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The production and properties of positrons

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Information of fundamental importance to the general problem of atomic structure has resulted from systematic studies of the cosmic radiation carried out by the Wilson cloud-chamber method.

After Skobelzyn in 1927 had first shown photographs of tracks of cosmic-ray particles, Professor R. A. Millikan and the writer in the spring of 1930 planned a cloud-chamber apparatus suitable for cosmic-ray studies, in particular to measure the energies of cosmic-ray particles by means of their curvatures in a strong magnetic field. The chamber, of dimensions 17 x 17 x 3 cm, was arranged with its long dimension vertical, and incorporated into a powerful electromagnet capable of maintaining a uniform magnetic field up to 24,000 gauss strength.

In the summer of 1931 the first results were obtained with this technique. The direct measurement of the energies of atomic particles was extended from about 15 million electron-volts, the highest energy measured before that time, to 5 billion electron-volts. In the spring of 1932 a preliminary paper on the energies of cosmic-ray particles was published in which energies over I billion electron-volts were reported. It was here shown that particles of positive charge occurred about as abundantly as did those of negative charge, and in many cases several positive and negative particles were found to be projected simultaneously from a single center. The presence of positively charged particles and the occurrence of "showers" of several particles showed clearly that the absorption of cosmic rays in material substances is due primarily to a nuclear phenomenon of a new type.

Measurements of the specific ionization of both the positive and negative particles, by counting the number of droplets per unit length along the tracks, showed the great majority of both the positive and negative particles to possess unit electric charge. The particles of negative charge were readily interpreted as electrons, and those of positive charge were at first tentatively interpreted as protons, at that time the only known particle of unit positive charge.

If the particles of positive charge were to be ascribed to protons then those

of low energy and sharp curvature in the magnetic field, (e.g. a curvature greater than that corresponding to an electron having an energy of about 500 million electron-volts), should be expected to exhibit an appreciably greater ionization than the negatively charged electrons. In general, however, the positive particles seemed to differ in specific ionization only inappreciably from the negative ones. To avoid the assumption, which appeared very radical at that time, that the positive particles had electronic mass, serious consideration was given to the possibility that the particles which appeared to be positively charged and directed downward into the earth were in reality negatively charged electrons which through scattering had suffered a reversal of direction and were projected upwards away from the earth. Although such a reversal of direction through scattering might be expected to occur occasionally it seemed inadequate to account for the large number of particle tracks which showed a specific ionization anomalously small if they were to be ascribed to protons.

To differentiate with certainty between the particles of positive and negative charge it was necessary only to determine without ambiguity their direction of motion. To accomplish this purpose a plate of lead was inserted across a horizontal diameter of the chamber. The direction of motion of the particles could then be readily ascertained due to the lower energy and therefore the smaller radius of curvature of the particles in the magnetic field after they had traversed the plate and suffered a loss in energy.

Results were then obtained which could logically be interpreted only in terms of particles of a positive charge and a mass of the same order of magnitude as that normally possessed by the free negative electron. In particular one photograph (see Fig. 1) shows a particle of positive charge traversing a 6 mm plate of lead. If electronic mass is assigned to this particle its energy before it traverses the plate is 63 million electron-volts and after it emerges its energy is 23 million electron-volts. The possibility that this partitle of positive charge could represent a proton is ruled out on the basis of range and curvature. A proton of the curvature shown after it emerges from the plate would have an energy of 200,000 electron-volts, and according to previously well-established experimental data would have a range of only 5 mm whereas the observed range was greater than 50 mm. The only possible conclusion seemed to be that this track, indeed, was the track of a positively charged electron. Examples similar to this and others in which two or more particles were found to be produced at one center gave additional evidence for the existence of particles of positive charge and mass,
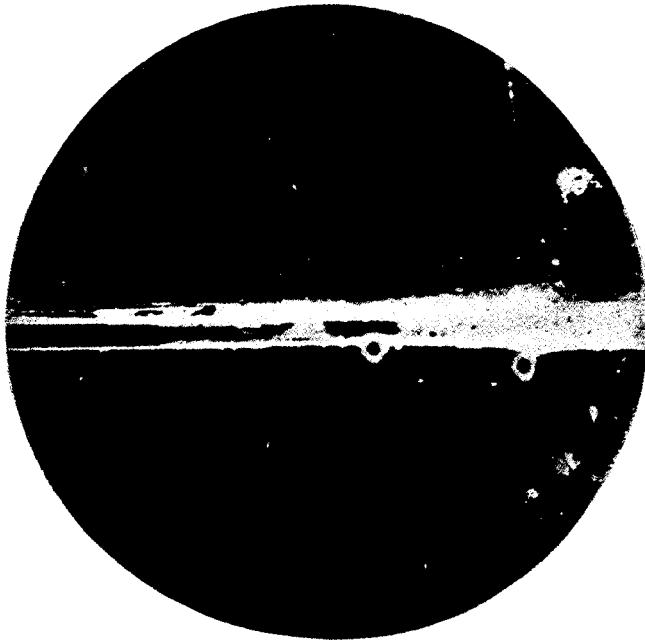
Fig. 1. A 63 million electron-volt positron passing through a 6 mm lead plate and emerging with an energy of 23 million electron-volts. The length of this latter path is at least ten times greater than the possible length of a proton track of this curvature. (Magnetic field 15,000 gauss.) *In all the photographs the magnetic field is directed into the paper.*

