Production of Electron Pairs by 550-Mev Electrons*†

F. J. LOEFFLER‡
Cornell University, Ithaca, New York
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The mean free path of high-energy electrons for direct electron pair production has been measured in Ilford G-5 nuclear emulsions. Electrons were produced by directing the 850-Mev bremsstrahlung beam from the Cornell synchrotron upon a Pb target and analyzing the negative members of the resultant electron pairs in a magnetic momentum analyzer. Electrons in the range 400 to 800 Mev were intercepted by glass-mounted emulsions 400 μ thick and, after processing, the resultant tracks were followed a distance of 1 cm in a search for electron pairs. Separation of bremsstrahlung-produced pairs from the real tridents was achieved by measuring the spatial distribution of the former about the primary tracks. This distribution, after being corrected for scanning efficiency and fitted with the theoretical distribution of Koshiba and Kaplon, indicated that for the conditions of this experiment 72% of the events classified initially as tridents were in reality bremsstrahlung pairs. The mean free path for the direct pair production process was found to be 143 ± 47 cm for a primary electron energy of 536 ± 94 Mev. The theoretical prediction of Racah for this energy is 148 cm and is in good agreement with this experiment.

I. INTRODUCTION

UNTIL recently most of the observations of the direct creation of electron pairs by the interaction of energetic electrons with the Coulomb fields of atomic nuclei have been made in photographic emulsions exposed to the cosmic rays at high altitudes.[1] These experiments dealt chiefly with electron primaries having energies between 0.5 Bev and 100 Bev since energetic electrons are relatively abundant in high altitude cosmic-ray showers, and since it is in this energy region that the effect of the trident process on electromagnetic cascades is likely to be appreciable and hence of particular interest. With the advent of electron accelerators in the 0.5 to 1.5 Bev range[2] it became both feasible and desirable to study the trident process utilizing artifically accelerated electrons. This type of experiment has two notable advantages over the cosmic ray experiments in that a well-collimated beam of high intensity and precisely known energy may be used.

The theoretical cross section for the trident process has been given by Bhabha[3] and Racah,[4] and it has been shown by Block *et al.*[5] that a re-evaluation and suitable modification of the original Bhabha result brings it into agreement with that of Racah. However, several of the experimental measurements,[6-8] notably at primary energies above 5 Bev, give results which are in rather serious disagreement with the theoretical predictions, and in fact indicate a trident cross section three to five times larger than the theoretical one. Since such a disagreement might have a bearing on the validity of both the electromagnetic cascade theory and the quantum electrodynamical theory at high energies, it was thought desirable to investigate the process further experimentally.

II. EXPERIMENT

A. Exposure of the Emulsions

The experimental arrangement shown in Fig. 1 was used to expose glass-mounted, 2 in.×3 in. Ilford G-5 nuclear emulsions, of 400 μ thickness, to electrons of known energies produced by the 850-Mev external bremsstrahlung beam of the Cornell synchrotron. The electrons were produced by directing the collimated and magnetically swept gamma-ray beam upon a 0.068-in. thick Pb target located in the gap of a uniform field analyzing magnet. The negative members of the electron pairs produced in the target were bent out of

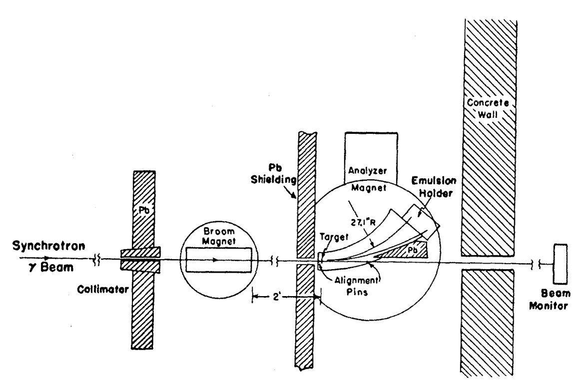

FIG. 1. Experimental arrangement for emulsion exposure shown in the median plane of the synchrotron.

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‡ Now at Princeton University, Princeton, New Jersey.

