A rise in temperature would also affect the radii a and b of the wire and tube. The maximum values of these expansion corrections were computed and their effects found to be negligible. The amount of expansion of the rod controlling the movements of the piston could be computed from the known temperatures, the known amount of rod exposed and its coefficient of expansion. All scale readings were individually corrected for this expansion.

Velocity of the Waves Along the Cable

From the accepted value for the velocity of the electromagnetic waves in free space, $c=2.99775\times 10^{10}$ cm/sec., and the true wave-length of the oscillator, $\lambda_0=151.89$ cm, the frequency of the latter was found to be 1.9736×10^8 cycles/sec. This combined with the measured wave-lengths along the cables containing copper, nickel and iron wires gave for the velocities of wave propagation along these cables at room temperature the following results. The velocity along the copper wire cable proved to be 2.993×10^{10} cm/sec., that along the nickel wire cable was 2.964×10^{10} cm/sec., and that along the iron wire cable was 2.936×10^{10} cm/sec. These differ from the wave-length in free space by 0.17 percent, 1.13 percent and 2.06 percent, respectively.

I wish to express my sincere appreciation to Professor J. Barton Hoag for suggesting this problem and for his encouragement and advice during the progress of the investigation. For the chemical analysis of the iron and nickel wire I am indebted to Mr. Alfred Klapperich.

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On the Creation of Pairs or Positrons by Fast Electrons

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By means of the cloud chamber a search was made for the creation of pairs or positrons by electrons of energies between one and 12 Mev, in air, mica, lead and platinum. A total of 2588 traversals of electrons through solid materials, and a total track length of 628 meters in air were examined. The abnormally large cross section for the process, as reported in numerous papers by other workers, was not confirmed. The data found point toward agreement with the theoretical calculations. A test for an anomaly at the threshold (one Mev) was not attempted, because of the difficulty of making a decisive experiment in a cloud chamber under conditions in which the pairs formed would have very small energy. A resumé of the literature on the subject of pair and positron formation by electrons, and a rather full discussion of the possibilities for error in the experimental method are given.

Introduction

A NUMBER of papers are now on record in which it is stated by the authors that the cross section for the creation of pairs by electrons is much higher than that predicted by theory. During the course of experiments carried out in this laboratory[1–5] a great many cloud-chamber photographs have been accumulated which show the passage of high energy electrons through thin sheets of absorbing materials and through air. We have recently examined these photographs for the creation of pairs by the high energy electrons, and are in a position to compare our findings with those of other workers. Because the literature on the subject is rather scattered, the following resumé will be of convenience.

[1] J. J. Turin and H. R. Crane, Phys. Rev. **52**, 63 (1937).
[2] J. J. Turin and H. R. Crane, Phys. Rev. **52**, 610 (1937).
[3] A. J. Ruhlig and H. R. Crane, Phys. Rev. **53**, 618 (1938).
[4] D. S. Bayley and H. R. Crane, Phys. Rev. **52**, 604 (1937).
[5] M. M. Slawsky, Thesis, University of Michigan, 1938, unpublished.

Experiments

Skobeltzyn,[6] in 1934, was the first to report the production of pairs by electrons. He observed

[6] D. Skobeltzyn, Nature **133**, 23 (1934).

several pairs which were produced by the passage of electrons of slightly over one Mev energy through nitrogen gas in a cloud chamber. He concluded that the probability for the event was much greater than that given by the theory. The total track length observed was several hundred meters.

Alichanow and Kosodaew[7] measured the energies of electrons and positrons emitted from a Ra(B+C) source by means of a magnetic analyzer. They surrounded the Ra(B+C) with aluminum and determined the number of positrons as a function of the thickness of aluminum. They found that an appreciable number of positrons was produced by the action of the beta-rays on the aluminum, and that positrons were also produced by pair-internal conversion in the radioactive atoms. The number of positrons produced in the aluminum was estimated at 20 to 50 percent of the number produced by internal conversion, but no absolute cross section was given.

Skobeltzyn and Stepanowa[8] placed a radium source in a cloud chamber and surrounded it with a thin layer of glass and lead. They observed about 30 positrons, which was 0.02 to 0.04 positron per disintegrating atom in the source. Because this was far greater than expected theoretically they proposed that the positrons were produced by the action of the beta-rays on the material surrounding the radium, and that a new mechanism must be involved.

