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Direct electron-pair production by 200-GeV pions

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By following 200-GeV pion-beam tracks in nuclear emulsions, we have observed 57 directly produced electron pairs. The production cross section of electron pairs up to energy $E=\gamma mc^2 \simeq 732$ MeV is found to be $\sigma_{\text{pair}} = 85 \pm 17$ mb in emulsion which in spite of its mixed-Z target atoms, agrees well with bubble-chamber results and is also in good agreement with quantum-electrodynamic calculations. For these pairs we have also analyzed (i) the total energy distribution, (ii) the energy partition between the two members, (iii) the angular divergence, (iv) the invariant mass of the electron pairs, and (v) the transverse-momentum distribution of each member of the pair. The experimental results are in general good agreement with the present theories.

I. INTRODUCTION

The process of direct electron-pair production by fast charged particles scattered in an electromagnetic field, briefly called trident production, has been of great interest from the point of view of checking quantum electrodynamics at large momentum transfers. The trident production process (e, μ, π, or p)$Z \to e^+e^-Z$(e, μ, π, or p) has been discussed extensively in the literature.[3-5] Some of the experimental data between 1 and 100 GeV have shown conflicting results[3-5] with the theories and one of these experiments was done with nuclear emulsion. Beyond 100 GeV there did not exist any reliable experimental data before 1973. The reason was that in most of these experiments, the primary beams used were either high-energy electrons or photons from cosmic rays where the beam energy is neither monoenergetic nor accurately determined. The accuracy of the energy of the primary beams is very essential in making any analysis of the observed data. Moreover, for electron primaries bremsstrahlung is the dominant process, and bremsstrahlung followed by conversion of the photon into electron pairs (pseudotrident) cannot be distinguished from a real trident (direct pair-production process), i.e.,

$$e^-Z \to e^-Z\gamma \quad \text{and} \quad \gamma Z_1 - e^+e^-Z_1 .$$

The proportion of pseudotrident increases with increasing primary energy. The cross section for a muon bremsstrahlung with the same Lorentz factor as an electron bremsstrahlung in the field of the nucleus is reduced roughly by a factor of $(m_e/m_\mu)^2$ for large E/mc^2. Thus, a considerable advantage is obtained by the use of muon primaries as compared to an electron beam.

Because of the above facts, we made a first attempt to look over the trident problem as soon as the proton and the muon monoenergetic beams were available at the Fermi National Accelerator Laboratory. In our experiments,[6-8] we used nuclear emulsion and our results were not in agreement with the theory. Our emulsion experiments were followed by bubble-chamber experiments[9-11] in which no discrepancy was found. We may remind the reader here that emulsion experiments are, in general, much more difficult, and in them it is harder to accumulate statistics. This will be explained in the following sections. In order to check the discrepancy between the emulsion and bubble-chamber experiments, we decided to perform another independent experiment at higher energy. As most of the theoretical predictions for the electron-pair-production cross sections depend on the ratio γ ($=E/m$) and not on E and m separately or on the type of the incoming particle, we used a 200-GeV pion beam with $\gamma \approx 1430$ in our present experiment.

II. EXPERIMENTAL PROCEDURE

A small stack of G-5 emulsion of 600-μ thickness was exposed to a monoenergetic beam of 200-GeV pions parallel to the emulsion plane. In order to avoid any pair production from a secondary beam, the scanning was done by an along-the-track technique where the incident pions were picked up at a distance of 0.5 cm from the edge of the plate and at about half-way up from the bottom of the pellicle. These tracks were followed through the emulsion by using a constant oscillation of the z-axis control to facilitate observation of events with dip angles greater than 0°. In our previous two experiments,[6,7] the average scanning speed was about 25 cm/h and in the third experiment,[8] which showed better results, we kept the average scanning speed of about 15 cm/h. Our scanners obviously missed some low-energy events due to fast scanning speed in the above experiments and also due to a large flux of primary particles in the pellicles. For the along-the-track scanning method, flux should be less than 10^4 particles/cm^2. In order to check the discrepancy between the emulsion and bubble-chamber work, we decided to follow the primary tracks very carefully, with an average scanning speed of ~8–10 cm/h so that we would not miss any low-energy event. Whenever an interaction is observed, the parent track is rechecked for its parallelism with the other beam tracks followed in the same field of view. We scanned a total of 90 m of track length. All the apparent knock-on electrons which did not satisfy the energy-angle relationship for a two-body process were examined very carefully for a second low-energy track for a possible electron trident. After selecting the three-pronged events (tridents) the vertex of each trident was carefully checked to eliminate spurious events. These coincidence pairs, called pseudotrident events, are produced either by (a) bremsstrahlung conversion, (b) by conversion of γ rays from the decay of a neutral particle like $\pi^0 \to \gamma + e^+ + e^-$ (Dalitz decay) which occurs only $\frac{1}{80}$ of the time, (c) trident from strong incoherent (p-n) interactions, or (d) coherent production of pion pairs through Coulomb or diffraction dissociation.[12] The characteristics of pions and electrons are quite distinctive in nuclear emulsion. One can see this when following a track for the measurements of the ionization density and the energy by multiple scattering. A relativistic electron, unlike more massive particles, loses a considerably greater fraction of the energy through bremsstrahlung than is to be expected from ionization alone.