[1] These directly produced pair events in emulsions are frequently called tridents and have been observed by many workers. A rather extensive bibliography of the observations on tridents prior to 1954 has been given by Block, King, and Wada, Phys. Rev. **96**, 1627 (1954). More recent observations are discussed by J. E. Naugle and P. S. Freier, Phys. Rev. **104**, 804 (1956).
[2] R. R. Wilson, Phys. Rev. **100**, 962(T) (1957).
[3] H. J. Bhabha, Proc. Roy. Soc. (London) **A152**, 559 (1935).
[4] G. Racah, Nuovo cimento **14**, 93 (1937).
[5] Block, King, and Wada, reference 1.
[6] M. Koshiba and M. F. Kaplon, Phys. Rev. **100**, 327 (1955).
[7] E. Lohrmann, Nuovo cimento **4**, 820 (1956).
[8] Debenedetti, Garelli, Talone, Vigone, and Wataghin, Nuovo cimento **1**, 226 (1956).

the main gamma-ray beam and into the emulsions at the end of the magnet.

Since a thin converter was used, and since the products of electromagnetic interactions of this type and energy emerge very nearly in the forward direction in the laboratory frame of reference, it was possible to obtain an unambiguous momentum resolution of the electrons entering the emulsions. Either entrance angle or position at the emulsion edge determines an electron's energy but in practice the position measurement was used since it could be made with greater precision. The analyzing magnet was aligned with the primary bremsstrahlung beam to within 0.2 degree and the magnetic field in the useful region of the gap was measured and plotted carefully, so that the value of an electron's energy as it entered an emulsion was known to better than 0.5%.

Electrons in the energy range 400 Mev to 800 Mev were intercepted by the emulsions and several exposures were made in order that electron track densities of about 10^4 electrons/cm^2 could be obtained throughout the total energy range. This value, in terms of the number of tracks seen in a 100-μ field of view with the microscope, is about 4 electrons/100μ, and represents a practical track density for microscopic scanning.

B. Scanning Procedure

The emulsions were developed by a standard temperature-development technique, and an average grain density of about 24 grains/100 μ for minimum tracks was obtained. This value is somewhat lower than desirable but did not result in any serious scanning difficulties.

All routine scanning was done with Bausch and Lomb binocular microscopes using oil-immersion objective lenses and an over-all magnification of 675. Because of distortion at the emulsion edge, it was necessary to move in about 200 μ from the edge before scanning was started. Tracks crossing the scan line at this point were examined to see if they had the proper entrance angle to within one degree. This angle criterion served to eliminate background electrons and also indicated that background tracks numbered less than 1% of the total number of tracks. Those tracks meeting the angle criterion were recorded in such a way that they could be located again at any time and then were followed for a distance of not more than 1 cm into the emulsion. All events were recorded though electron pairs were of primary interest. From a preliminary scan point of view these were of two types: those whose origins seemed to be coincident with a primary electron track and therefore were possible tridents; and those which were clearly bremsstrahlung-produced pairs.

The possible tridents were recorded for future inspection and the bremsstrahlung pairs were analyzed to the extent of measuring their projected separation, x, and their vertical separation, z, from the nearest primary electron track. Knock-on electrons were seen quite frequently and while they were not of direct interest to the measurement of the trident cross section, they were considered important enough to record. In the pair creation process by bremsstrahlung or by electrons directly, it is possible for one member of the pair to receive a very small amount of the total pair energy. If this happens, the low-energy electron may be difficult to observe in an emulsion because of its short range and large scattering. For this reason it was considered important to scrutinize all apparent knock-on events under higher magnification to make sure there was not a third low-energy electron track also present.

All events involving electron pairs whose origins were within 1 μ of the primary electron tracks were examined very carefully. In most cases the relative spatial positions of the three tracks comprising an event were measured by using a scattering microscope. The event was then plotted on graph paper in order to measure the separation with some precision. In general, if the pair origin was greater than 0.5 μ in projected separation and 2 μ in vertical separation from the primary track, the event could be classified with confidence as a bremsstrahlung pair. There were several events whose geometrical orientation or low grain density prevented such a classification. The plots were not infallible since multiple scattering distorted the tracks in many events. In order to avoid classification of any real tridents as bremsstrahlung pairs, it was decided to consider all pairs with origins less than 1 μ projected distance from the primaries as possible tridents. All others were called bremsstrahlung pairs.