Skobeltzyn and Stepanowa,[9] in reporting a continuation of their experiments give evidence that the cross section for production of positrons by electrons of one to three Mev energy is of the order 10^{-22} cm^2 in lead and varies as the atomic number. This was based upon 130 positron tracks obtained in 1650 cloud-chamber photographs.

Skobeltzyn and Stepanowa,[10] in a further publication, reported that positrons were produced in abundance when fast electrons were allowed to strike a piece of carbon. They placed a carbon filter three mm thick in front of a small amount of radium, and observed the electrons which emerged by means of a cloud chamber. They found one positron for every 10 to 20 electrons which penetrated the filter.

Alichanow, Alichanian and Kosodaew[11] were unable to confirm the large cross section found by other workers. They irradiated thin foils of lead and aluminum with a mixture of gamma-rays and beta-rays and with gamma-rays alone, obtained from radon and its products. They found that the cross section for production of positrons (or pairs) by the gamma-rays of RaC was at least several times greater than the cross section for their production by the beta-rays of RaC, in both lead and aluminum. The experiment was done by means of a magnetic focusing apparatus and coincidence Geiger counters.

Champion[12] observed the passage of electrons through nitrogen gas in a cloud chamber, and in a total length of 200 meters of track along which the electrons had more than one Mev energy, he found no indication of the production of positrons.

Staub[13] carried out a cloud chamber experiment in which the beta-particles were preselected as to energy before entering the chamber, by means of an auxiliary magnet. He searched for pairs or positrons which might have been formed in the material which comprised the window of the cloud chamber. The mean energy of the electrons was 1.9 Mev. No positrons resulted from the passage of 565 electrons through lead weighing 0.23 g per cm^2, 675 electrons through aluminum weighing 0.27 g per cm^2 and 227 electrons through carbon weighing 0.23 g per cm^2. This indicates that the cross section is not larger than the order 10^{-24} for lead and 10^{-25} for aluminum and carbon.

Marques da Silva[14] performed an experiment with a cloud chamber and obtained a cross section of the order 10^{-22} cm^2 for the production of positrons by electrons of energy between 1.1 and 2.2 Mev passing through lead.

Skobeltzyn and Stepanowa[15] again reported

[7] A. I. Alichanow and M. S. Kosodaew, Zeits. f. Physik **90**, 249 (1934).

[8] D. Skobeltzyn and E. Stepanowa, Nature **133**, 565 (1934).

[9] D. Skobeltzyn and E. Stepanowa, J. de phys. et rad. **6**, 1 (1934).

[10] D. Skobeltzyn and E. Stepanowa, Nature **133**, 656 (1934).

[11] A. I. Alichanow, A. I. Alichanian and M. S. Kosodaew, Nature **136**, 719 (1935).

[12] F. C. Champion, Proc. Roy. Soc. **A153**, 353 (1935).

[13] Hans Staub, Helv. Phys. Acta **9**, 306 (1936).

[14] Marques da Silva, Comptes rendus **202**, 2070 (1936).

[15] D. Skobeltzyn and E. Stepanowa, Nature **137**, 272 (1936).

the results of a cloud-chamber experiment. In this instance the electrons from three to five millicuries of radium were pre-selected as to energy by a magnet outside the chamber, so that most of those entering had energies above two Mev. The electrons passed through sheets of lead 0.07 and 0.13 mm thick and of aluminum 0.5 and one mm thick at the center of the chamber. Ten pairs were found in about 1200 tracks. They concluded that beta-rays were more effective in producing pairs in lead than were gamma-rays of the same energy. They also confirmed the production of pairs by electrons in nitrogen gas.

Champion and Barber[16, 17] studied the tracks of electrons in a cloud chamber containing five percent mercury dimethyl vapor and 95 percent nitrogen. They observed the production of pairs, and concluded that it was due to the presence of the mercury, in view of the negative results obtained by Champion for pure nitrogen. The effective cross section for pair production by electrons of greater than one Mev energy in mercury was found to be about 3×10^{-22} cm^2. Their results also indicated that the cross section was greater for electrons having just slightly more than one Mev energy than for electrons of higher energy. They express the opinion that the cross section increases rapidly with atomic number.