small compared with that of the proton. These results formed the basis of the paper published in September 1932 announcing the existence of free positive electrons.

Measurements by the droplet counting method of the magnitude of the specific ionization of the positive and negative electrons which occur with energies low enough to be appreciably curved in the magnetic field have shown that the mass and charge of the positive electron cannot differ by more than 20 percent and 10 percent, respectively, from the mass and charge of the negative electron.

Blackett and Occhialini using an apparatus similar to ours but with the added advantage that through the use of control by Geiger-Müller tube counters their apparatus was made to respond automatically to the passage of a cosmic-ray particle, in the spring of 1933 confirmed the existence of positive electrons, or positrons, and obtained many beautiful photographs of complex electron showers.

That positrons could be produced by an agent other than cosmic rays was first shown by Chadwick, Blackett and Occhialini when they observed that positrons were produced by the radiation generated in the impact of alpha particles upon beryllium. The radiation produced in the beryllium is complex in character, consisting both of neutrons and gamma rays. In their experiment it was not possible to determine which of these rays was responsible for the production of positrons. Curie and Joliot by a similar experiment, in which they interposed blocks of lead and paraffin into the path of the rays from beryllium and measured the yield of positrons as a function of the thickness and material of the absorber concluded that the positrons arose more likely as a result of the gamma rays than of the neutrons.

Direct proof that the hard component of the gamma rays from ThC" can give rise to positrons was first given by Neddermeyer and the writer, and independently by Curie and Joliot, and by Meitner and Philipp in the spring of 1933. In Figs. 2 and 3 positrons produced by gamma rays from ThC" are shown.

In addition to the methods of producing positrons already mentioned, i.e. by absorption of cosmic-ray photons and electrons, and by the absorption of sufficiently high energy gamma rays from terrestrial sources, positrons have also been observed among the disintegration products of certain radioactive substances. The artificially produced radioactive elements first discovered by Curie and Joliot in 1934 are found to distintegrate either by the ejection of a positive or negative electron. Those elements whose atomic number is greater than that of the stable elements of the same mass number in general distintegrate by the ejection of a positron. Fig. 4 shows positrons resulting from the disintegration of $^{11}_{6}C$ prepared by bombarding a boron target with deuterons.

