The Energy Loss of Positive Electrons in Passing Through Aluminum*

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The energy loss of positive electrons between the energies of 0.3 and 1.5 Mev has been determined in a hydrogen-filled cloud chamber for three thicknesses of aluminum. The positive electrons, which were obtained by bombarding iron with deuterons, were passed through aluminum absorbers of 0.0275, 0.053, and 0.114 cm thickness, and the values of the average energy loss were compared with the values predicted by the theoretical formula of Bloch. The value of the average energy loss for the 0.0275 cm thickness was 0.123 Mev, which is roughly 20 percent greater than the theoretical value; whereas for the 0.053 cm thickness, the loss was 0.274 Mev, an increase in difference to 40 percent. A direct comparison of the energy lost by the negative electron with that lost by the positive electron was made using electrons obtained from radioactive phosphorus. The results show that there is no essential difference in the amount of energy lost by the two particles.

INTRODUCTION

WHEN iron is bombarded with deuterons[1] a radioactive isotope attributed to cobalt is formed. This emits positive electrons of energies up to 1.6 Mev. The problem in this study is to determine the amount of energy lost by these particles in passing through various thicknesses of aluminum. At the same time a direct comparison is made with negative electrons to ascertain whether or not there is any difference in the amount of energy lost by the two particles.

Within the past few years a great deal of work has been done with negative electrons. The experiments show good agreement with theory for substances of low atomic number; whereas for high atomic numbers the experimental values are much higher than theory would predict.[2–4] Absorption measurements with positive electrons of low energy indicate that they lose energy in much the same manner as the negative electrons.[5] In the case of the high energy positrons found in cosmic radiation, the evidence seems to indicate that the amount of energy lost by the positive and negative electrons is the same,[6] although one experiment has seemed to indicate a difference.[7]

* A preliminary report of this investigation was given at the Chicago meeting of the American Physical Society in November, 1937.

[1] B. T. Darling, B. R. Curtis and J. M. Cork, Phys. Rev. **51**, 1010 (1937).
[2] J. J. Turin and H. R. Crane, Phys. Rev. **52**, 63, 610 (1937).
[3] A. J. Ruhlig and H. R. Crane, Phys. Rev. **53**, 618 (1938).
[4] J. Laslett and D. Hurst, Phys. Rev. **52**, 1035 (1937).
[5] J. Thibaud, Phys. Rev. **45**, 781 (1934).
[6] P. M. S. Blackett and J. G. Wilson, Proc. Roy. Soc. **A160**, 304 (1937).
[7] J. Crussard and L. Leprince-Ringuet, J. de phys. et rad. **8**, 213 (1937).

APPARATUS

The cloud chamber used in these experiments has been described by Crane.[8] It was 15 cm in diameter and 4 cm deep, filled with hydrogen and ethyl alcohol vapor at a pressure of 100 cm of mercury. The magnetic field was obtained from a pair of air core solenoid coils. In the earlier experimental work, the current through the coils was turned on and off, but in the later experiments, the current was allowed to flow continuously. This removed the possibility of any errors due to the contacts of the circuit breaker or to misreading the swing of the ammeter needle. A collimated beam of parallel light, obtained from a carbon arc, illuminated the center 1.5 cm section of the chamber. A diagram of the experimental arrangement is shown in Fig. 1. By locating the source S at the correct position, it was possible to obtain a partial magnetic separation of the positrons so that particles of only a certain definite energy range entered through the thin window in the wall of the chamber. This prevented the appearance in the pictures of too many extraneous tracks which did not strike the absorber at approximately normal incidence.

The aluminum absorbers were coated with paraffin and lamp black and were placed across the center of the chamber parallel to the light beam. By measuring the radii of curvature of the incident and emergent tracks, the amount of energy lost by the particles in traversing the absorber could be determined.

The method used for determining the curva-

[8] H. R. Crane, Rev. Sci. Inst. **8**, 440 (1937).

ture of the tracks was to project the full-sized image upon a white card and then to measure the radii of the tracks by means of a celluloid or cardboard template upon which circles of radii varying by 0.5 cm had been drawn. In order to be included in the data actually used, a track was required to satisfy the following conditions:

(1) It must come from the window in the side of the chamber and must strike the absorber at approximately normal incidence (within 10°). Of course this criterion does not exclude the chance that an electron may be ejected from the absorber by a gamma-quantum and come back toward the window.

(2) The track must be of sufficient length to make possible an accurate measurement of its curvature. Since only half of the 15 cm of the chamber is being considered, at least 6 cm of track must be measured.

