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FERMILAB-PUB-74-142-E

DIRECT ELECTRON-PAIR PRODUCTION BY 200-GeV PROTONS*

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ABSTRACT

Forty directly produced electron pairs have been found by following 713.4 meters of 200 GeV proton track length in nuclear emulsion. For these pairs we have analyzed (i) the total energy distribution, (ii) energy partition between the two members, (iii) the angular divergence, (iv) the transverse momentum distribution and (v) the invariant mass of the electron pairs. The present theories disagree with our experimental results.

Observations of the direct-production of electron pairs arising from the interaction of fast charged particles with the Coulomb fields of nuclei have been studied extensively.[1] Some of the experimental data between 1-100 GeV have shown conflicting results with the theories, and beyond 100 GeV, there does not exist any reliable experimental data. 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 is it accurately determined. The accuracy of the energy of the primary beam is very essential in making any analysis in the observed data. Several authors[2,4] have computed the cross section of direct pair production and have modified the theories to fit the experimental data.

Recently the availability of a monoenergetic beam of 200 GeV protons at NAL makes it very appropriate to look into this fundamental problem from the point of view of checking quantum electrodynamics at small distances, which has attracted considerable attention over the years. In the present experiment we have considered electron pair production by a monoenergetic

(submitted to Phys. Rev. Lett.)

beam of 200 GeV protons in the Coulomb potential of an emulsion nucleus with an effective charge $Z \simeq 21.4$. Electron-position pairs used in the present analysis were obtained by scanning along 713.4 meters of track length in Ilford G-5 emulsion, 600μm thick exposed[5] to a flux of 2×10^4 particles / cm^2 in a 200 GeV proton beam parallel to the emulsion plane. At a distance of 0.5 cm. from the edge of the plate we pick up a track parallel to the primary beam at about half way up from the bottom of the pillicle and follow it with others along the X-motion of a Koristka microscope stage at an average speed of about 25 cm/hour. Whenever an interaction was observed, the parent track was rechecked for its parallelism with the other beam tracks followed in the same field of view. Thus we find the inelastic interaction mean free path of 200 GeV protons in nuclear emulsion to be $\lambda_{int} = 32.1 \pm 0.6$ cm. The percentage of white stars[6] with $N_h = 0$ for all interactions is 17% out of which 18% are tridents. Our scanning efficien of low multiplicity events is quite high (>96%). Out of a total of 76 tridents, 40 were identified by scattering measurements as directly produced electron pairs. The vertex of each trident was carefully checked to eliminate spurious events such as (a) bremsstrahlung pairs, (b) conversion of γ-ra from the decay of a neutral particle like $\pi^0 \rightarrow \gamma + e^+ + e^-$ (Dalitz decay) whic occurs only 1/80 of the time, (c) tridents from strong incoherent (p-n) inte actions, and (d) coherent production of particles through Coulomb or diffrac dissociation of pion pairs[5,7]. The calculated total background was < 1%. Th 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 relativisti electron, unlike more massive particles, loses a considerably greater fractic

of its 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 the opposite side of the primary and be nearly coplanar; (ii) the middle track, which is the proton, should be practically undeviated from its original direction; (iii) the ionization density for electron track should be less than or equal to the plateau value; (iv) for the separation of fast electrons from low energy pions, $p\beta c$ value should be <0.21 GeV; and (v) at least one track, if not both, must show sufficient multiple scattering which is characteristic of an electron. Events produced through the coherent process were separated as mentioned earlier[7], giving a mean free path $\lambda_{3,coh} = (19.1 \pm 4.2)$m and $\sigma_{3,coh} = (11.2 \pm 2.5)$mb in nuclear emulsion. By observing tridents with the above criteria, we obtained 40 events which were produced due to direct pair production with $\lambda_{pair} = (17.8 \pm 2.9)$m and thus $\sigma_{pair} = (7.1 \pm 1.1)$mb. In order to see the dependence of σ_{pair} on the nature of the primary particle interacting with the same γ-factor ($\gamma_p \sim 200$), we used 15.8 GeV/c negative muons[8] ($\gamma_\mu \sim 150$) giving $\lambda_{pair} = (15.6 \pm 3.9)$m and $\sigma_{pair} = (6.2 \pm 1.5)$mb which show the independence of the nature of the incoming particle at these energies The errors shown are statistical. Recently, on the basis of very low statistics[9] of only 8 electron pairs found in 130 meters of track length, in nuclear emulsion exposed to 200 GeV protons the value of $\lambda_{pair} = (19.1 \pm 6.8)$m and $\sigma_{pair} = (6.7 \pm 2.4)$mb were presented. For the 8th event of their[9] Table I, we calculated the values of different parameters (i.e. $E_1 = 900$ MeV, $E_2 = 4100$ MeV, $R = 0.18$, $Q = 181$ MeV, and $\omega/\omega_o = 140$) as defined in our Figs. 1(a) to 1(e). We find that the values of these parameters for this