Feather and Dunsworth[18] used a new and ingenious method of detecting the formation of low energy positrons by electrons. Beta-rays from *UX* were absorbed in lead, brass and aluminum. Since the materials used were thick, it was expected that most of the positrons formed would be stopped and annihilated within the materials. The resulting pairs of oppositely directed 0.5 Mev quanta were detected by means of coincidence Geiger counters set 180° apart. Their results indicated a cross section of about 1.4×10^{-22} cm^2 per atom of lead, when all electrons above the threshold (one Mev) were considered.*

TABLE I. *Some calculated cross sections for pair formation in lead.*

Energy (Mev)	1.5	2.5	5	10
Gamma-rays (10^{-25} cm^2)	6.5	30	83	144
Electrons (10^{-25} cm^2)	0.1	0.4	1.1	2.5

Theoretical values

A number of theoretical papers are available,[19–25] and they are in general agreement among themselves as to the cross section for production of pairs by electrons, under conditions in which the energies of the primary electron and of the pair are large compared to mc^2 and in which the energy of the primary electron is large compared to the energy of the pair formed. Although the extrapolation of the formulae to the comparatively low energies in which we are interested is not strictly permissible, it is to be expected that the cross section will decrease with decreasing energy over the whole range. This view is encouraged by the similarity of the formulae to those for the production of pairs by gamma-rays. It is known that in the latter case there is no anomaly at low energies, even at the threshold. Some calculated cross sections for pair formation in lead by both gamma-rays and electrons are given in Table I.

On the Choice of Experimental Conditions

In deciding upon the thicknesses of material and the energy range of the electrons with which to work, the following points should be kept in mind.

Chance that a pair will emerge from a material

The kinetic energy of a pair is expected to be less than that of the primary electron by *at*

[16] F. C. Champion and A. Barber, Nature **140**, 105 (1937).
[17] F. C. Champion and A. Barber, Proc. Roy. Soc. **A168**, 159 (1938).
[18] N. Feather and J. V. Dunsworth, Camb. Phil. Soc. Proc. **34**, 435 (1938).

* *Note added in proof.*—Since the time of writing, a paper by R. L. Sen Gupta has appeared (Proc. Phys. Soc. **51**, 355 (1939)) which deals mainly with the scattering of electrons in xenon gas. The author states that in a total track length of 330 meters in a gas mixture containing about 50 percent xenon at atmospheric pressure no pairs were formed. The energy of the electrons was 2.1 Mev ±10 percent.
[19] W. H. Furry and J. F. Carlson, Phys. Rev. **44**, 237 (1933).
[20] L. Landau and E. Lifschitz, Physik. Zeits. Sowjetunion **6**, 244 (1933).
[21] W. Heitler and L. Nordheim, J. de phys. et rad. **5**, 449 (1934).
[22] E. J. Williams, Nature **135**, 66 (1935).
[23] E. C. G. Stueckelberg, Helv. Phys. Acta **8**, 325 (1935)
[24] L. Nordheim, J. de phys. et rad. **6**, 135 (1935).
[25] J. J. Bhabha, Proc. Roy. Soc. **A152**, 559 (1935).

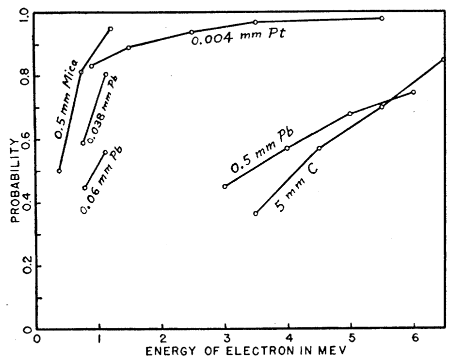

FIG. 1. The probability that an electron will emerge into the visible part of the cloud chamber if it starts at a given depth below the surface of the sheet of solid material and in an initial direction perpendicular to the surface. The kind of material and the depth at which it starts are given for each curve.