(3) The track must emerge from the absorber within 15° of the normal and must not make an angle greater than 10° with the plane of the chamber. Any track which satisfies condition (2) will satisfy this condition.

(4) A track must not be visibly scattered. When working with particles of energy as low as

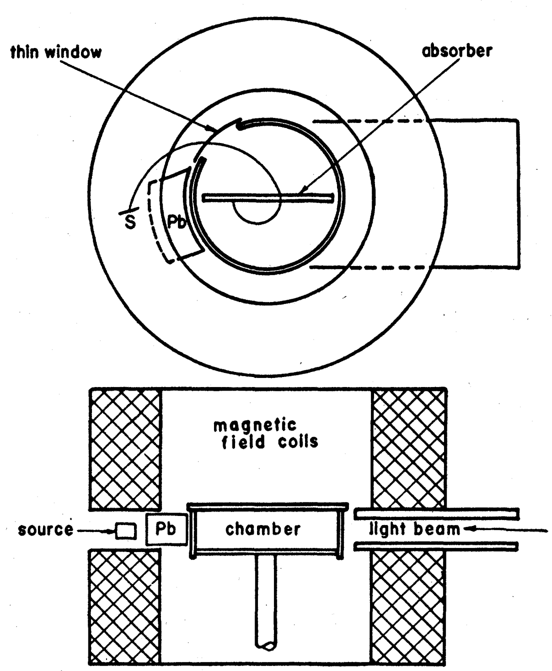

FIG. 1. Experimental arrangement of cloud chamber and electron source.

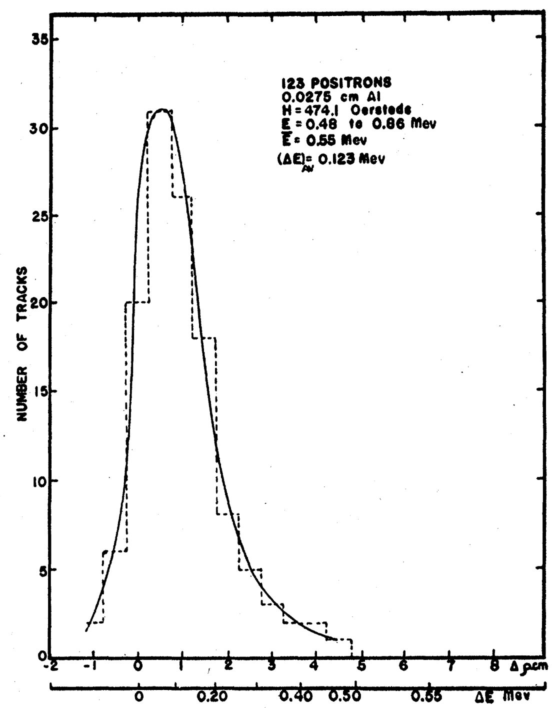

FIG. 2. Energy losses plotted against the number of positive electrons, for 0.0275 cm aluminum and initial energies of 0.48 to 0.86 Mev.

0.5 to 1.0 Mev, it is necessary to fill the chamber with hydrogen in order to keep down scattering to a minimum. The probability for scattering is inversely proportional to the square of the kinetic energy of the particle and directly proportional to the square of the atomic number of the scattering material. Thus if hydrogen is used, the scattering for these energies is very small.

RESULTS

Positive electrons

The principal source of positive electrons was iron bombarded in the cyclotron with deuterons. These electrons have an upper limit in energy of 1.6 Mev and a half-life of 18 hours.

For the 0.0275 cm aluminum, approximately 200 positrons were obtained which satisfied the necessary criteria. In Fig. 2 the momentum loss curve is shown for positrons ranging in initial energy from 0.48 to 0.86 Mev. The curve contains a total of 123 positrons. For convenience, the scale of energy loss is plotted below the $\Delta\rho$ (change in radius of curvature) scale. To obtain the change in momentum, the latter may be multiplied by the value of the magnetic intensity, H. The following values are recorded in the figure: number of positrons observed, thickness of aluminum used, intensity of the magnetic field, H, interval of initial energies, average value of the initial energies, $\bar{E}$, and the average loss of energy in Mev, $(\Delta E)_{Av}$.

It will be noted that the curve is roughly symmetrical and fairly sharp. A large number of tracks appear to have passed through the absorber with no change in momentum, and a few appear to have acquired actual gains in momentum. This can be attributed to several factors: (1) Coincident effects. (a) Occasionally a gamma-quantum may eject, from the wall of the cloud chamber, an electron which hits the absorber at a point opposite that at which a positron has entered. If this electron has an energy equal to, or greater than, the initial energy of the positron, it will seem that the positron has actually gained energy. (b) Another positron which is at first out of the light beam may be scattered into view on the far side of the absorber in such a way as to appear to be the emergence of a first particle. (2) Small angle scattering. When working with particles of such low energies as those used in this experiment, scattering is certain to occur. For every large angle scattering which can be easily observed, there is a considerable amount of small angle scattering which cannot be noticed. (3) Errors in measurement.