event are quite different from the rest of their[9] electron pairs as well as from our present data and hence this event does not belong to electron pair production. The theoretical total cross-sections with the screening effect, which were calculated by different authors[2,3], lie in range of 26-100 mb. The detection efficiency of low energy electron (~1 MeV) pairs in emulsion is quite good. We may also mention that the contamination of the trident production from an electron beam in this experiment is practically negligible as the energy transferred from the parent electron to the created pair is generally very large[3] (5 to 50%) with the result that the opening angle of the pair may be very small, ~mc^2/E radians. On the other hand, for the direct pair production with a proton beam, a very small fractional energy <0.05% is transferred to the created pair with a relatively large opening angle.

In Fig. 1(a) is shown the experimental histogram of the total energy transferred to the 36 electron pairs with scattering measurement errors up to ~15%. Because of unsuitable physical conditions of the emulsion in the vicin of the electron pairs, the energy determination of either one or both of the tracks from four of the electron pairs were not dependable and hence these events are excluded from our discussion. In the energy distribution of these electron pairs about 50% of the events are produced with energy $E_o \leq 100$ MeV, where $E_o = E_1 + E_2$, the total energy of the electron pair. In Fig. 1(b) the histogram shows the total electron pair energy up to 100 MeV and this is comp with the theoretical curve given by the modified Bhabha's theory[1,4] for $2mc^2$ $E_o < \gamma\, mc^2$, where γ in our experiment is ~200 and mc^2 is the rest mass of an electron. All theoretical curves are here normalized to our experimental data and the theory does not fit well with the observed data. The total cross sec calculated by this theory for the range $E_o \leq 100$ MeV is 26 mb which is ten ti larger than the experimental value observed for the same range of E_o. In Fig

we evaluated the angular divergence ω of the electron pair in terms of Borsellino's characteristic angle[10] $\omega_o = E_o mc^2/E_1E_2$. The calculated error[11] in the space angle is less than 5%. The theoretical curve is calculated fro Equation (14) of reference (10) in which we used from our experiment the overall average value $\langle E_o \rangle = 250$ MeV and the imbalance ratio R = 0.25. The theoretical curve gives approximately the shape of the experimental histogra In Fig. 1(d) is shown in histogram, the invariant mass $Q = (E_o^2-p^2)^{1/2}$ distri bution for the electron pairs in units of 2 mc^2, where p is the total moment of the pair. The value $\langle Q \rangle_{pair} = (4.8 \pm 0.8)$ MeV for the present experiment and for 15.8 GeV/c muon beam[8] $\langle Q \rangle_{pair} = (4.3 \pm 1.0)$ MeV. More than 50% of t events have $Q \leq 3$ MeV. For events with $E_o \leq 100$ MeV, the values of Q are plotted in Fig. 1(e). For these events, the average value of the energy observed for the electron pairs is $\langle E_o \rangle = 38$ MeV. Hence, the theoretical curve was fitted to this distribution for this average value of E_o. We see the sharp peak in the theoretical curve, but it is shifted to the left of the experimental data. Figs. 1(f) and 1(g) show the experimental histograms of the imbalance ratio $R = E_1/E_o$ for $E_o \leq 100$ MeV and >100 MeV, respectively. The theoretical curves in Figs. 1(f) and 1(g) were calculated from Eq. (31) of Bethe and Heitler[12] for $E_o = 35$ MeV and 350 MeV respectively. Fig. 1(h) shows the net p_t distribution of each electron pair. The value $\langle p_t \rangle_{pair} = (4.9 \pm 0.8)$ MeV/c and for 15.8 GeV/c muon beam[8] $\langle p_t \rangle_{pair} = (3.6 \pm 0.8)$ MeV/c. More than 50% of the events fall in the region of $p_t < 4$ MeV/c, with an upper limit of $p_t \approx 20$ MeV/c.

In conclusion, the theoretical predictions on the cross section, the energy spectrum, the angular divergence, and the invariant mass distribution of the electron pairs do not explain the observed experimental results. The discrepancies are rather large, e.g., $\sigma_{pair}(\text{theory}) >> 5\ \sigma_{pair}(\text{experiment})$ in particular, for small E_o and Q regions. Nuclear emulsion has a large detectio efficiency for even extremely low energy particles and here we have been able

detect electrons with kinetic energy <1 MeV. We feel that the present systematic experimental observations will be useful to the theoreticians to look into these discrepancies very seriously.