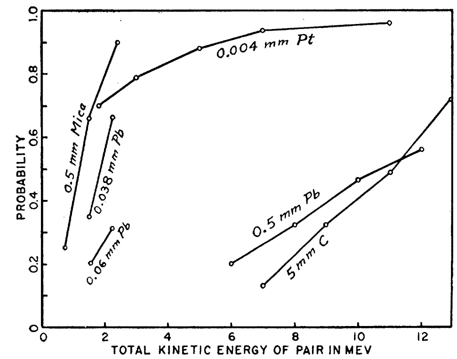

FIG. 2. The probability that both members of a pair will emerge into the visible part of the cloud chamber if the pair starts at a given depth below the surface of the sheet of solid material and in an initial direction perpendicular to the surface. The kind of material and the depth at which the pair starts are given for each curve.

least one Mev, and this is divided between the two members. Therefore if the pair is to have a reasonable chance of emerging from a solid material the primary electron must have much more than one Mev energy. We can give experimental data upon the chance that an electron will emerge, if it starts in a direction normal to the surface at a given depth below the surface. This is obtained by observing electrons which strike absorbing materials in a direction normal to the surface, and recording the relative numbers which apparently fail to pass through. The geometry of the cloud chamber is automatically taken into account, in that the few electrons which emerge in nearly the vertical direction are not seen and are recorded as not emerging. The chance of emergence for a single particle (Fig. 1) is easily transformed into the chance of emergence of both members of a pair in which the energy is divided equally between the two members (Fig. 2). Equal division of energy gives the greatest chance of emergence for the pair, so the curves in Fig. 2 must be considered as upper limits.

Double process

In thick absorbers of high atomic number a double process, in which the primary electron produces a gamma-ray quantum and the quantum produces a pair may become more probable than the direct production of a pair by the electron. Since the cross sections for the separate processes increase as Z^2, that of the double process will increase as Z^4. The probability of the double process will also increase roughly as the square of the thickness of the material (for small thicknesses) and will increase very rapidly with increasing energy of primary electron. A rough calculation indicates that for a 10-Mev electron passing through 0.5 mm of lead the probability of the double process is as large as

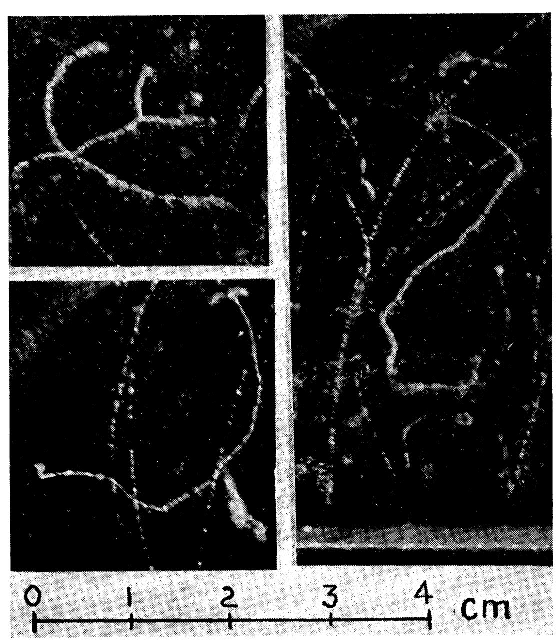

FIG. 3. Typical tracks of very low energy electrons, showing that the scattering by the gas largely masks the effect of the magnetic field. The chamber contained air at atmospheric pressure, and the strength of the field was 600 gauss.

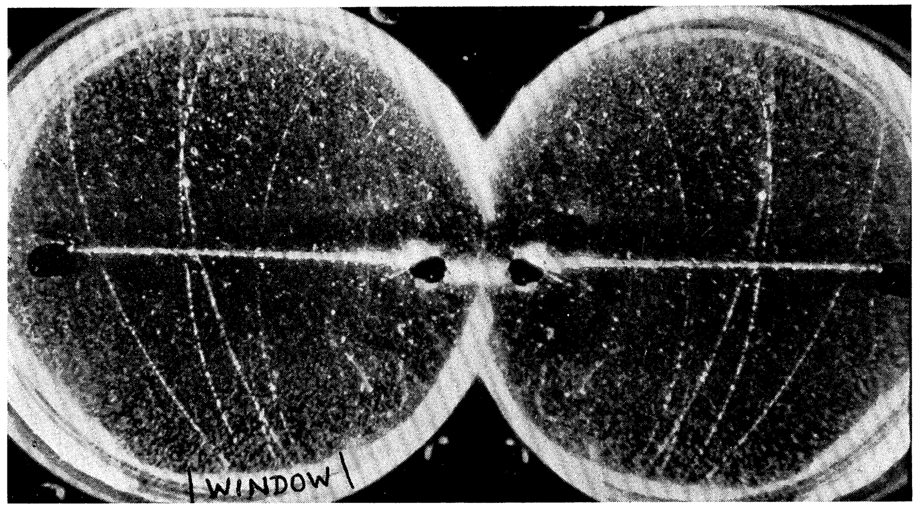

FIG. 4. Typical photograph of the tracks of electrons passing through a sheet of solid material in the center of the cloud chamber. A band of energies is selected by a slit system in the magnetic field outside the chamber. The electrons enter the chamber through a thin aluminum window. $H=1450$ gauss.

the probability of pair formation by the electron directly, as given in Table I. Thus the double process is important only for the highest energy electrons which we have observed (8 to 11 Mev, 0.5 mm lead), and there is no possibility that it could have introduced an error into the results so far reported by other workers.

