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HIGH ENERGY ELECTRON-ELECTRON SCATTERING

Walter H. Barkas, Robert W. Deutsch,
F. C. Gilbert, and Charles E. Violet

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High Energy Electron-Electron Scattering
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In the above article it was noted that in two cases tracks of 185 Mev particles rather mysteriously stopped abruptly in the emulsion. In our opinion the events were real, and we could not disregard them. The behavior was considered anomalous because there was good reason to believe that the electrons being studied were negative. The direction of the analysing magnetic field had been carefully established by the direction of the force on a current carrying conductor.

Since it is obviously important to understand the process in question, we have followed up the original study with a further investigation of this behavior. These additional observations now satisfy us that we were mistaken regarding the sign of the particles studied.

With the original plates a number of other plates were exposed simultaneously to electrons of various energies of the same and the opposite signs. On scanning some of these plates we have obtained the following results:

1. Particles of ~36 Mev and of the same sign as those which were found to disappear were studied. Six disappearances were found when 185 cm of track was scanned.
2. Particles of ~36 Mev and of the opposite sign were then studied. In scanning 171 cm of track no disappearances were found.
3. Particles of ~185 Mev of the opposite sign were also studied. In scanning 53 cm of track no disappearances were observed.

Apparently particles of the same sign as those in the original experiment

disappear, but particles of the opposite sign do not. This is the anticipated behavior if the original particles were positive electrons which annihilate in flight. That they actually are positive must be concluded from another experiment[1] carried out by one of us in collaboration with Dr. S. A. Colgate who suggested the investigation. This experiment utilized the same equipment as before, but the particle disappearances were detected by counters. The signs of the particles were established with certainty, and positive particles were found to be lost from the beam in traversing matter much more frequently than negative particles in accordance with the theory of Dirac. All the observations were consistent if we assume that between the time the direction of the magnetic field was established and the time the original plates were exposed the position of the reversing switch in the magnet circuit was (unexplainable) altered. The scattering experiment should be then interpreted as a study of the scattering of positive electrons by negative electrons. No observable difference between positron-electron and electron-electron scattering in the region investigated is to be expected.

It is believed that this is the first time that the annihilation in flight of high energy positrons has been directly observed, although the effect is well known from studies of the annihilation photons. We have looked for electron pairs from photons produced when the tracks terminate, but have found none. However, we estimate that the probability of a pair being found in the volume of emulsion which could be searched beyond the terminii of the tracks is only 0.1.

In the above article on page 61, line 36 a typographical error should also be corrected. For "relative humidity was maintained at 10 percent" read "relative humidity was maintained at 100 percent".

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[1] F. C. Gilbert and Sterling A. Colgate, Bull. Am. Phys. Soc. 27, 13 (1952)

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ABSTRACT

Eradicated electron sensitive nuclear emulsions were exposed to 200 Mev electrons at the Berkeley synchrotron. 427 events were observed in which the scattered electron of lower energy, or knock-on electron, had an energy greater than 30 Kev. The observed differential cross-section was found to agree in absolute value with Møller's theoretical cross-section, although an insufficient number of high energy knock-on electrons were observed to distinguish between the Møller, relativistic Mott and relativistic Rutherford formulae. Two pairs initiated by primary electrons and two cases in which primary electrons vanished in the emulsion were also observed in 102.6 cm of track. No heavy particle events were seen.

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I. INTRODUCTION

Historically, the electron is the best known of the fundamental particles. However, a lack of information still exists concerning its actual structure. An electron-electron scattering experiment would seem to be the ideal way to investigate the boundaries of the electron and the possibility of non-Coulomb electron-electron forces. To find deviations from a Coulomb potential, one would roughly estimate that it is necessary to have an impact parameter of the order of the classical electron radius. In order for the impact parameter to be well defined the de Broglie wave length, λ, of the electron in the relativistic center of mass system must be of the order of 2.8 x 10^{-13} cm or less. A simple calculation shows that such a wavelength would require an energy of about 19 Bev. in the laboratory system. In the present experiment 200 Mev electron primaries were used which have a de Broglie wavelength of about 10 times the classical electron radius in the relativistic center of mass system. Even for this wavelength, the possibility seemed to exist of observing a deviation from the Coulomb potential if the effect were strong.

