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Direct Production of Electron Pairs in Nuclear Emulsion by 13.75-BeV Electrons*

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A measurement has been made of the total cross section for direct production of electron pairs by 13.75-BeV electrons in nuclear emulsion. The result, $(4.03\pm0.36)\times10^{-25}$ cm^2, is in good agreement with quantum electrodynamics.

Many experiments[1] on the direct production of electron pairs in the field of nucleus, $e^-+(A)\rightarrow e^-+e^++e^-+(A)$, have been carried out in nuclear emulsion. These experiments have used electrons and positrons produced in cosmic-ray showers as the parent particle. The observed large cross sections have led to uncertainty as to whether the process may not have a cross section as much as a factor of five times the value predicted by quantum electrodynamics (QED). Previous works have been hampered in their efforts to resolve this difficulty by the uncertainty in the energy of the primary cosmic-ray electron, unsatisfactory approximation methods for correcting for pseudotridents (false direct pairs) produced by bremsstrahlung radiation, and poor statistics.

Cloud-chamber[2] and counter[3] observations of the trident process at low energies, below 15 MeV, have been in general agreement with theory. Recently, Grossetête[4] *et al.* have measured the differential cross section using counters and a primary electron beam of 500 MeV from the Stanford accelerator. Their results are in good agreement with the calculations made for the trident process, using the Feynman-Dyson method, by Murota, Ueda, and Tanaka.[5]

Expressions for the total cross section for tridents have been discussed extensively in several articles.[6] At very high primary electron energy, the expression for the cross section obtained by Racah, and Murota, Ueda, and Tanaka, and the Bhabha equation, modified by Block *et al.*,[7] are in basic agreement. The expression for the total cross section, as developed by Block and King,[8] is used in this paper when comparing theoretical and experimental results.

Twenty-four Ilford G5 emulsion plates of size $(2.5\times13\text{ cm}^2)\times(200\ \mu)$ were exposed to a 13.75-BeV electron beam at SLAC. The beam contained about 2.5% pion contamination. In an along-the-track scan of the entering primary particles, each beam track was followed a distance of 1 cm into the emulsion. A total scanned track length of 4951 cm yielded 984 apparent tridents. The general characteristics of the apparent trident events were a sudden increase (three times) in grain density of the primary electron, and the subsequent appearance of three minimum-ionizing tracks proceeding nearly parallel to the direction of the primary electron. Electron pairs materializing at transverse distances greater than 1 μ from the primary electron were not considered to satisfy the criteria of apparent trident. The grid coordinates of each entering primary electron and each apparent trident were recorded, so that no events would be measured twice. The efficiency of locating trident events was checked by a complete and independent rescan of each track recorded in the first scan. The scanning efficiencies were found to be between 96% and 97% for each plate.

Apparent tridents include contributions from both real tridents and pseudotridents, which are pairs created along the primary electron track by real photons from a previous bremsstrahlung scattering of the primary electron. Because of the small scattering angle of the bremsstrahlung process, the photon-produced pair frequently falls within 1 μ of the primary electron's track, resulting in an event which is observationally indistinguishable from a real (virtual-photon-produced) trident. The separation of the above two processes is the most serious problem of the experiment. It is approached here from two distinct points of view. In one case an effort is made to correct for the pseudotridents. In the other, no correction is made, and the cross section for real tridents is obtained by making use of the fact that the integral number of pseudotridents increases quadratically with distance, while the number of real tridents increases linearly. The number of real tridents can be obtained by extrapolating the differential distribution to zero distance.

(a) Correction method. It should be possible to determine the real trident cross section by calculating the expected number of pseudotridents and making a subtraction. Such a correction method, developed by Koshiba and Kaplon,[9] has been used in most previous emulsion studies. This method has led to real trident cross sections two to five times greater than is expected on the basis of QED. Weill *et al.*[10] have eliminated some of the difficulties inherent in the Koshiba and Kaplon method, by making a direct calculation of the number of pseudotridents per radiation length. Following this method, we have calculated that for the conditions of our experiment, there are 0.32 pseudotridents/radiation length (3.0 cm) at a primary electron energy of 13.75 BeV. This correction yields an estimate of 431 ± 22 real tridents in a total distance of 1511 radiation lengths. The corresponding real trident cross section is $(12.07 \pm 0.55) \times 10^{-25}$ cm^2.