We are very grateful to the members of NAL and especially to Dr. L. Voyvodic for the exposure of our stack.

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6. White stars with $N_h = 0$ are those primary events in which there is no black or grey track present along with all the light tracks. The nomencl for black, grey and light tracks is as follows: light tracks, $g_s \leq 1.5g_o$; grey track, $1.5\ g_o < g_s < 2.5g_o$; black tracks, $g_s > 2.5g_o$.

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FIGURE CAPTIONS

Fig. 1 (a) The energy distribution of the electron pairs.

(b) The energy distribution of the electron pairs with $E_o < 100$ MeV and the theoretical curve is given by references (1,4). All theoretical curves in the figures are normalized to the experimental data.

(c) The angular divergence ω for electron pairs in terms of Borsellino angle ω_o. The theoretical curve is given by reference (9).

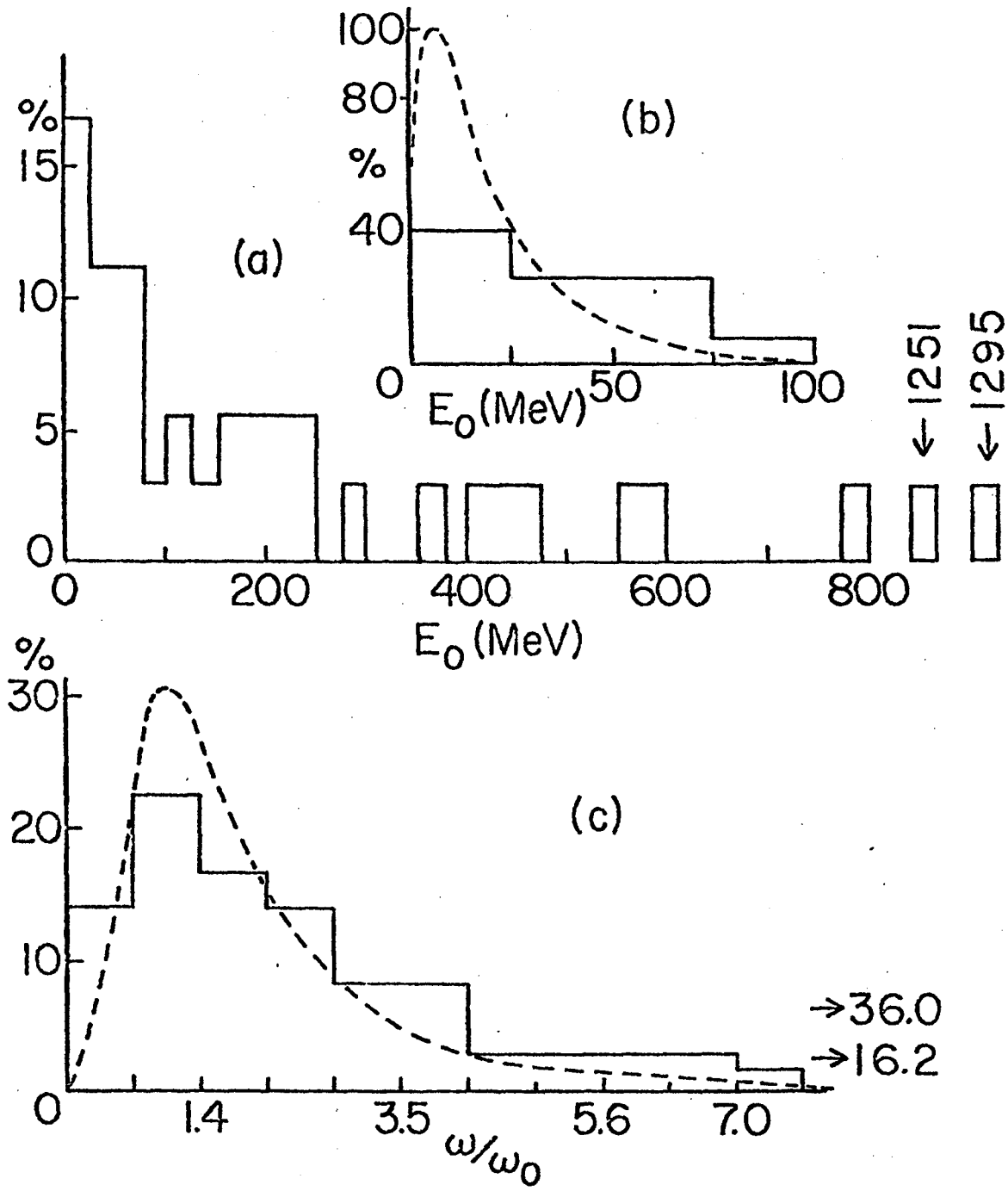
(d) The invariant mass Q distribution for all events in unit of $2mc^2$.