The generally accepted formula giving the scattering cross-section of electrons by electrons has been derived by Møller.[1] This formula in terms of the scattering angle, θ, in the relativistic center

of mass system is the following:

$$\sigma(\theta)d\theta = \frac{(\gamma+1)\pi r_o^2 \sin\theta d\theta}{\gamma^2\beta^4}\left[\csc^4\frac{\theta}{2} + \sec^4\frac{\theta}{2} - \csc^2\frac{\theta}{2}\sec^2\frac{\theta}{2} + \frac{(\gamma-1)^2}{\gamma^2}\left(1+4\csc^2\theta\right)\right] \quad (1)$$

where r_o is the classical electron radius, $\beta = \frac{v}{c}$, $\gamma = \frac{1}{\sqrt{1-(\frac{v}{c})^2}}$ and v is the velocity of the primary electron in the laboratory system. The first two terms in the bracket correspond to the classical, relativistic Rutherford scattering formula. The third term is the quantum mechanical exchange term. The inclusion of this term with the Rutherford formula gives the relativistic Mott formula. The fourth term represents retardation and spin interaction effects.

Equation (1) is more conveniently expressed in terms of the parameter A, defined as the ratio of kinetic energy given to the secondary or knock-on electron to the kinetic energy of the primary electron. It is not possible to distinguish between the primary and secondary electrons after collision. The knock-on electron is by definition the lower energy electron after collision. The maximum value of A is obviously 0.5. By a simple transformation, as shown by Møller,[1] Equation (1) becomes:

$$\sigma(A)dA = \frac{2\pi r_o^2}{\beta^2(\gamma-1)}\left[\frac{1}{A^2(A-1)^2} - \frac{3}{A(1-A)} + \frac{(\gamma-1)^2}{\gamma^2}\left(1+\frac{1}{A(1-A)}\right)\right]dA \quad (2)$$

The corresponding relativistic Rutherford cross-section is:

$$\sigma(A)dA = \frac{2\pi r_o^2}{\beta^2(\gamma-1)}\left[\frac{1}{A^2(A-1)^2} - \frac{2}{A(1-A)}\right]dA \quad (3)$$

The relativistic Mott cross-section is:

$$\sigma(A)dA = \frac{2\pi r_o^2}{\beta^2(\gamma-1)}\left[\frac{1}{A^2(A-1)^2} - \frac{3}{A(1-A)}\right]dA \qquad (4)$$

Several previous experiments[2,3,4,5,6], have been performed to verify Møller's theory. The primary energies used in these experiments have ranged from 0.05 to only 2.64 Mev. Except for the experiment of Williams and Terroux,[2] all results are in good agreement with Møller's theory. Champion[3] and Groetzinger, et al.,[6] attempted to find discrepancies between the Rutherford, Mott, and Møller formulae, Equations (3), (4), and (2). Champion found good agreement with the Møller equation but not with the other two equations. Groetzinger, et al., were not able to discriminate between any of the three. However, combining their data with Champion's, they ruled out the Rutherford equation; but within statistical error, they could not discriminate between the Mott and Møller equations.

For a 200 Mev electron, Equation (2) can be approximated by the following:

$$\sigma(A)dA = \frac{2\pi r_o^2}{\beta^2(\gamma-1)}\left[\frac{1}{A^2(1-A)^2} - \frac{2}{A(1-A)} + 1\right]dA \qquad (5)$$

Comparison of Equations (3), (4), and (5) shows that in the region of A less than 0.01, the three equations are indistinguishable. For A, in the region between 0.1 to 0.5, the percentage deviation of Rutherford's cross-section from Møller's cross-section varies from 1 percent to 11 percent, while that of Mott's to Møller's varies from 12 percent to 56 percent. The expected number of knock-ons in photographic emulsions in the entire region from A = 0.1 to A = 0.5 (Fig. 1) is

about one per 100 cm of track. Therefore one cannot hope to resolve these three equations without scanning enormous quantities of track. The scope of this experiment therefore has been limited to verifying Møller's formula for the absolute scattering cross-section of 200 Mev electrons, realizing that the Rutherford and Mott formulae are equivalent to Møller's in the region when most of the data can be obtained.