C. Scanning Efficiency

With good justification it was assumed that no tridents would be overlooked in the scanning procedure. This assumption is not valid, however, for the bremsstrahlung pairs. Roughly one-third of them lie at distances greater than 20 μ from the primary tracks and the scanner who is concentrating on the region immediately adjacent to the primary track being followed can easily miss some of these pairs. Since the true number of pairs associated with the total track length scanned was very important in making the correction for pseudotridents, it was necessary to find how many bremsstrahlung pairs were missed. This was done by making a very careful volume scan of two representative regions in the emulsions. The number of pairs found in this volume and the amount of track length equivalent to this volume were used to determine the true number of bremsstrahlung pairs per unit track length.[9] It was felt that the efficiency for finding

[9] The possibility of pair production in the emulsions by gamma-ray contamination entering the emulsions along with the primary electron flux was investigated. Since the number of bremsstrahlung pairs resulting from the primary electrons will increase quadratically with distance into the emulsion, this process can be separated from the pair production process by external gamma-ray

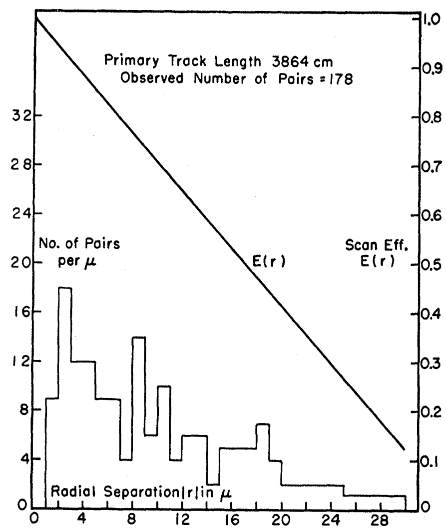

FIG. 2. Observed spatial distribution, $M(r)$, of bremsstrahlung pair origins about the primary electron tracks, where r is the separation of the pair origin from the nearest primary track. The linear scanning efficiency function, $E(r)$, is also shown. The observed distribution contains 178 pairs and when it is corrected for scanning efficiency the total number of pairs becomes 391. Pairs found at distances greater than 30 microns from a primary track were not used.

pairs in the volume scan was 100%. In order to check this surmise, a calculation of the expected number of pairs was made using the Bethe-Heitler formulas[10] for the radiation processes involved. The number of pairs observed in the efficiency scan was 27. A large number of similar observations would given rise to a distribution with a standard deviation of 5.2 pairs. The theoretical prediction for the same track length is 31.5 pairs. The agreement between the observed and the calculated values is considered excellent.

These considerations led to the conclusion that the over-all efficiency for finding bremsstrahlung pairs in the routine scanning was 46%. The observed spatial distribution of pairs had to be corrected for this inefficiency. The correction was made as follows.

D. Spatial Distribution of Bremsstrahlung Pairs

There are two reasonable ways to plot the spatial distribution of pairs. The first way is to plot the number of pairs as a function of the actual distance, r, of the pair origins from the primary tracks. This is called the $M(r)$ distribution. It is shown in Fig. 2. The total number of pairs observed in this plot corresponding to a track length of 3864 cm was 178. The efficiency measurement indicated that there should be 391 ± 75 pairs. In order to correct the observed $M(r)$ distribution, a linear efficiency function $E(r)$, was assumed as shown in Fig. 2. $E(r)$ is defined in such a way that when the observed distribution $M(r)$, is divided by $E(r)$ a new distribution $M'(r)$, which contains 391 pairs is obtained. The precise shape of the efficiency function $E(r)$, would be difficult to determine and since the pseudotrident correction is not sensitive to this shape, it was felt that the linear choice was a reasonable *a priori* selection. Certainly the gross features are correct. At $r=0$ the efficiency goes to 100%, and as r increases the efficiency must fall off. The function shown in Fig. 2 has been adjusted so that the integral of the resulting $M'(r)$ distribution agrees with the results of the efficiency scan.

The second way to present the spatial pair distribution is to plot the number of pairs as a function of the separation projected onto the scanning plane. This projected separation is called x and the observed projected distribution, $N(x)$. This distribution is more useful for the pseudotrident correction than the $M(r)$ distribution for the following reason. If one considers the geometry of the situation it is evident that for any bremsstrahlung pair event the projected separation x, is at most equal to the true separation r, and generally smaller. In fact, for a given r the possible values for x are $0\leqslant x\leqslant r$. From this consideration it is apparent that the $N(x)$ distribution will have a larger percentage of the bremsstrahlung pair events in the region of small separations than the $M(r)$ distribution. Hence the $N(x)$ distribution is statistically better determined in the region where information for the pseudotrident correction is needed ($x<1\mu$) than is the $M(r)$ distribution. A linear efficiency function is no longer valid for this distribution. However one can easily transform the radial efficiency function $E(r)$ into the projected efficiency function once the corrected radial distribution $M'(r)$ has been found. This has been done and the observed distribution, $N(x)$, has been corrected to give the $N'(x)$, shown in Fig. 3.