Low energy pairs originating in a gas

Evidence[16, 17] has suggested an anomalously high probability for the formation of pairs of very low energy (a few thousand ev) by electrons of slightly over one Mev energy. We have decided against performing an experiment of this type ourselves, because of the difficulty of determining the sign of an electron of very low energy. It has been our experience that electrons having less than about two cm range in air ($\sim$33 kev) are so much scattered that the effect of a magnetic field of 500 to 1000 gauss is to a large extent masked. In fact many negative electrons are observed to have "curvatures" which indicate the opposite charge, under these circumstances. Some typical tracks of electrons of a few cm range in air are shown in Fig. 3. The field is 600 gauss, and it is seen that the electrons of higher energy are bent into smooth circles.

Negative electrons moving backwards

Electrons are very often reflected from the wall of the cloud chamber in such a way that they return to the source or to the emergent side of the absorbing material. Reflection coefficients range up to 20 percent for light materials and up to 50 percent for lead, depending, of course, upon the energy. Tracks of reflected electrons will have curvatures indicating that

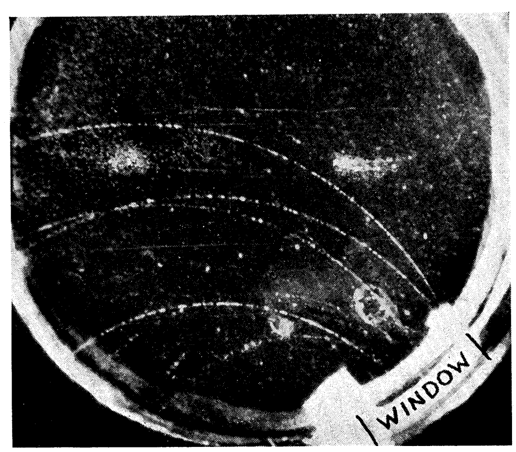

FIG. 5. Typical photograph used for determining the cross section for production of pairs by electrons in passing through air. The slit system and the window are the same as described under Fig. 4. $H=2850$ gauss.

they are positrons, and can easily be mistaken as such. The chance of making this mistake is greatly reduced if an arrangement is used in which the tracks are visible on both sides of the absorbing material, so that a positron or pair can be identified with the particular primary electron which produced it. For this reason we have not considered it worth while to repeat the type of experiment[8–10, 13, 14] in which the absorbing foil comprises part of the wall of the cloud chamber.

Gamma-rays and other confusing influences

When sources are used which emit both beta-rays and gamma-rays, it is difficult to keep the chamber clear of tracks which are due to the gamma-rays. Accidental coincidence in position of these tracks (especially the low energy ones) with the beta-ray tracks can easily indicate falsely the formation of pairs. The same is true even for a pure beta-ray source, if too many tracks are allowed on each picture. We have restricted our experiments to the use of sources which emit no appreciable gamma-radiation and have restricted the number of tracks per picture to between two and four, to avoid this kind of confusion as far as possible.

Experimental Method

Beta-rays from Li^8 or P^{32} were allowed to enter the cloud chamber through a thin aluminum window in the wall. A sheet of lead or other material was placed in the center of the chamber, so that the electrons passed through it nearly normal to the surface. The energy of each particle striking the material was determined by its curvature in the magnetic field. A slit system outside the cloud chamber placed very rough limits upon the energies of the electrons entering the chamber. This was done mainly to eliminate confusion by keeping the unwanted low energy electrons from entering, and not for the purpose of determining the energies, because the latter was done inside the chamber, on the tracks individually. The intensity of the source was so adjusted that only two to four electron tracks appeared on each photograph. Stereoscopic pairs of photographs were taken, by means of a mirror. In examining the photographs only very clear tracks were included in the data, and in order to select them in an unbiased way the following procedure was used for each photograph. A mask was placed over the far half of the chamber (the side on which the electrons emerged from the absorber), and those tracks which appeared to strike the absorber normally and which, particularly, were very clear in the neighborhood of the absorber were chosen. After the curvatures were measured, the mask was removed and the points of emergence on the other side of the absorber were examined for possible pairs or other secondaries.