II. EXPERIMENTAL PROCEDURE

The existence of electron sensitive emulsions and a technique for eradicating accumulated background has made possible this study of high energy electron processes taking place within the nuclear emulsion. 200 micron Ilford G-5 plates were exposed to 200 Mev electrons obtained by magnetic separation in the pair spectrometer at the Berkeley synchrotron (Fig. 2). The plates were exposed so that electrons from the target entered the emulsion at a slight angle to the surface and perpendicular to the leading edge of the plate. In order to insure that only electrons which came directly from the converter were accepted, only tracks whose initial directions lay within 2-1/2° of the perpendicular were scanned. This criterion included over 90 percent of all the high energy electrons entering the plate. On plates exposed with no converter in the beam a number of acceptable tracks were found which was less than one percent of that found on plates exposed with the converter in place.

Because of the high background of low energy electrons found in all but freshly prepared electron sensitive emulsions, it was necessary to eradicate[7] the latent image of old tracks immediately before

exposure. The eradication was accomplished by storing the plates in a warm, water saturated atmosphere for several days before use. The temperature was controlled at about 97°F by immersing a watertight box containing the plates in a thermostatically controlled water bath. The relative humidity was maintained at 10 percent by placing a wet sponge in the box with the plates. Immediately after exposure the plates were developed by a temperature cycle process[8] in order to obtain a uniform and highly sensitive development.

In order to reconstruct stereoscopically the ranges and angles of the knock-on electrons, it was necessary to measure the shrinkage factor of the emulsion. This was accomplished by passing 380 Mev alpha particles through the undeveloped emulsion at an angle of 45° to the emulsion surface[9] and then measuring the ratio of the horizontal projection to the vertical projection of the alpha track after development. This ratio gave the shrinkage factor directly as 2.5 ± 0.1.

III. METHOD OF ANALYSIS OF PLATES

The plates were scanned under ~ 500x magnification and all events of interest were measured under ~ 2500x magnification. In these plates, the grain density of a 200 Mev electron is 41.9 ± 1.0 grains per 100 microns of track. The length of primary track scanned was measured by means of the microscope stage coordinates. In order to reduce the percentage of knock-on electrons missed, each track used was scanned independently by two observers and all questionable events were examined by a third observer before a decision was reached. No track was scanned for more than 0.8 cm or beyond a detectable

single scatter or a high energy electron-electron scatter. Tracks were not scanned and no event was recorded within 10 microns of either surface of the emulsion. The average track length in emulsion was 0.40 cm giving an average energy loss due to both ionization and radiation of 30 Mev. Thus the average primary electron has a mean energy of 185 Mev. The energies of some primary electrons were measured by their multiple scattering and found to be consistent with the above calculated values.

In order to insure that no events were being missed (especially those in which the knock-on electron track was nearly vertical in the emulsion), a plot was made of the distribution of the azimuthal angles of the knock-ons about the direction of the incident electron. This distribution was found not to be significantly different from a symmetric distribution.

To determine the energy of the knock-on electron, both its range and the angle between its direction and the direction of the incident electron were measured wherever possible. For very low energy knock-on electrons, the angle became difficult to measure because of nuclear scattering. Therefore, the range was the principal means of determining the energy up to about 0.6 Mev.[10] Above this energy, few knock-ons stayed in the emulsion, but the angle became a practical means of determining the energy. The angle, θ, is related to the knock-on kinetic energy, Q, and the incident electron kinetic energy, E, by $Q = \frac{E \cos^2\theta}{1 + E/2mc^2 \sin^2\theta}$ where mc^2 is the rest energy of the electron. For $\frac{E \sin^2\theta}{2\, mc^2} >> 1$, the knock-on energy as determined by the angle θ is nearly independent of the primary energy. For a 200 Mev primary

electron, this condition is met by all observed events, so we have disregarded the variation in primary energy caused by losses in the emulsion in calculating the knock-on energy. In the region where the angle and range methods of determining energy overlap, good agreement was found for the knock-on energy considering the large electron range straggle.