The $x<1\mu$ column is missing in the $N'(x)$ histogram and it is just the height of this column which determines the pseudotrident correction. The height can be determined by extrapolation of the remainder of the distribution into this column. This was done by fitting the theoretical function of Koshiba and Kaplon[11] to the histogram. The derivation of this function is based on small-angle scattering theory, an assumed distribution for the angle of emission of photons radiated by electrons in emulsions, and the normal exponential attenuation function for high-energy photons in matter with the conversion length for pair production taken to be 9/7 of a radiation length. Under the conditions of this experiment the theoretical function predicts that

contamination. The number of pairs from the latter will increase linearly with distance into the emulsion. Measurements indicated a purely quadratic increase of the number of pairs with distance and thus ruled out the possibility of appreciable gamma contamination.

[10] H. A. Bethe and W. Heitler, Proc. Roy. Soc. (London) **A146**, 83 (1934). A correction was made to these formulas for the inaccuracy of the Born approximation and for the effect of atomic electrons.

[11] M. Koshiba and M. F. Kaplon, Phys. Rev. **97**, 193 (1955).

of all the bremsstrahlung pairs seen, about 40% of them will lie within 2 microns projected distance of their primaries. The fit of the function to the histogram is shown in Fig. 3.

In matching the theoretical curve three individual fits were considered. First, the area under the curve was made equal to the 391 events comprising the total corrected number of bremsstrahlung pairs present. Second, the curve was normalized to fit the $N'(x)$ distribution at the $1<x<2$-μ column. The number of observed events in this column was 34. Finally, the shape of the theoretical distribution can be changed by altering the values of the scattering and opening angle parameters used. It was found, however, that if the generally accepted values[6,11] for these parameters were used, the measured and the theoretical distributions agreed well within the statistical uncertainty of the points in the measured distribution. The extrapolation of the theoretical function indicated that there should be 66.2 events in the first column. On the basis of the fitting criteria mentioned above, it was decided that this number was determined to within 7%.

E. Evaluation of the Mean Free Path

The various data utilized in calculating the mean free path for trident production are given in Table I. The uncertainties associated with the various values represent total experimental uncertainty and are largely statistical in nature.

(*1*) *Track Length of Primaries*

The two primary measurements made in this experiment were the number of directly produced pairs and the primary electron track length associated with these pairs. These two quantities together determine the mean free path for the process. Since the primary electrons were energetic, the mean angle of scattering after traversing 1 cm of emulsion was small and a good approximation to the length of a given track could be made by assuming that it was straight and merely using the coordinates of the end points to determine the length. This was done in all cases and an estimation of the error involved in making this assumption was made. The total primary track length followed was $H=4957\pm20$ cm.

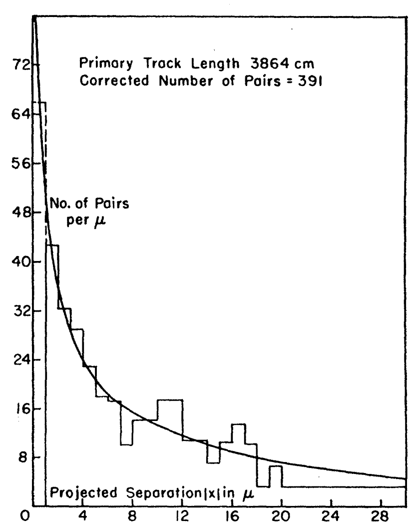

FIG. 3. Projected pair distribution, $N'(x)$, corrected for scanning efficiency, where x is the separation of the pair origin and the nearest primary track projected onto the plane of the emulsion. The smooth curve is the theoretical distribution of Koshiba and Kaplon fitted to the corrected histogram. A primary electron energy of 500 Mev was used in evaluating the theoretical distribution.

TABLE I. Correction for pseudotridents and evaluation of mean free path for trident production by electrons in the energy interval 400–800 Mev.