In searching for pairs produced in the gas by electrons, the same arrangement was used except that no sheet of material was placed in the chamber. The electrons entered through the aluminum window and traveled completely across the chamber, each making a track about 15 cm long. Stereoscopic views of the chamber were not taken in this case.

Figures 4 and 5 show typical photographs taken with each of the two arrangements. These are shown because they give a good idea as to the geometrical conditions and also because it is of great importance in an experiment of this kind for the reader to know the general appearance, clarity and degree of confusion in the photographs, since this determines how easily a pair may escape notice, or how easily a "pair" may be seen where there is none.

Results

Platinum

Five hundred and forty-one electrons were observed to strike a platinum sheet 0.004 mm thick (8.3 mg/cm^2). The numbers of electrons in various energy ranges are given in Table II. No pairs or positrons were observed. It is difficult to place an upper limit upon the cross section when the number of pairs observed is zero. However, the following statement indicates the order of magnitude: We would expect, on the average, one pair to be formed by the

Table II. *Energy ranges of electrons striking platinum.*

Energy (Mev)	1–2	2–3	3–4	4–5	5–6	6–7
Number	73	144	158	86	53	27

TABLE III. *Energy ranges of electrons striking mica.*

Energy (Mev)	1–2	2–3	3–4	4–5	5–6	6–7	7–8
Number	67	59	117	200	167	67	33

TABLE IV. *Energy ranges of electrons passing through air.*

Energy (Mev)	6–8	8–10	10–12
Length (meters)	105	104	31

above group of tracks if the cross section in platinum were 7×10^{-23} cm^2.

Mica

A total of 710 electrons, having energies as shown in Table III were observed to strike a sheet of mica about 0.5 mm thick (150 mg/cm^2). No indication of the formation of a pair or positron was found. We can give some idea as to the limit to be placed upon the cross section by stating that we should have expected one pair if the effective cross section were 4×10^{-25} cm^2. The mica used was of the form $H_2KAl_3\times(SiO_4)_3$, having an average atomic weight 19 and a density about 3.

Air

A large number of tracks produced by the beta-rays of Li^8 were examined for the production of pairs in air at atmospheric pressure. The total length of the tracks examined was 240 meters, distributed in energy according to Table IV. No pairs or positrons were found. The expectation would be one pair if the cross section were 1×10^{-24} cm^2. It should be remarked that also in those photographs in which the chamber contained a sheet of solid material, an examination was made for the formation of pairs in the gas, with negative results. The track length examined in this way was 388 meters, distributed in energy according to Table V. Combining the data of Tables IV and V, we can say that we should have found one pair if the effective cross section in air were 4×10^{-25} cm^2.

TABLE V. *Energy ranges of electrons passing through air.*

Energy (Mev)	1–2	2–4	4–6	6–8	8–10	10–12
Length (meters)	21	72	76	112	82	25

TABLE VI. *Energy ranges of electrons striking lead.*

Energy (Mev)	6–8	8–10	10–12
Number	625	548	164

Lead

We have examined a large number of photographs in which electrons strike a lead sheet 0.5 mm thick. According to Fig. 1 the probability that a pair will emerge from 0.5 mm of lead is very small unless it has several Mev energy. For this reason we have only examined those cases in which the energy of the primary electron is greater than six Mev. It should be kept in mind that the double process, which was mentioned earlier, may produce pairs under these conditions. 1337 tracks were examined, having energies according to Table VI. No pairs or positrons were found in these photographs. We should have expected one pair if the cross section in lead were 5×10^{-25} cm^2. However, because a pair or positron would not have more than a 50 percent chance of emerging from the lead, we must revise the above figure to about 1×10^{-24} cm^2.

CONCLUSIONS

As the above data show, we have been unable to find any indication that the cross section for pair formation by electrons is abnormally large, for energies below 12 Mev in substances of either low or high atomic number. The energies of the electrons we have used have, in the main, been greater than those used by the other experimenters. The use of electrons well above one Mev should, for many reasons, give a clearer test for the formation of pairs. However, this same choice of energies makes it impossible for us to offer any information concerning the possibility of an anomaly in the cross section at the threshold, one Mev.