Knock-on electrons of energy less than 30 Kev were not included in this study because of their small range (< 7 microns) and because of the effect of electron binding.

IV. EXPERIMENTAL RESULTS

In Figure 3 is shown a histogram of the results compared with the cross-section as predicted by Møller. In the energy range from 30 kev to 0.1 Mev, there were 182 events found in 33.4 cm of electron track. The rest of the histogram represents 245 events found in 102.6 cm of electron track. The number of electrons per cubic centimeter of emulsion was calculated to be 1.07×10^{24} from the emulsion composition given by Ilford Ltd. The effect of water absorbed in the emulsion from the atmosphere on the electron density has been measured and is negligible in this experiment.

The fact that the experimental data provides such a good fit to Møller's curve indicates that with these conditions there is no measurable deviation from a Coulomb potential for 185 ± 15 Mev electron primaries.

A similar study is being carried out using primary positrons of 200 Mev. Preliminary results[11] indicate that positron-electron scattering is similar to the electron-electron scattering in the

range of knock-on energies studied here.

V. OTHER HIGH ENERGY ELECTRON PROCESSES

In the course of scanning for electron-electron collisions the following events were also noted. In 102.6 cm of electron track, two events were found in which the primary electron track divided into three tracks (Fig. 4) suggesting pair production in the field of the nucleus. By an approximate calculation, one would expect 1.1 pairs for this length of track.

An event was found on each of two separate plates (total path length of 102.6 cm) in which the electron track terminated in the center of the emulsion. Fig. 5 is a photograph of one of the disappearances. The lengths of track before disappearance were 0.7 and 1.5 mm. The experimental arrangement and selection criteria rule out the possibility that these tracks were positrons. It is improbable that the tracks traversed an insensitive volume of the emulsion since the single grain background remains uniform and other primary tracks have no apparent change in grain density in the region of the disappearance. A short distance back on one of the disappearing electrons there is a knock-on coming off in the forward direction confirming the assumed direction of this primary; this rules out the possibility of a Compton electron in the backward direction for this case. The fact the endings are near the center of the emulsion reduces the probability of not observing a large angle scatter out of the emulsion. The mechanism by which a high-energy electron could disappear in emulsion has not been satisfactorily explained. In scanning about 230 cm of electron track no events were found in which protons or mesons were

ejected from nuclei. Large angle nuclear scattering has been observed, but the study of such events has not been completed.

VI. ACKNOWLEDGMENTS

The emulsion method of studying electron-electron scattering was first found to be practical using fast electrons from a linear accelerator at Stanford University. Dr. G. E. Becker kindly assisted one of us (W.H.B.) in this experiment. Much of the microscope work of the preliminary experiments was done by Professor Lawrence Germain and Mrs. Edith Goodwin, and we are indebted to Mr. A. Oliver for his microphotographs and helpful advice on emulsion technique. The work was assisted greatly by the continued interest and encouragement given the film program by Professor E. O. Lawrence. We have enjoyed the invaluable cooperation of the synchrotron operating crew under the direction of Mr. George McFarland and Professor A. C. Helmholz.