Theoretical interpretation

The present electron theory of Dirac provides a means of describing many of the phenomena governing the production and annihilation of positrons. Blackett and Occhialini first suggested that the appearance of pairs of positive and negative electrons could be understood in terms of this theory as the "creation" of a positive-negative electron pair in the neighborhood of an atomic nucleus. The energy corresponding to the proper mass of both of the particles, as well as to their kinetic energies, is, according to this view, sup-
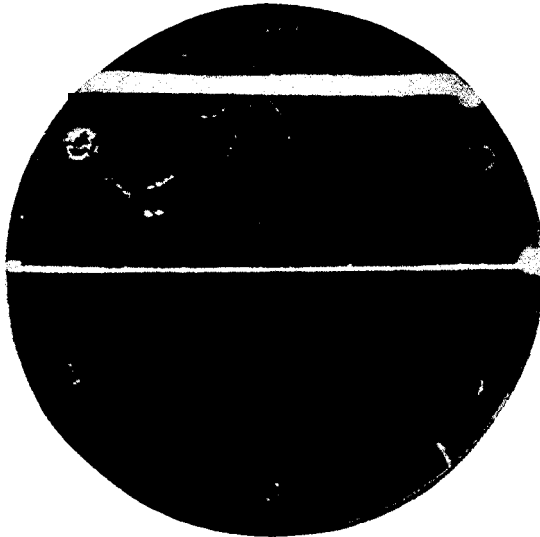
Fig. 2. A positron of 0.82 million electron-volts ejected from a lead plate by gamma rays from ThC" passes through a 0.5 mm aluminium plate and emerges with an energy of 0.52 million electron-volts. (Magnetic field 430 gauss.)
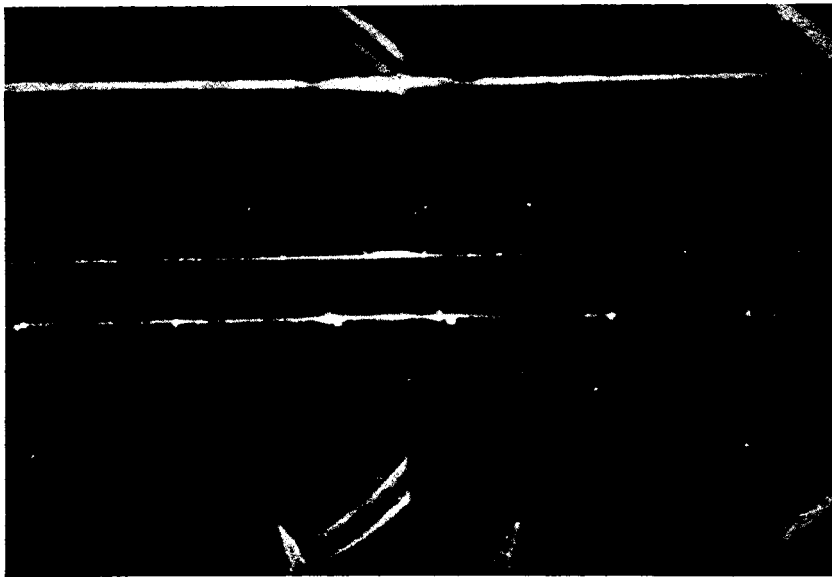

Fig. 3. A positive-negative electron pair produced in a lead plate by the gamma rays from ThC". (Magnetic field 800 gauss.) *In this and the remaining photographs the direct image is at the left; the right-hand reversed image is taken for stereoscopic observation.*
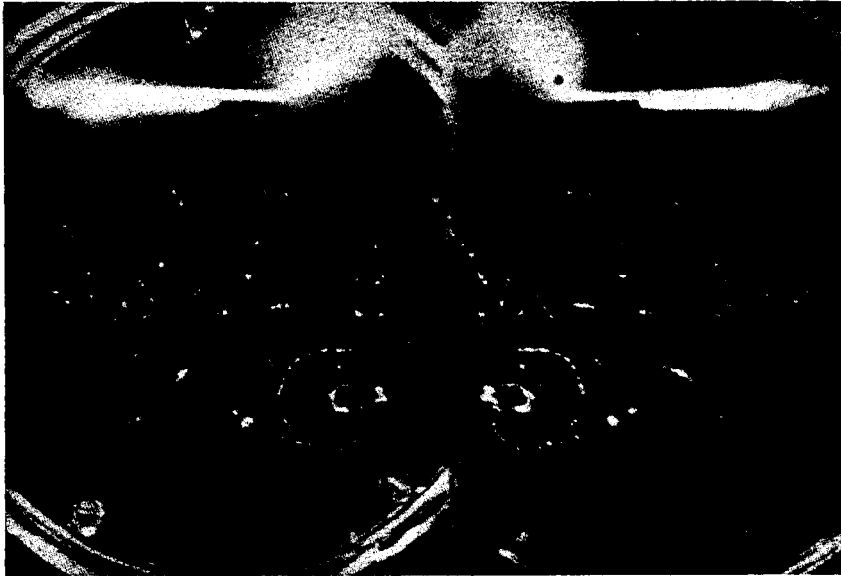
Fig. 4. Positrons produced in the distintegration of radioactive carbon of mass eleven units. (Magnetic field 780 gauss.) (The radioactive carbon was kindly supplied by Professor C. C. Lauritsen and his collaborators who prepared it by bombarding with deuterons a target containing boron.)

plied by the incident radiation. Since the energy corresponding to the proper mass of a pair of electrons is approximately one million electron-volts one should expect gamma rays of energy greater than this amount to produce positrons in their passage through matter, and further that the sum of the kinetic energies of the positive and negative electrons should be equal to the energy of the radiation producing them diminished by approximately one million electron-volts.