Of these three factors, the last two are by far the most important. Only one case was observed in the 800 tracks obtained in which a positron appeared to gain so much energy that it was definitely a coincident effect with an electron emitted from the wall. Since it was required that the tracks appear to within 0.5 cm of the absorber on both sides, then from the geometry of the apparatus, it would be impossible for any track to have sufficient path length in the light beam to pass either over or under the absorber. It is still possible, of course, that a particle might be scattered in such a way as to appear to be the continuation of a track which has been stopped by the absorber. Small angle scattering is a factor which is always a great difficulty in this type of experimental work. Its effect is to broaden the general curve.

Undoubtedly the errors in measurement are the chief cause of the large number of tracks which appear to have lost no energy. Since the accuracy of measurement is not high enough to distinguish any loss of energy less than 0.05 Mev, a large number of tracks will be obtained for thin absorbers which seem to have lost no energy.

The number of tracks which have definitely appeared to gain energy is not very large, constituting less than 5 percent of the total number. These cases are probably due to a combination of the two factors, small angle scattering and errors in measurement, although a few of the cases may be due to coincident effects.

The most probable loss of energy may be found by inspection of the curve to be approximately 0.09 Mev. The average energy loss may be found by two different procedures: (1) by determining the energy loss for each particle separately and then averaging; (2) by determining the average $\Delta\bar{\rho}$ and, from the value of $\Delta H\bar{\rho}$ and the initial energy, finding the corresponding $(\Delta E)_{Av}$.

In order to test these two methods of considering the data, 200 tracks were chosen having energies between 0.50 and 1.00 Mev. The first method gives an average energy loss of 0.128 Mev. It is undoubtedly fortuitous, but the value determined by the second method was again 0.128 Mev.

All of the data were treated by both methods. For energies above 0.5 Mev, the two values were

TABLE I. *Energy loss.* (−) *indicates a negative electron. An asterisk indicates that tracks have already been included in the data and that the initial energy of all the particles was the same.* (?) *This low value is attributed to the fact that the initial energies of the particles are so low that large energy losses are discriminated against in measurement.*

Thickness (cm)	Number of Tracks	Initial Energy (Mev)	Most Probable Loss	Average Loss (Mev)	
				Exp.	Theor.
0.0275	123	0.48 to 0.86	0.09	0.123	0.098
	77	0.80 to 1.0	0.10	0.123	0.105
	96(−)	0.48 to 0.86	0.08	0.121	0.098
0.053	209	0.48 to 0.86	0.19	0.266	0.205
	101	0.30 to 0.55	0.21	0.230?	0.214
	52*	0.60		0.270	0.204
	73*	0.74		0.278	0.204
	161	0.67 to 0.93	0.21	0.265	0.205
	114	0.90 to 1.40	0.22	0.285	0.206
0.114	30	0.8 to 1.40		0.480	0.434

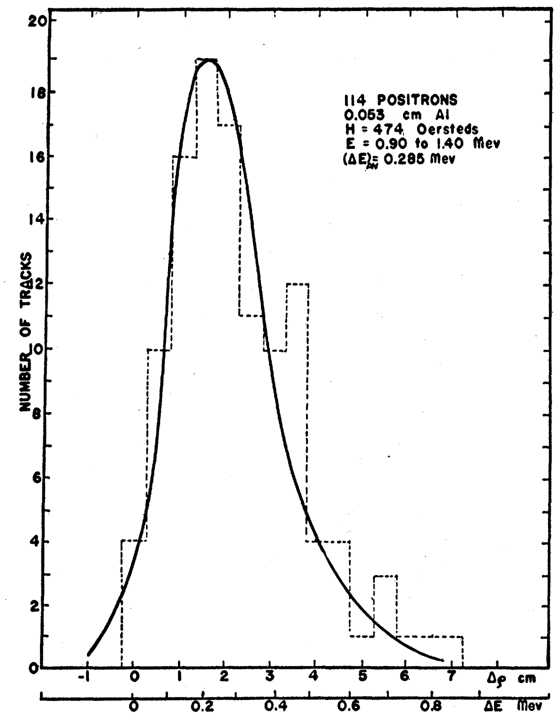

FIG. 3. Energy losses plotted against the number of positive electrons, for 0.053 cm aluminum and initial energies of 0.90 to 1.40 Mev.

usually the same; when any difference occurred the value obtained from the loss of energy of the individual particles was considered to be the final result. Method (1) was found to be advantageous, for there is no necessity in this case for determining the average initial energy of the particles.