For the direct production of electron pairs, we used the criteria that (i) the two outgoing secondary tracks should appear on opposite sides of the primary and be nearly coplanar, (ii) the middle track which is the pion should be practically undeviated from its original directions (without any recoil of a nucleus), (iii) the ionization density for electron tracks should be less than or equal to the plateau value, (iv) for the separation of fast electrons from low-energy pions, $p\beta c$ should be < 0.21 MeV, and (v) at least one track, if not both, must show sufficient multiple scattering which is characteristic of an electron. This is the case where the second track cannot be followed due to the local distortion or the edge of the plate, etc. Events produced through the coherent process were separated, as mentioned earlier.[12] The selected electron-pair events were further checked for energy-momentum balance. Because of unsuitable physical conditions of the emulsion in the vicinity of the electron pairs, the energy determination of either one or both of the tracks from three of the electron pairs was not dependable and hence these events were used only in the measurements of the cross section and were excluded from the discussion in the rest of this paper.

III. EXPERIMENTAL RESULTS

A. Mean free path and total cross section

By scanning with the along-the-track method, we followed a total of 90 m of track length and found 57 direct electron pairs with $\lambda_{\text{pair}} = 1.57 \pm 0.21$ m. The scanning efficiency at the slow speed was about 90%, thus giving an overall pair-production cross section for 200-GeV pion in nuclear emulsion as $\sigma_{\text{pair}} = 80.2 \pm 10.7$ mb. For electron pairs of energy $< \gamma mc^2$, $\sigma_{\text{pair}} = 62 \pm 9$ mb. In the above measurements, we have measured the mean free path in a conventional way, i.e., $\bar{\lambda}$ is equal to the total path length divided by the number of events. However, if the total path length is finite, the true mean free path is in general somewhat larger than $\bar{\lambda}$ and approaches $\bar{\lambda}$ as the number of events increases.[3] This effect is due to events occurring near the end of the total path where the available remaining path length may be smaller than the mean free path. The magnitude of this effect is evaluated by employing the statistical maximum-likelihood method. Thus, from Eq. (15) of Ref. 3, mean free path

$$\lambda_t = \bar{\lambda}\left[1 + M^{-1} \sum_{i=1}^{M} i\,(e^i - 1)^{-1}\right], \qquad (2)$$

where M is the number of events observed. The statistical uncertainty is given by Eq. (14) of Ref. 3. Thus, the mean-free-path length for pairs of energy $< mc^2\gamma$ is $\lambda_t = 2.1 \pm 0.33$ m, which corresponds to a cross section of $\sigma_{\text{pair}} = 60.27 \pm 9.30$ mb where the number of atoms per cm^3 is taken to be 7.898×10^{22} for G-5 emulsion, and the uncertainties indicated are probable errors. The theoretically calculated total cross section from Bhabha's modified Eq. (5) of Ref. 3 for emulsion with effective $Z = 22.1$ is equal to $\sigma_{\text{cal}} \simeq 93.0$ mb for $2mc^2 < E_0 < \gamma mc^2$, where E_0 is the total energy of electron pair. Thus in this experiment, our results fairly agree with the theory within the statistical errors. After this experiment, we looked over our previous experimental results, where our scanning speed was more than twice as fast as in this experiment. With the slow scanning speed, we found almost double the number of