Experiments by Neddermeyer and the writer, and by Chadwick, Blackett and Occhialini, and others, have shown this relation to obtain in the production of positrons by ThC" gamma rays, providing evidence for the correctness of this view of the origin of positive-negative electron pairs.

The theory of Dirac requires further that a positron, when it finds itself in a very ordinary environment, as, for example, in passing through common substances, will, on the average, have only a very short life, of the order of one billionth of a second or less. The positrons and negative electrons will mutually annihilate one another in pairs, and in their stead will appear a pair of photons, each of approximately one-half million electron-volts energy.

Although the lifetime of positrons has not been actually measured, it has been shown to be very short, and the radiation which results from their annihilation has been observed. The first to do this were Joliot and Thibaud. The annihilation radiation is of the proper intensity and the energy of its individual corpuscles is approximately the required amount of one-half million electron-volts, corresponding to the complete annihilation of the positrons.

Positrons of high energy

The experimental results on the production of positrons out of radiation have been shown to be in approximate agreement with the theory for those processes where the quantum energies are not too high. Gamma radiations of quantum energy extending up to some 15 million electron-volts arise in certain nuclear transformations produced in the laboratory. Measurements of the absorption of these radiations and of the numbers and distribution in energy of the positive and negative electrons produced by these radiations are in sufficiently good agreement with the calculations of Oppenheimer, Heitler, and Bethe based on the Dirac theory to provide evidence for the essential correctness of the theory of absorption of gamma radiations in the range of quantum energy up to some 15 million electron-volts.

In the broad range of energies, however, which lies above 15 million electron-volts and extends up to at least 20,000 million electron-volts, such as the energies with which the cosmic-ray particles are endowed, the experiments have only very recently provided strong evidence leading to a detailed understanding of the absorption of photons and electrons in this range of energies and to an explanation of the cosmic-ray showers.

Closely related to the process of the production of positive and negative electrons out of radiation, is the one which may be considered its inverse, namely, the production of radiation through nuclear impacts by a positive or negative electron in its passage through matter. Direct measurements on the energy loss of electrons, in the energy range up to about 400 million electron-volts, in their traversals through thin plates of lead, have shown that the loss in energy due to direct ionization by the electrons is but a small fraction of the total energy loss, and that the loss in energy over that due to ionization is in good accord with that to be expected theoretically through the production of radiation by nuclear impact. Furthermore a small number of measurements at energies up to 1,000 million electron-volts has shown no

significant deviation from the theoretical loss. These data on energy loss of high-energy electrons afford strong evidence that, at least in part, the origin of the cosmic-ray showers of photons and positive and negative electrons can be understood in terms of a chain of successive processes of photon production by radiative impacts with nuclei on the part of the high-energy positive and negative electrons, and the subsequent absorption of these photons in nuclear collisions resulting in the production of numerous positive-negative electron pairs which appear as the cosmic-ray showers. After more detailed theoretical computations have been carried out on the rate of building-up of positive and negative electron secondaries resulting from these multiple processes, and their subsequent removal through absorption, will a more adequate test of the theory be possible. At present, however, it is very difficult to doubt that the highly absorbable component of the primary cosmic-ray beam consists largely of electrons absorbed principally through the mechanisms discussed above, which give rise to the electron showers.

Until quite recently it was not clear that the high-energy positive and negative electrons which have now been shown to exhibit a high absorbability, behaved in a manner essentially differently from the cosmic-ray particles of highly penetrating character. These highly penetrating particles, although not free positive and negative electrons, appear to consist of both positive and negative particles of unit electric charge, and will provide interesting material for future study.