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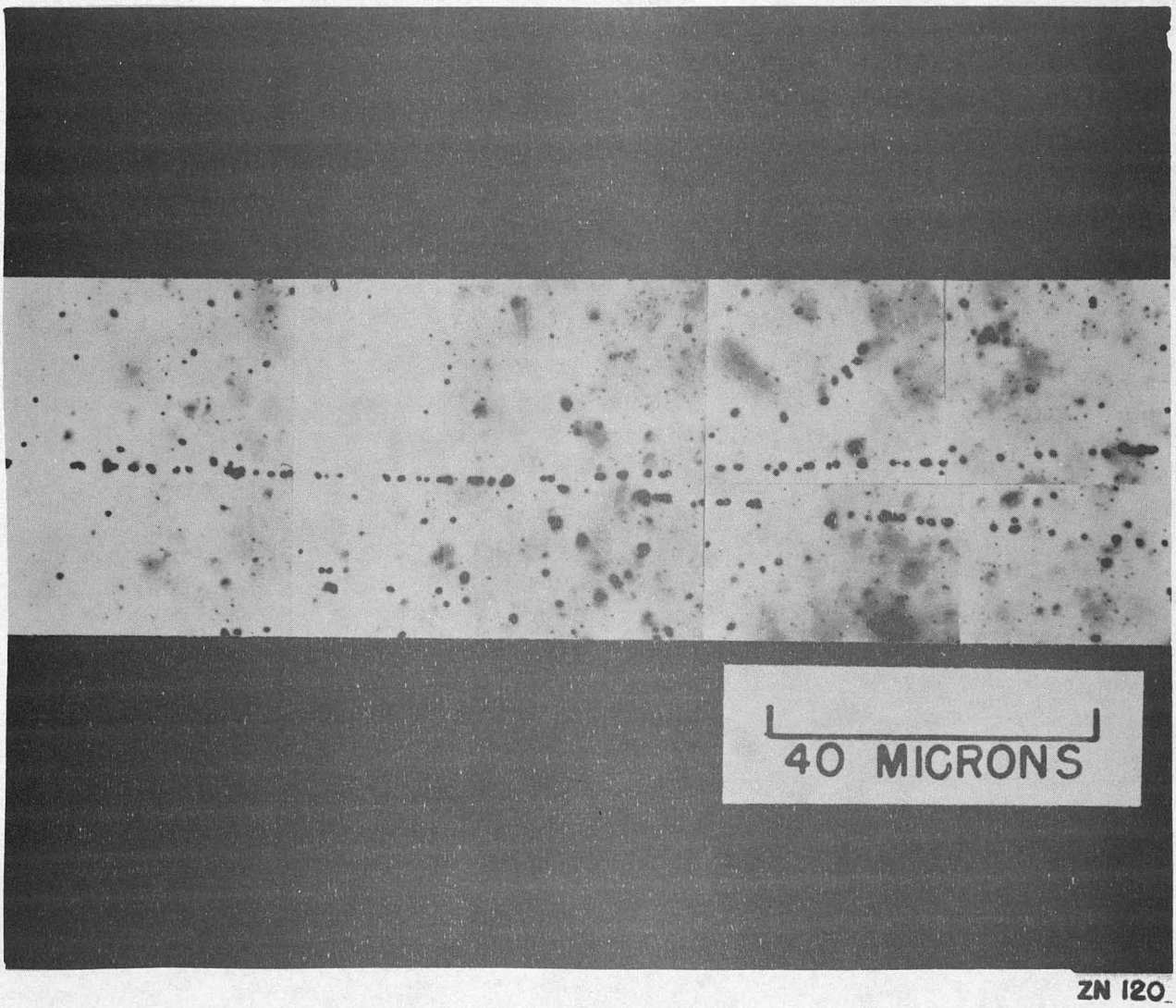

Fig. 1: Microphotograph mosaic of an electron-electron collision of large energy transfer initiated by an ~185 Mev primary electron. The angles of scatter are 9° and 2° corresponding to 32 Mev for the electron of lower energy.

