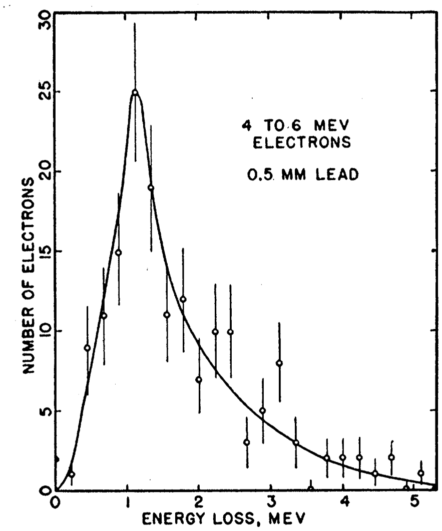

FIG. 2. Energy losses plotted against the number of electrons, for 5 mm carbon and primary energies 4 to 6 Mev.

of the absorber, extending to within ½ cm of the absorber was required before a track was accepted for measurement. A track was not used if other tracks appeared on the picture in such a way as to provide any doubt as to the association of the incident and emergent parts of the track. In addition only those tracks which made angles of less than 15° with the normal to the absorber on the incident side were used. No restriction was made as to angle in the horizontal plane of the emergent tracks. The angle in the vertical plane was, however, limited to approximately 15 degrees on either side of the horizontal direction, because of the requirement that at least 5 cm length of track be included in the light beam.

The strength of the magnetic field was always so chosen that it was never necessary to measure tracks with radii of curvature greater than 15 cm, regardless of the energy in question. The curvatures were measured to half-centimeter intervals by matching the tracks in the full size reprojected image to circles drawn on a celluloid card. Very few tracks showed visible departure from circularity due to scattering in the gas, and it is believed that in the region of energy dealt with here the errors due to this cause are quite small.

Taking into account all the sources of error discussed above a fair estimate for the average error in the determination of the energies of individual electrons seems to be 0.3 Mev. Since the determination of energy loss depends upon the difference between two measured energies, the average error in these values is expected to be somewhat larger. However, in combining all the data to obtain the values for average energy loss given in the table, the errors in the individual measurements of the tracks balance out to a great extent, so that the error in the values in the table due to measurement is almost certainly less than 0.1 Mev.

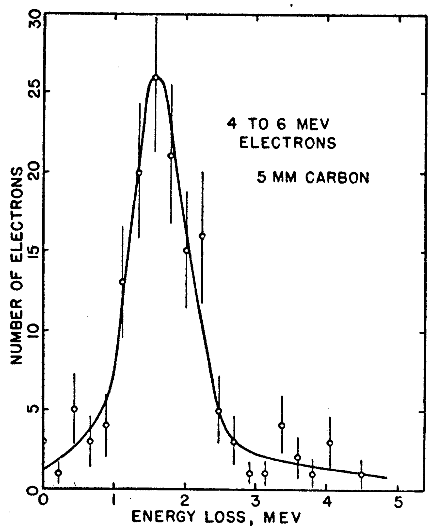

FIG. 3. Energy losses plotted against the number of electrons, for 0.5 mm lead and primary energies 4 to 6 Mev.

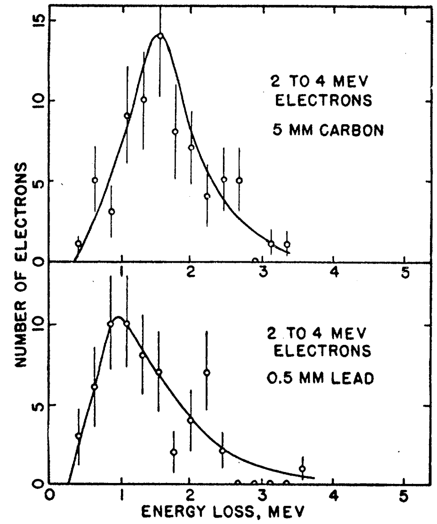

FIG. 4. Energy losses plotted against the number of electrons, for 5 mm carbon and 0.5 mm lead absorbers, primary energies 2 to 4 Mev.

Tracks which end at the absorber

Tracks which are incident upon the absorber but do not appear to emerge from the absorber at all are not included in the data. Cases of this kind are numerous enough to change the value of the average energy loss considerably, if included. The exclusion of this class of tracks from the data can, however, be justified. Unless the present radiation theory is seriously wrong, the energy

TABLE I.

ABSORBER	INCIDENT ENERGY	AVERAGE LOSS	MOST PROBABLE LOSS
5 mm carbon	2 to 4 Mev	1.70 Mev	1.5 Mev
5 mm carbon	4 to 6 Mev	1.73 Mev	1.6 Mev
0.5 mm lead	2 to 4 Mev	1.41 Mev	0.9 Mev
0.5 mm lead	4 to 6 Mev	1.73 Mev	1.2 Mev

loss curves do not rise abruptly at the extreme right sides of the diagrams in Figs. 2, 3 and 4, but continue to fall; i.e., the number of electrons which lose almost their entire energy by means of radiation and electron collisions is relatively small. Our faith in the correctness of this general shape of theoretical energy loss curve is strengthened by the fact that the present data are in agreement with it over the region of low and moderate energy losses. We therefore prefer at present to attribute the apparent complete stopping of this considerable number of electrons to some other cause, such as scattering out of the field of vision or to a separate mechanism by which an electron may be stopped catastrophically. The number of electrons which are expected actually to lose their entire energy by known processes in a length of path equal to the thickness of the absorber used can be estimated and should be applied as a correction to the data obtained. Both from the trend of our experimental curves and from the shapes of the accepted theoretical energy loss curves, the number of such cases should be small and would not be expected to raise the values for the average energy losses by more than a few percent.