(b) Extrapolation method. Lohrmann[11] has shown that if $y \ll \langle y \rangle$, the differential distance y between the entrance of the electron into the emulsion and the *first* pseudotrident is $P'(y)dy = (ys/X_c)dy$, where s is the number of photons with energy $>2mc^2$ radiated per unit path length by a high-energy electron, X_c is the photon conversion length (3.84 cm), and $\langle y \rangle$ is the average distance at which the first pseudotrident materializes. The differential contribution of pairs originating from direct production is given by $P''(y)dy = dy/L$, where L is the mean free path for direct pair production.

The total distribution in a unit distance for both processes is

$$[P'(y) + P''(y)]dy = [ys/X_c + 1/L]dy.$$

L can be determined by plotting the differential distribution of y and finding its value at $y = 0$. A straight-line fit to the differential distribution is shown in Fig. 1. The value of L obtained is 10.5 ± 0.9 radiation lengths, or a cross section $\sigma = (4.03 \pm 0.36) \times 10^{-25}$cm^2.

Conclusion: The cross section obtained for 13.75-BeV trident production, based on calculating a correction for pseudotridents, is some three times larger than the trident cross section predicted by theory; $\sigma_{\text{theory}} = 4.11 \times 10^{-25}$cm^2. The correction

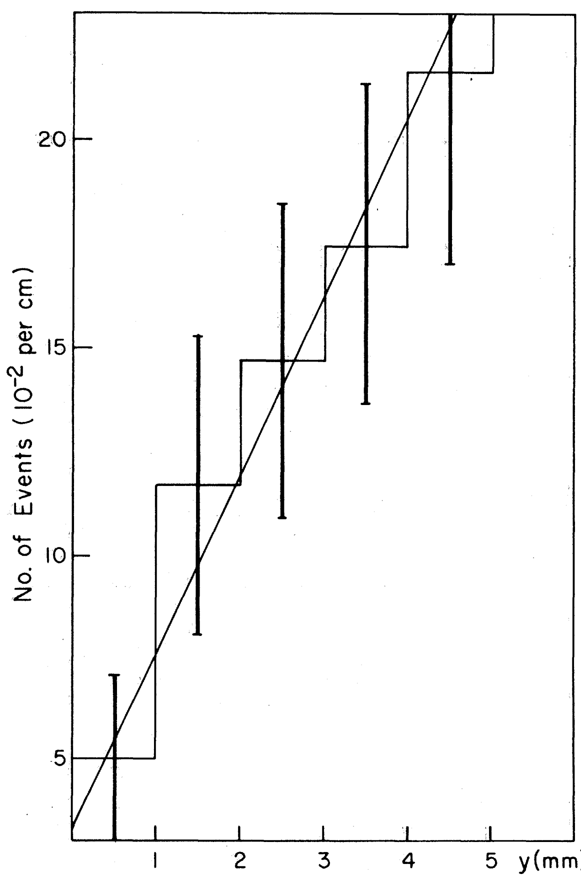

FIG. 1. Differential distribution of apparent tridents in distance.

TABLE I. Comparison of results obtained using the method of numerical integration with the results obtained using the direct method.

	Method of numerical integration	Direct method
Number of real tridents	431 ± 21	145 ± 12
Mean free path of real tridents (radiation lengths)	3.5 ± 0.16	10.5 ± 0.90
Number of pseudotridents	492 ± 22	788 ± 28
Mean free path of pseudotridents (radiation lengths)	3.07 ± 0.51	1.94 ± 0.38

method for pseudotridents also results in a mean free path for pseudotridents that is almost twice that expected for bremsstrahlung pairs produced at these energies[9] (1.6 radiation lengths). A comparison of the results obtained by both methods is shown in Table I.

The trident cross section resulting from an extrapolation of the differential distribution is in excellent agreement with theory. The extrapolation method depends essentially on observing a large number of events. This experiment has recorded 40 times more apparent tridents events than reported in previous emulsion experiments, and the number of real tridents, as determined by the extrapolation method, is at least 15 times greater. The overestimation of cross sections inherent in experiments using correction methods is probably due to the criteria chosen for observing pseudotridents, to the sensitivity to the multiple-scattering constant selected, and possibly to the Landau[12] effect at very high energies.

From the agreement between our results and theory, we conclude that for energies up to 13.75 BeV there is no contradiction between the prediction of QED and experiment, for low-momentum-transfer trident production.

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