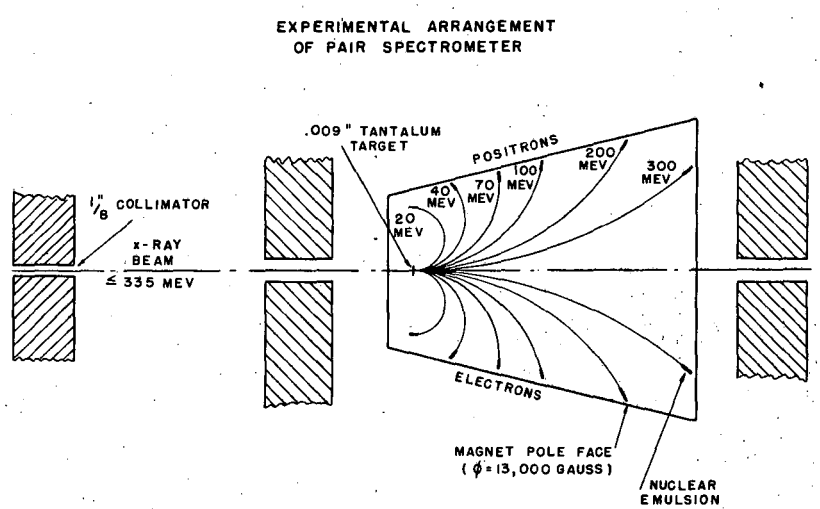

Fig. 2: Arrangement of the photographic emulsions in the magnetic field of the synchrotron pair spectrometer.

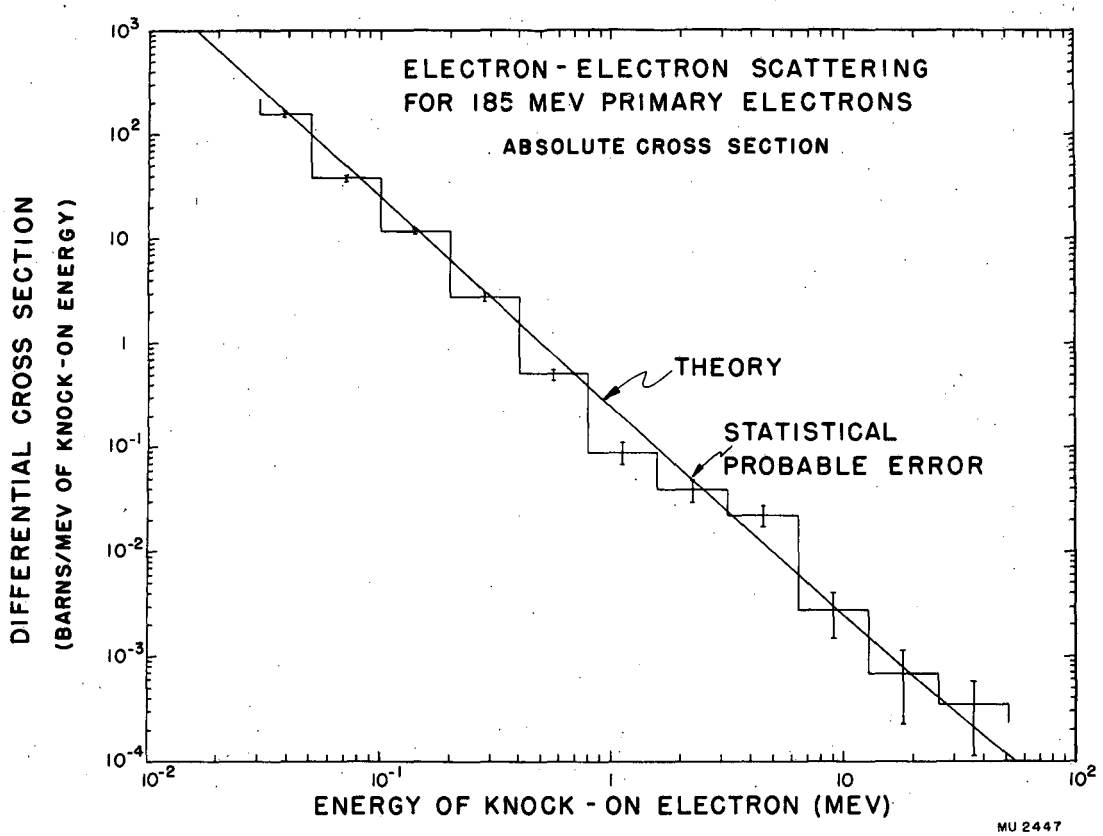

Fig. 3: Histogram of the experimental results shown with statistical probable errors. The effect of the energy resolution upon the magnitude of the absolute cross-section is negligible in comparison with the statistical errors.