We are grateful to the Rackham Endowment Fund for the financial support of this work.

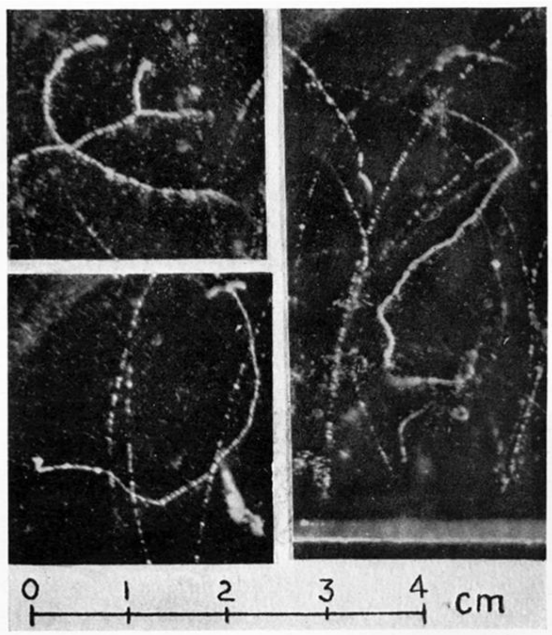

FIG. 3. Typical tracks of very low energy electrons, showing that the scattering by the gas largely masks the effect of the magnetic field. The chamber contained air at atmospheric pressure, and the strength of the field was 600 gauss.

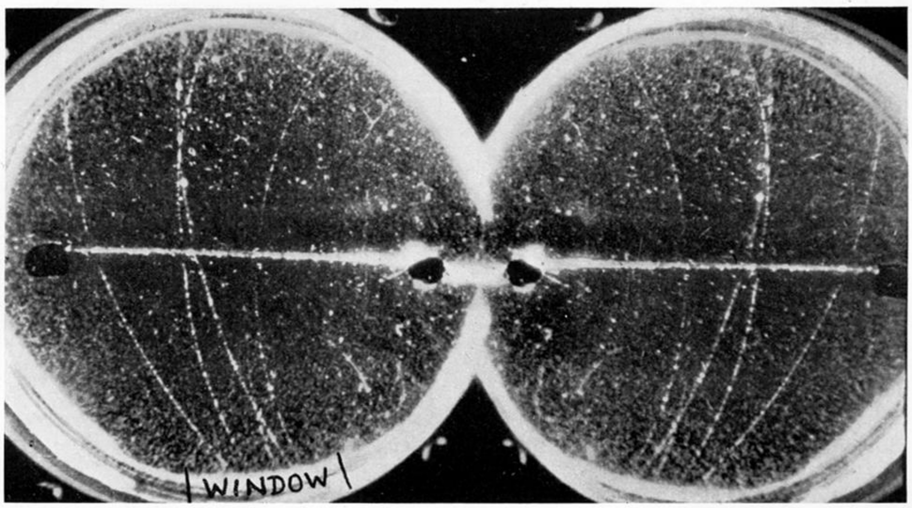

FIG. 4. Typical photograph of the tracks of electrons passing through a sheet of solid material in the center of the cloud chamber. A band of energies is selected by a slit system in the magnetic field outside the chamber. The electrons enter the chamber through a thin aluminum window. $H=1450$ gauss.

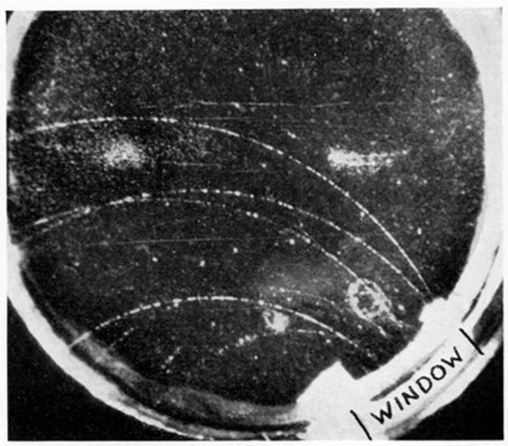

Fig. 5. Typical photograph used for determining the cross section for production of pairs by electrons in passing through air. The slit system and the window are the same as described under Fig. 4. $H=2850$ gauss.