Figs. 5-11 show examples of cosmic-ray showers of positive and negative electrons, and Fig. 12* an example of a large energy loss of a fast positive electron. Figs. 5,6,7,8, and 11 were photographed at 4,300 meters above sea level, the remainder near sea level.

It is a pleasure to express my sincere gratitude to Professor Millikan and to Dr. Neddermeyer for the great part they have played in these investigations on the properties of positrons, and to the Carnegie Institution of Washington, whose funds administered to Professor Millikan have made the investigations   possible.

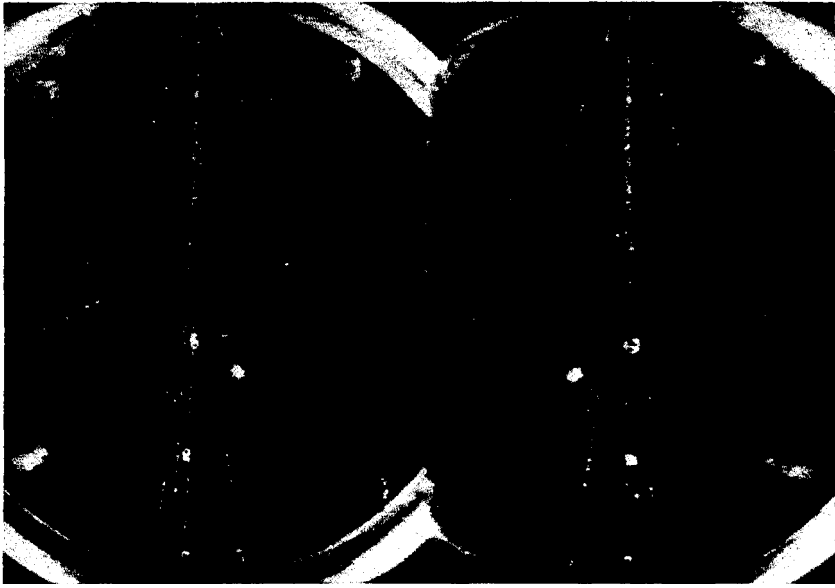* No reproduction of this figure was given in the original.

Fig. 5. A small cosmic-ray shower of positive and negative electrons. (Magnetic field 7,900 gauss.)
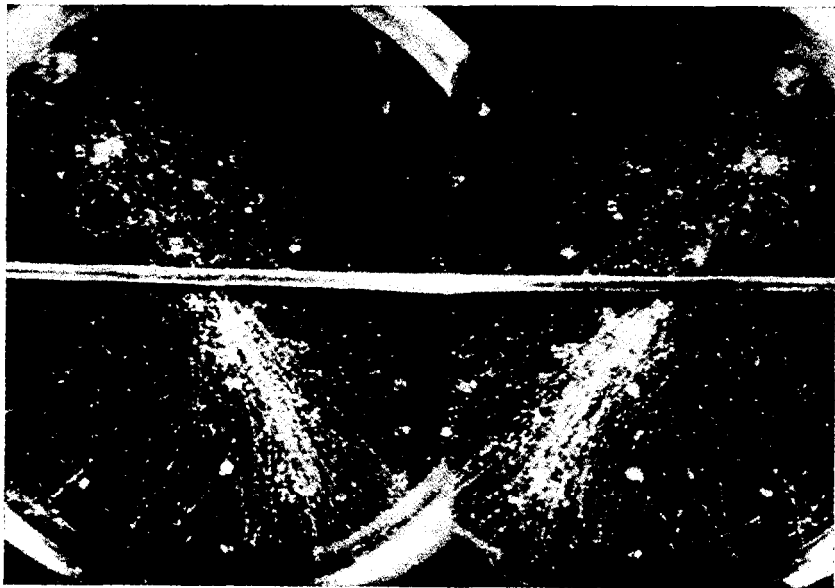

Fig. 6. A cosmic-ray shower of more than one hundred positive and negative electrons (Magnetic field 7,900 gauss.)

Fig. 7. A shower in which eight electrons (+ and -) strike the upper surface of a 0.35 cm lead plate, and more than fifteen emerge from its lower surface. This photograph is an example of the multiplication of shower tracks in a thin piece of absorbing material, due to the production by radiative impacts of photons and their absorption through pair-production (Magnetic field 7,900 gauss.)