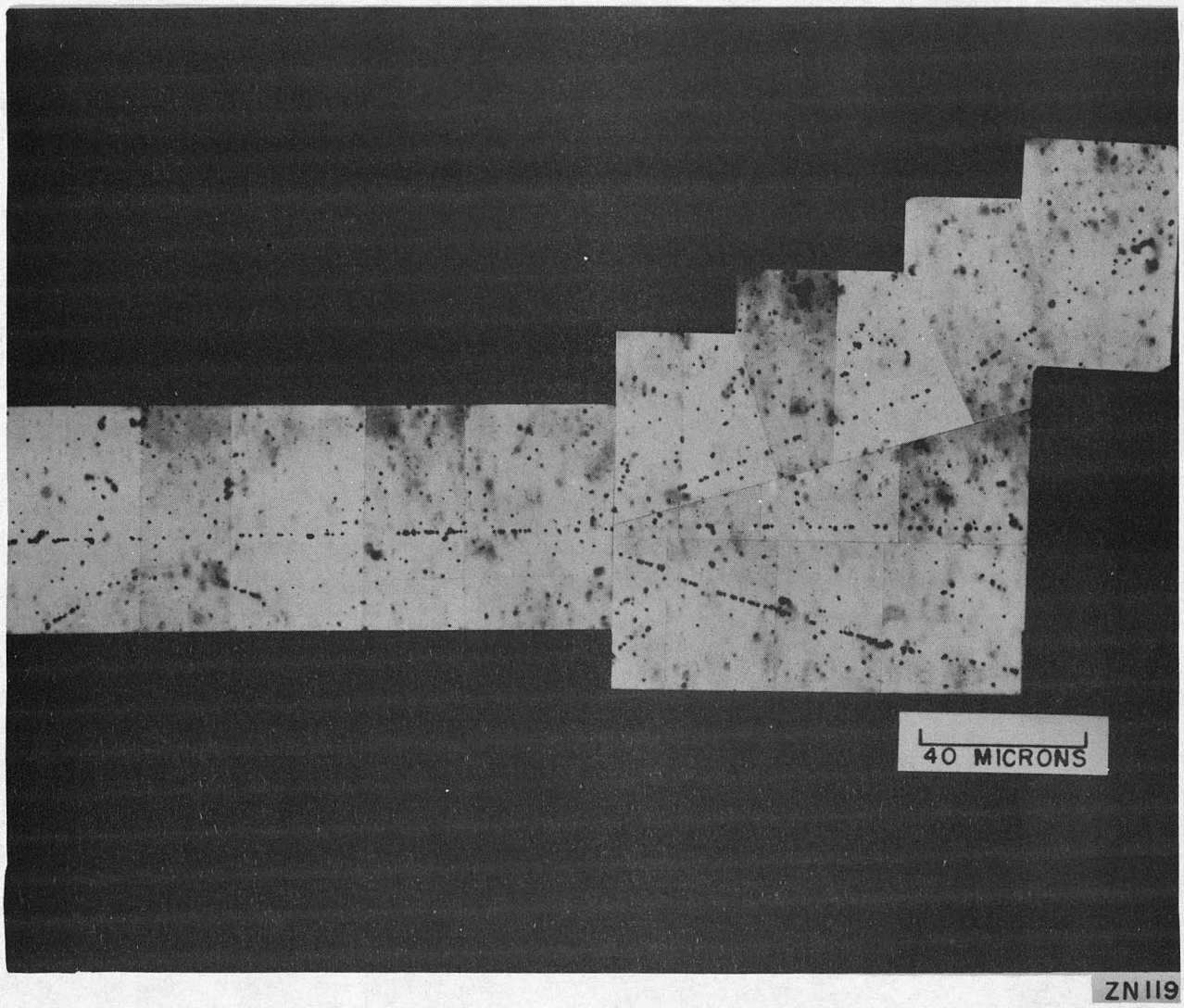

Fig. 4: Microphotograph mosaic of an electron-positron pair apparently produced in the field of a nucleus by an ~ 185 Mev electron.