The apparent gains in momentum are attributed to instrumental error. They should therefore be regarded as the accuracy of the measurement, and a corresponding error allowed for the values of the large energy losses. If the data are regarded in this way, then the average energy loss for the 0.0275 cm thickness of aluminum is 0.123 Mev. (See Fig. 2.)

The 0.053 cm aluminum was used in obtaining the greater part of the data because it proved to be sufficiently thick to prevent cases of apparent gain in energy without being thick enough to stop an excessive number of particles.

The particles have been grouped into intervals of initial energy, which are kept as small as possible and yet have a sufficient number of tracks so that statistical variations are not too important. Some of the groups overlap slightly, but they have been kept as nearly as possible within 0.2 Mev intervals from 0.3 to 1.5 Mev. These are tabulated in Table I.

The general shape of the curve (see Fig. 3) obtained from this thickness of aluminum illustrates two points: first, that the curve is not quite so symmetrical as those for lesser thicknesses but extends farther to the right; and second, that the width of the curve is in general greater. Theoretically, the half-width of the curve is dependent upon the thickness of the material traversed and the incident energy of the particle considered. Since this thickness is double that first used, the width of the curve will be more pronounced, due to the increased scattering.

The unsymmetrical character of the curve may be attributed to several processes which cannot be distinguished from one another: (1) scattering, which tends to increase the straggling in the energy loss values since the particle actually traverses a greater thickness of material; (2) electron collisions, in which a large fraction of the initial energy has been lost; (3) radiative collisions. The last two of these have very little effect, for the probability of radiative collisions is very small at the energies considered in this work, and electron collisions in which a particle suffers a head-on impact are relatively rare, making the contribution from this process small.

In Fig. 3 the distribution for 114 positrons is shown for particles whose initial energy ranges from 0.90 to 1.40 Mev. The most probable energy loss occurs at an energy of approximately 0.20 Mev. The average energy loss is equal to 0.28 Mev. This illustrates the nature of the curves obtained when sufficient numbers of particles are used so that statistical variations are not large. The other curves for this thickness are similar in nature, the results of which appear in Table I.

The amount of data obtained for the 0.114 cm aluminum is too meager to make any very accurate estimate of the energy loss, but from the results available, the most probable energy loss has been found to be approximately 0.35 Mev, and the average energy loss, 0.48 Mev.

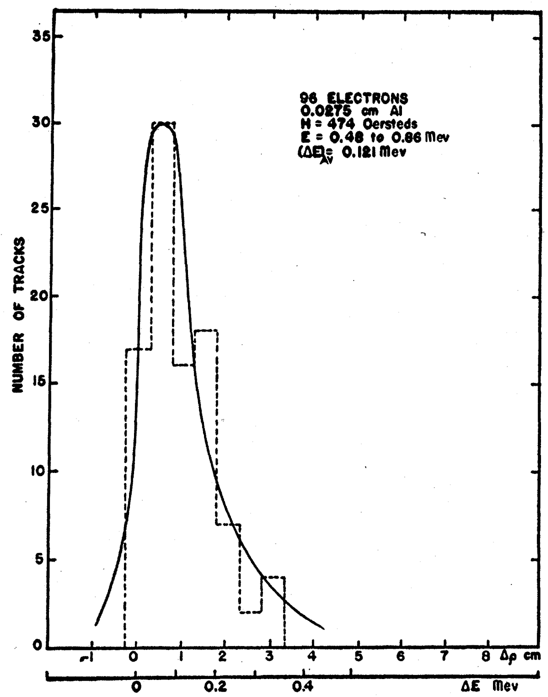

FIG. 4. Energy losses plotted against the number of negative electrons, for 0.0275 cm aluminum and initial energies of 0.48 to 0.86 Mev.

Negative electrons

To compare the energy loss of positrons directly with the energy loss of electrons, radioactive phosphorus was used as a source of particles. The upper limit of the energy obtainable is 1.5 Mev as compared with the limit of 1.6 Mev for the cobalt (55) positrons, so that a direct comparison is possible without changing the experimental arrangement. There was a sufficient number of tracks obtained to show that there is no essential difference between the energy lost by the positive electrons and that lost by the negative electrons. The results procured from 96 particles are shown in Fig. 4. The value of the energy loss is 0.121 Mev, in good agreement with the energy loss of the positrons. It can be definitely stated that, within the accuracy of these experiments, the energy lost by the positive electron is the same as that lost by the negative electron, at least for the energies of the particles considered here.