(e) The experimental and the theoretical invariant mass Q distribution for electron pairs with $E_o \leq 100$ MeV, in units of $2mc^2$.

(f) and (g)

Experimental and theoretical distributions for $R = E_1/E_o$ for $E_o \leq 100$ MeV and $E_o > 100$ MeV, respectively, where $E_1 < E_2$.

(h) P_t distribution for all electron pairs.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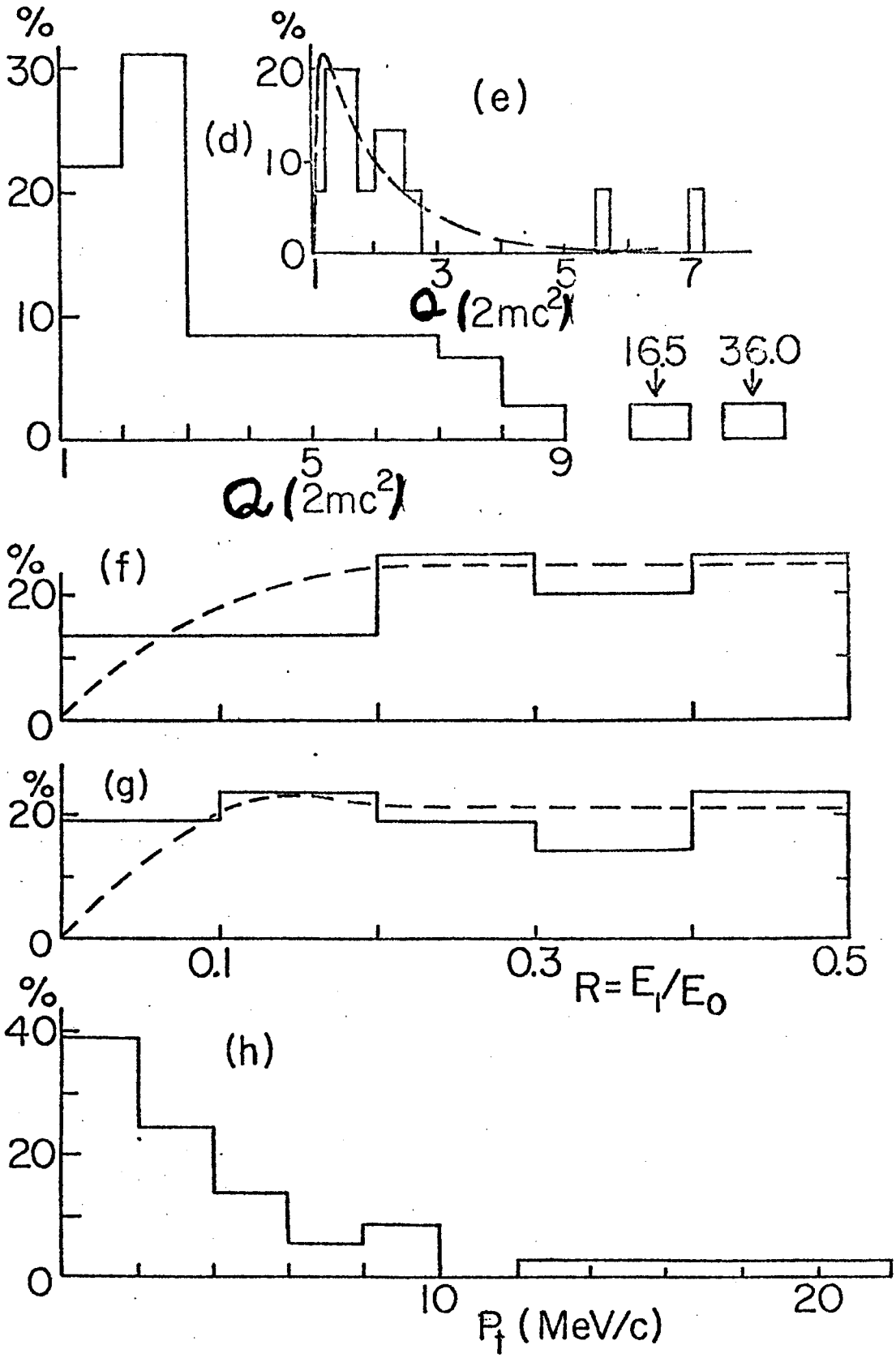
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