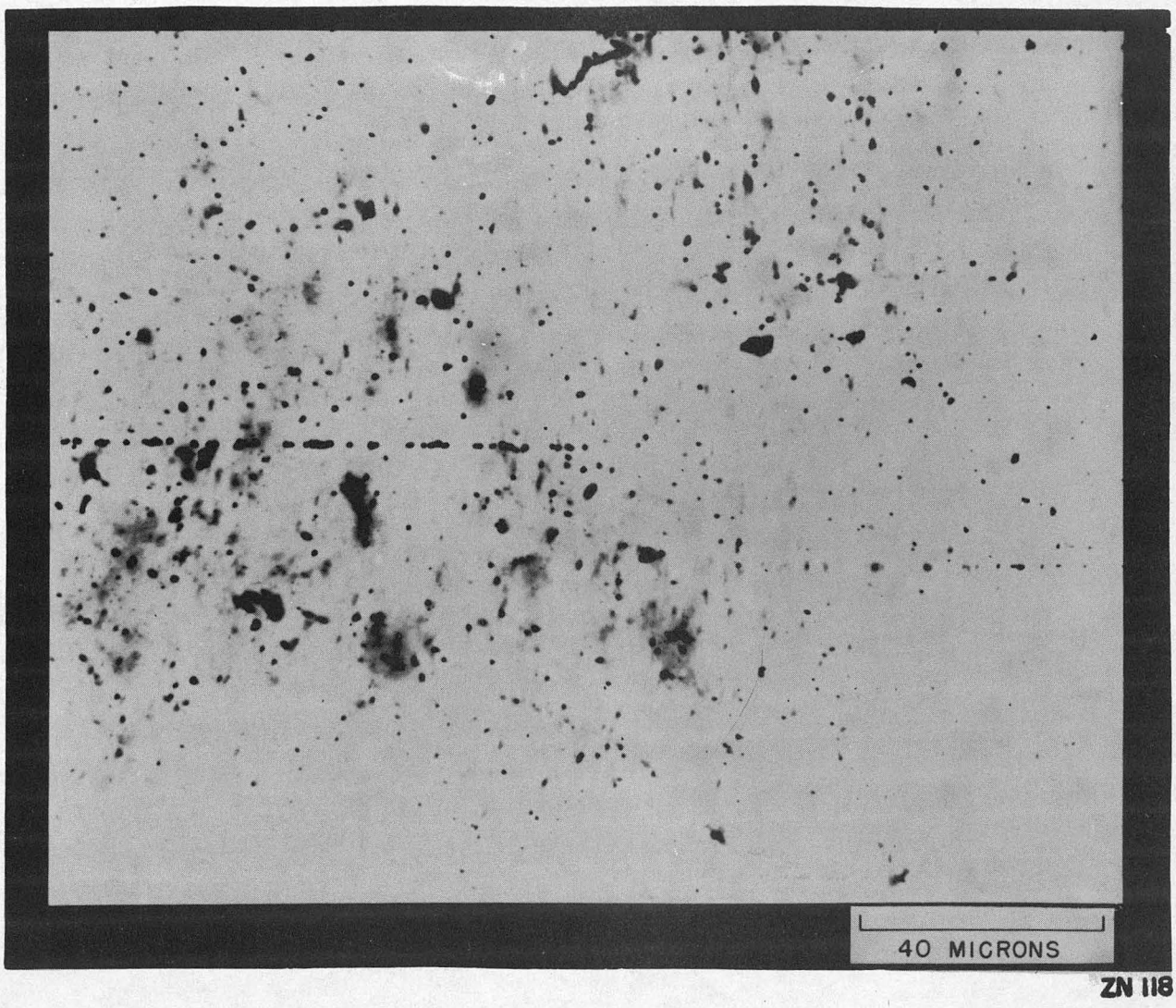

Fig. 5: Microphotograph of the disappearance of an ~185 Mev electron near the center of the emulsion.