Fig. 8. A positive-negative electron pair (energies of negative and positive 4.6 and 140 million electron-volts respectively) generated in the gas (argon) of the chamber by a photon associated with the cosmic rays. (Magnetic field 7,900 gauss.)
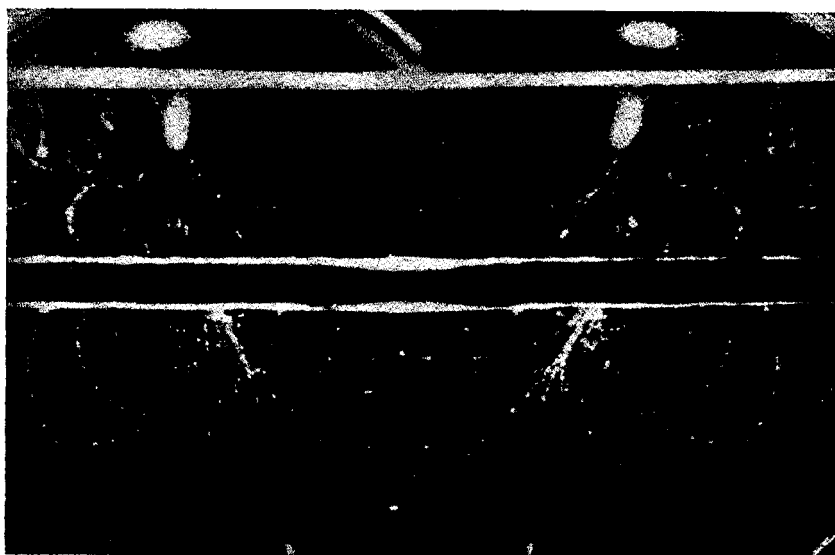
Fig. 9. A cosmic-ray shower of 22 positive and negative electrons produced by one or more photons initially incident on the upper surface of a 1 cm lead plate. (Magnetic field 17,000 gauss.)
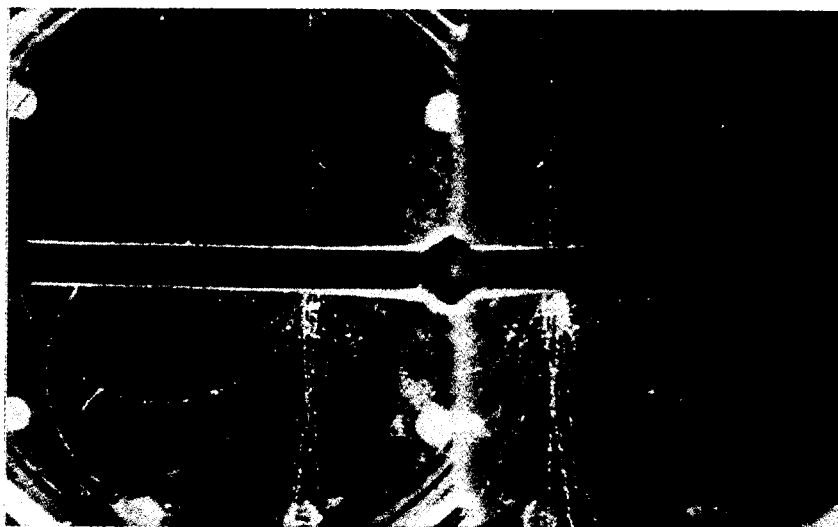

Fig. 10. Three high-energy cosmic-ray electrons incident on the upper surface of a 1 cm platinum plate. A shower of more than 20 positive and negative electrons emerges from the lower surface of the plate from a region below two of the three incident electrons. The shower appears as a result of the production of photons by radiative impacts and their absorption by pair-production in the platinum plate. (Magnetic field 7,900 gauss.)

Fig. 11. A positron of 480 million electron-volts strikes a 0.35 cm lead plate. Below the plate three electrons appear having energies (in million electron-volts) respectively: positron 45, negatron 45, and positron 31. One of the tracks below the plate presumably represents the incident positron after passage through the plate, and the other two tracks a pair generated by the absorption of a photon generated in the plate. The energy lost in the plate by the incident positron is at least 435 million electron-volts and since the loss by ionization in a plate of this thickness should not be greater than IO million electron-volts, the greater part of the energy lost by the positron in this instance must have appeared in the form of radiation. (Magnetic field 7,900 gauss.)