Discussion

The theoretical values of the average energy loss have been calculated from Bloch's formula.[9] The energy used in this formula has been taken as the energy which the particle possessed at the center of the absorber. These values are compared with the experimental ones in Table I.

Theoretically, there is no difference between the phenomena of energy loss of the positive and the negative electron, except for the fact that the positive electron may be annihilated somewhere along its path and thus decrease its effective range. It can be seen from the values given in Table I that the average energy loss determined by the experiment is about 20 percent higher than the theoretical value for the 0.0275 cm aluminum and that this difference increases to nearly 40 percent when the thickness of the absorber is doubled (0.053 cm aluminum). This fact is interesting, for it would seem to indicate that the discrepancy is increasing with the thickness, and that some process must be taking place which causes this. One explanation might be multiple scattering within the absorber, which would tend to make the actual path traversed by the particle greater than the actual thickness of the absorber. Whether this is the case or not cannot be determined until further data are obtained.

It must be remembered that none of the tracks which are stopped by the absorber are included in the calculation of the average energy loss. These are excluded on the assumption that the particles have been scattered out of the light beam as well as stopped by the absorber. If these tracks were included in the calculation, the value of the energy loss would be much greater.

From the results of this investigation, it may be stated that the experimental value of the energy loss of the positive electron in passing through aluminum seems to be greater than the theoretical formula of Bloch would predict. The direct comparison with the negative electron shows that there is no difference between the amounts of energy lost by the two particles. This is in agreement with the conclusions of Anderson,

[9] Heitler, *The Quantum Theory of Radiation* (Oxford Press, 1936), p. 218.

Blackett and J. G. Wilson, and Ruhlig and Crane, but is in disagreement with the results of Crussard and Leprince-Ringuet for cosmic-ray electrons.

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Calculations on a New Neutron-Proton Interaction Potential

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On the basis of a neutron-proton interaction potential of the form $Ce^{-r/\alpha}/r$ numerical calculations for the deuteron and for the scattering of neutrons by protons have been made.

INTRODUCTION

THERE has recently been suggested,[1] on theoretical grounds, a new neutron-proton interaction potential of the form $J(r) = -(C/r)\exp(-r/\alpha)$, where $\alpha = \hbar/M_0c$, M_0 being the mass of the heavy electron. Of the two unknown constants, α determines the range, $A = C\cdot\alpha$ the strength of the interaction. If this potential is to give the correct energy[2] for the ground state of the deuteron ($E_0 = 2.17$ Mev) a relation between A and α must be fulfilled. For other two-constant potentials, namely the spherical well, inverse fifth power, exponential, and Gaussian type interaction, the dependence of the magnitude of the forces on the range of the forces and the neutron-proton scattering cross sections have previously been calculated.[3] In this paper the same calculations are made for the new potential.

[1] H. Yukawa, Proc. Phys-Math Soc. Japan **17**, 48 (1935); **19**, 1084 (1937). N. Kemmer, Nature **141**, 116 (1938). H. J. Bhabha, Nature **141**, 117 (1938).

[2] H. A. Bethe, Phys. Rev. **53**, 313 (1938).

[3] H. S. W. Massey and R. A. Buckingham, Proc. Roy. Soc. **163**, 281 (1937). Morse, Fisk and Schiff, Phys. Rev. **50**, 748 (1936); **51**, 706 (1937).

1. THE GROUND STATE OF THE DEUTERON

The differential equation for the eigenfunction, ψ_0, of the ground state of the deuteron is[4]

$$\frac{\hbar^2}{M}\frac{d^2u_0}{dr^2}+(-E_0)u_0=-A\frac{e^{-r/\alpha}}{r/\alpha}u_0;\quad u_0=r\psi_0,$$

where E_0 is taken positive.

The transformation $r=\alpha x$ yields

$$u''+a(e^{-x}/x-\epsilon_0)u=0, \tag{1}$$

where $$a=A\alpha^2M/\hbar^2,\quad \epsilon_0=E_0/A; \tag{2}$$

$u(x)=u_0(r)$, and primes indicate differentiation with respect to x. The problem is now to determine, for given values of a, the constant ϵ_0 which yields a wave function u satisfying the boundary condition.

In the range between $x=0$ and $x=\frac{1}{2}$ (the value $\frac{1}{2}$ is chosen for convenience) the integration of (1) is made by using the first six terms of a power series development of $u(x)$. The boundary condition that u be zero (ψ_0 be finite) at $x=0$ is

[4] H. A. Bethe and R. F. Bacher, Rev. Mod. Phys. **8**, 82 (1936).