Total track length followed	$H=4957\pm20$ cm
Number of pairs observed with projected separation, $x<1\mu$	$N_p=97$
Efficiency for finding such pairs	Eff. $=0.805$
Corrected number of pairs with $x<1\mu$	$N_p'=120.5$
Number of pseudotridents in total track length	$N_{pt}=85.8$
Number of tridents in total track length	$N_t=120.5-85.8=34.7$
Mean free path for trident production	$\lambda=H/N=143\pm47$ cm
Mean primary electron energy	$\bar{E}=536\pm94$ Mev

(*2*) *Pseudotrident Correction*

The $N(x)$ distribution of bremsstrahlung pairs has been discussed in Sec. D. There it was pointed out that in a track length of 3864 cm there were found 178 pairs whose origins lay more than 1 micron from the nearest primary. The scanning efficiency measurement, as well as the Bethe-Heitler pair calculation, indicated that the efficiency for finding pairs was 46%. Hence for 3846 cm of track length there were really 391 pairs whose origins lay more than one micron from their primaries. The extrapolation of the theoretical curve of Koshiba and Kaplon indicates that in the first column ($0<x<1\ \mu$) there are 66.2 pairs. The uncertainty in this number is 7%. Thus the number of pseudotridents among the events with $x<1\ \mu$ is 66.2 ± 4.6 for a track length of 3864 cm. For the total track length scanned then there will be 85.8 ± 5.9 pseudotridents.

(*3*) *Mean Energy of the Primaries*

In order to define the appropriate mean energy of the electrons in this measurement of the trident process, it is necessary to know the primary electron energy spectrum in the emulsions. This spectrum was both calculated and measured. The mean energy of the primary electrons as they entered the emulsion edge was found to be 636 Mev. Since the electrons lose energy while traveling through the emulsion material and since the tridents are made inside the emulsion, a correction must be made for the energy loss. Upon

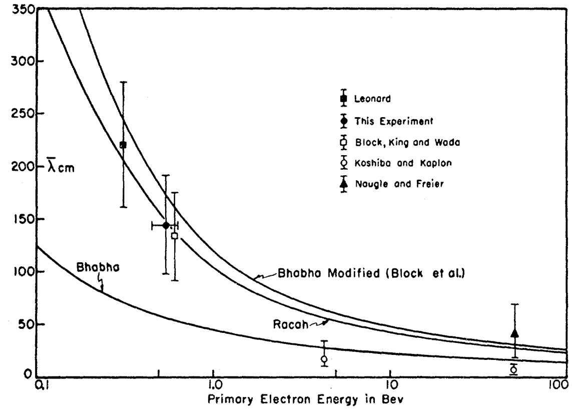

FIG. 4. Comparison of theoretical and observed values for the mean free path, λ, for trident production.

taking both ionization and radiation loss into account and using the appropriate average track length, the corrected mean energy is 536 Mev. The considerable amount of straggling associated with the radiation loss requires that an energy interval of ± 94 Mev about the mean value be taken in order to include 50% of the tracks which make tridents. The other 50% lie outside this interval. These considerations give significance to the following number: $\bar{E}=536\pm 94$ Mev.

(4) *Mean Free Path*

Utilizing the values for the total track length and the corrected number of tridents as given in Table I, we arrive at a value for the mean free path for trident production by 536-Mev electrons of $\lambda=143\pm 47$ cm. This can also be expressed as a cross section. If the number of atoms per cm^3 for G-5 emulsions is taken to be 8.03×10^{22} the cross section is found to be $(8.62\pm 2.8)\times 10^{-26}$ cm^2. This result is shown in Fig. 4 and compared with other experimental observations[5,6,12,13] and with the theoretical mean free paths.

III. CONCLUSIONS

Since the value of the mean free path measured in this way depends strongly on the pseudotrident correction, it is very important that the total number of bremsstrahlung pairs be determined accurately. The low value of efficiency for finding these pairs, as measured in this experiment, indicates that care must be taken in determining this efficiency.

At primary electron energies below 1 Bev the various experimental results including this measurement are in good agreement with both the Racah and the modified Bhabha predictions. The uncertainties are unfortunately too large to make a convincing selection between the two. At energies above 10 Bev there is still some disagreement between observation and theory although several recent experiments[12,14,15] tend to agree rather well with the theory. It has been suggested by Naugle and Freier[12] and others[14,15] that, for electron energies above 1 Bev, previous discrepancies between experiment and theory might be due partially to a tendency to underestimate the primary energies.

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[12] J. E. Naugle and P. S. Freier, Phys. Rev. **104**, 804 (1956).
[13] Stanley L. Leonard, Bull. Am. Phys. Soc. Ser. II, **1**, 167 (1956).
[14] Debenedetti, Garelli, Tallone, and Vigone, Nuovo cimento **4**, 1151 (1956).
[15] Brisbout, Dahanayake, Engler, and Perkins, Nuovo cimento **4**, 1496 (1956).