Length of path in the absorber

If appreciable scattering occurs along the path of the particle inside of the absorber the real length of path traversed will be greater than the thickness of the absorber. Theory predicts that scattering by nuclei is proportional to the atomic number squared, and is therefore very much smaller in carbon than in lead. Actually the electrons emerging from the carbon absorber were found to be well concentrated in the forward direction, with few large deviations apparent. For this reason the thickness of the carbon (5 mm) represents quite closely the actual length of path of the electrons traversing it. In lead, however, the scattering is large. About 50 percent of the emerging electrons were observed to lie within $\pm 30°$ of the forward direction in the horizontal plane, and within $\pm 15°$ of the forward direction in the vertical plane. In consideration of this, we estimate that the real average length of path in the lead may be as large as 1.5 times the thickness of the lead.

Scattering which accompanies energy loss

If a large change in direction of an electron takes place in the same event in which it loses a large amount of its energy, this will tend to introduce an angular dependence upon energy loss for the emerging particles. This must be considered in the case of the lead absorber. Head-on electron-electron collisions in which large loss and large deflection occur simultaneously are known both from experiment and from theory to be too rare to influence the present results. In the process of radiation large losses are, on the average, accompanied by large deflections, although there is no exact correspondence for the individual case between loss and deflection. However, because of the circumstance that the electron pursues a tortuous path through the lead absorber, due to multiple nuclear scattering, any correspondence between energy loss and angle of emergence will be largely obliterated. Therefore the sample of electrons which emerges within the solid angle visible in the present experiment may be expected to give a fair representation of the average energy loss by all the particles.

DISCUSSION

The curves obtained for the energy loss in carbon are in excellent agreement with the theoretical predictions, both as to shape and as to the value of the average energy loss, on the assumption that the loss by radiation is very small compared to the loss by electron collisions. The widths of the curves for carbon are not too great to be attributed mainly to the errors in the measurements of the individual tracks, and it is therefore not feasible to estimate the amount of real straggling which accompanies the energy loss. The curves for lead definitely show a large amount of straggling, which indicates that large losses of energy occur in single events in the absorber. On the basis of present theoretical knowledge these large losses can only be attributed to radiation. The values for the average losses contributed by radiation alone are found to be 0.38 and 0.64 Mev for 2–4 and 4–6 Mev electrons, respectively. In consideration of scattering effects, we have used in this calculation 0.75 mm as the effective thickness of the lead. Using Bethe and Heitler's formulae for radiative loss, we find values of 0.28 and 0.57 Mev, for the two energy ranges. All the possible sources of error pointed out in the foregoing discussion, however, are in the direction of tending to favor the electrons which have lost the least energy. Therefore it is probable that the real values are somewhat higher than our experimental values, which would make them differ still more from the theoretical values. On the other hand, it has been pointed out to us by Professor H. A. Bethe that the use of the Born approximation for lead may give theoretical values which are as much as 30 percent too low. We believe that the largest uncertainty in our experiment lies in the estimation of the average length of path of the electrons in the absorber. We have had valuable discussions on this point with Dr. M. E. Rose of Cornell University, who is making some calculations[6] on the path length-thickness ratio in this energy region. Dr. Rose suggested that the ratio which would be necessary to bring our results into agreement with theory might be well within the calculated limits.

The large discrepancy between the results reported here and those of Skobeltzyn and Stepanowa, Leprince-Ringuet and of Klarmann and Bothe should not be considered as a direct contradiction, because the methods used are by no means the same. The most important difference in the various experiments lies in the treatment of those electrons which appear to lose their entire energy in the absorbing material. We have excluded tracks of this class on the assumption that the great majority of them do not represent actual energy loss, but scattering out of the field of vision or stopping by a separate process. At the same time, we do not wish to lose sight of the possibility that the theory may be quite wrong in the region in which the electron loses nearly its entire energy in a single event, and that these cases should rightfully be included in the data. If so, the value for the average energy loss will be much higher. There remains also the possibility, as suggested by several authors, that this complete stopping may be a new process which is separate from radiative stopping in the ordinary sense.

Investigations similar to these are now under way on the absorption of the beta-rays from Li^8, which will extend the data up to about 11 Mev. These results will follow shortly in a separate publication.

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[6] M. E. Rose, Abstract, Washington Meeting, 1937.

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Absorption Coefficients for Thermal Neutrons

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A discussion is given of several integrals arising in the interpretation of experiments on the absorption of thermal neutrons in a $1/V$ absorber. In order to evaluate these integrals they have been expressed in the form of convenient series. There is also given a table of numerical values, which should be useful in the interpretation of experimental data on slow neutron absorption.

In studying the absorption of slow (thermal) neutrons one has in general to deal with neutrons having a given angular distribution and approximately a Maxwellian energy distribution, and with absorbers whose coefficient of absorption is a function of the relative energy of the neutrons with respect to the individual absorbing nuclei. If the scattering cross section is of importance, as in the case of neutron-proton collisions, the general problem (of the absorption and back-scattering of the a layer of absorber-scatterer) is complicated by the scattering; but if the scattering cross section is negligible in comparison with the absorption cross section, then the neutrons may be considered as moving in straight lines without deviation until they are