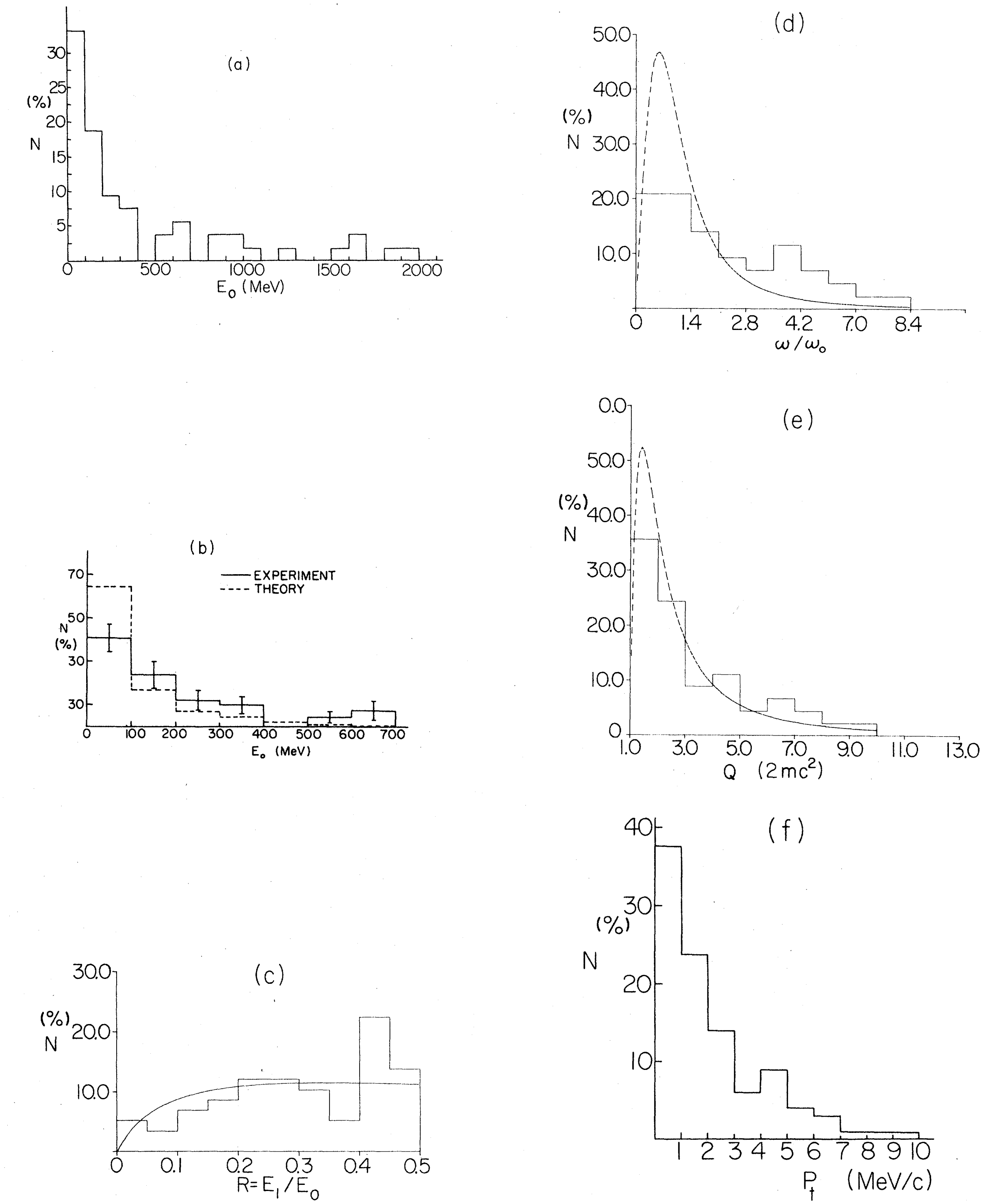

FIG. 1. (a) Energy distribution of the electron pairs. (b) Energy distribution of the electron pairs with $E_0 \leq 700$ MeV. Theoretical curve is given by Eq. (3) of Ref. 3. All theoretical curves in the figures are normalized to the experimental data. (c) Experimental and theoretical distributions [Eq. (10) of Ref. 3] of R, where $R = E_1/E_0$ and $E_1 < E_2$. (d) Angular divergence ω for electron pairs in terms of the Borsellino angle ω_0. The theoretical curve is given by Eq. (14), Ref. 13. (e) Invariant-mass (Q) distribution for all events, in units of $2mc^2$. The theoretical curve is given by Eq. (7), Ref. 3. (f) p_t distribution for all electron pairs.

events in the previous experimental results, which brings them closer to the theoretical predictions.

B. Energy distribution

The energy of the electron tracks was measured by multiple Coulomb scattering. The reliability of the method was checked by the measurement of knock-on electrons having a spectrum of momenta representative of those measured for pairs. In Fig. 1(a) is shown the experimental histogram of the total energy transferred to the electron pairs with scattering measurement errors ~10 to 15%. The energy values were corrected for all other observed experimental errors. In the energy distribution of the electron pairs, about 80% of the events are produced with $E_0 \leq 1000$ MeV, where $E_0 = E_1 + E_2$ is the total energy of the electron pair ($E_1 < E_2$); $E_0 < mc^2\gamma \approx 732$ MeV. In Fig. 1(b) the histogram shows the electron-pair energy up to 700 MeV, with $\langle E_0 \rangle = 225.6 \pm 30.14$ MeV; this is compared with the theoretical histogram given by the modified Bhabha theory, Eq. (3) of Ref. 3, for $2mc^2 < E_0 < \gamma mc^2$, where $\gamma \simeq 1433$ for our experiment and mc^2 is the rest mass of an electron. All the theoretical curves here are normalized to our experimental data and the theory fits well with the observed data. The total cross section calculated by this theory for the range $E_0 < 732$ MeV is ≈93 mb and is very close to the experimental values (within the statistical limits) observed for the same range of E_0. In Fig. 1(c) is shown the experimental histogram of the imbalance ratio $R = E_1/E_0$ (where $E_1 < E_2$) for all events, along with a theoretical curve which was calculated from Eq. (10) of Bhabha's modified theory of Ref. 3. The fit is quite reasonable.

C. Angle measurement

We may point out here that among all the particle detectors, nuclear emulsion has the best space resolution. The angle of all electron-pair tracks is measured with respect to the primary direction. As the angles are very small, we measured them with the help of filer micrometers attached to scattering microscopes. For angle measurement, the distance between the vertex and the point of observation should be kept small in order to minimize the multiple scattering of light tracks. In Fig. 1 (d) we evaluate the angular divergence of the electron pair in terms of Borsellino's[13] characteristic angle $\omega_0 = E_0 mc^2/E_1E_2$. The calculated errors in space angles are less than 5%. The theoretical curve is calculated from Eq. (14) of Ref. 13. The theoretical curve reproduces approximately the shape of the experimental histogram which appears a little broader than the theoretical curve for small values of ω/ω_0. The $\langle \omega/\omega_0 \rangle$ is equal to 2.3 ± 0.2. We also measure the quantity Q which depends on the angle ω between the electron and positron and on the ratio in which the energy of the electron pair is divided between the two particles. In Fig. 1 (e) is shown the experimental data for the invariant mass Q, where $Q^2 = (E_1 + E_2)^2 - (\bar{p}_1 + \bar{p}_2)^2$ for electron pairs in units of $2mc^2$, in the center-of-mass system of the pair. Q is calculated by using Eq. (2) of Ref. 14. $\langle Q \rangle = 3.45 \pm 0.32$ MeV for the present experiment. The theoretical curve for Q was obtained from the following relation, i.e., Eq. (7) of Ref. 13:

$$d\sigma = 4\sigma_0 (F/Q^3) dQ,$$

where

$$\sigma_0 = (z^2 r^2)/137$$

and $F \propto \ln Q$. The experimental data within the statistical limits fit well with the theory. About 70% of the events have Q value between 1–3 MeV and the most probable values of Q are now close to 1, and since F in Eq. (7) increases as $\ln Q$, the distribution after the maximum drops down as $1/Q^3$. In Fig. 1(f) is shown the net transverse-momentum p_t distribution of each electron from the pair produced by 200 GeV pion beam. The $\langle p_t \rangle = 1.55 \pm 0.19$ MeV/c. More than 70% of the events fall in the region of $p_t < 3$ MeV/c.

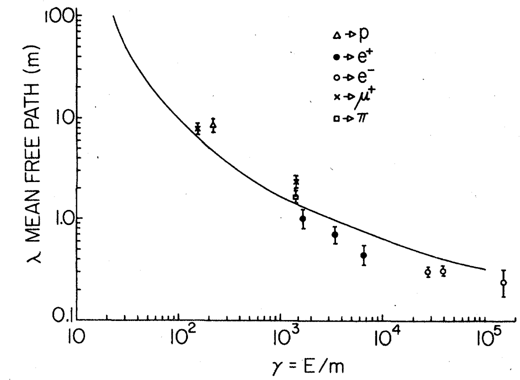

FIG. 2. Electron-pair mean free paths in nuclear emulsions as a function of γ ($\simeq E/M$) for electrons (Refs. 3, 15–20), protons (Ref. 6), muons (Ref. 7), and pion (this experiment). The theoretical curve is given by Eq. (5) of Ref. 3.

IV. CONCLUSION

Our results in the present experiment for electron-pair production from 200-GeV pions in nuclear emulsion are reasonably in agreement, within the statistical errors, with the predictions of quantum-electrodynamic calculations. This is shown again in Fig. 2 along with all the data of other investigators[3,15-20] using nuclear emulsion. Our data from previous experiments have been corrected for scanning bias and are also plotted in this figure. The theoretical curve is plotted from Eq. (5) of Ref. 3.

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