High-energy test of quantum electrodynamics

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Thirty-five directly produced electron pairs have been observed by following 150 m of 150-GeV muon track length in nuclear emulsion. These pairs have been compared with the pairs produced by 200-GeV protons and 15.8-GeV/c muons in terms of (i) their total energy distribution, (ii) the fractional transfer of the primary energy to the pairs, (iii) the energy partition between the two members, (iv) the angular divergence, (v) the invariant mass of the electron pairs, and (vi) the net transverse-momentum distribution of each pair. Present theories disagree with the experimental results.

In order to test the predictions of the theories based on quantum electrodynamics at small distances, recently we reported the direct electron-pair production from the Coulomb field of an emulsion nucleus by 200-GeV protons[1] from the Fermi National Accelerator Laboratory and 15.8-GeV/c muons[2] from BNL. From most of the present theories,[3-6] the predictions for electron-pair production are quite similar. They all conclude that the pair-production cross section depends on the ratio γ ($=E/m$) and not on E and m separately or on the type of incoming particle. In order to check the independence of the type of incoming particle, we performed the above-stated two experiments[1,2] with two different primary particles, with their γ factors not too different from one another. In both cases we found that the experimental results are not represented very well by any present theories. The total cross section for direct pair production by muons at 15.8 GeV/c ($\gamma \approx 150$) indicates a discrepancy of approximately twice Bhabha's modified[6] cross section, while for 200-GeV protons ($\gamma \approx 200$), the discrepancy was greater than 5 times Bhabha's modified cross section. Thus, in these two experiments the cross-section values for small regions of E_0 differ by a factor of at least $2\frac{1}{2}$. We may point out that nuclear emulsion has a large detection efficiency for low-energy particles and we have detected electrons with kinetic energy ~1 MeV. The total cross section given by Racah[4] is in close agreement with the modified Bhabha theory. But the theory of Murota *et al.*[5] gives a slightly higher cross section than the modified Bhabha theory[6] for a given primary energy in the same region of transferred energy. All the above theories have been computed under Born approximation and have neglected the nuclear recoil and the extended shape and structure of the target particles, which may be essential to include at such high energies to explain the results of our two previous experiments.

In order to check the validity of the present theories for the direct electron-pair production at still higher γ values, we used muons at 150 GeV ($\gamma \approx 1420$), about ten times higher than our previous muon experiment, from the Fermi National Accelerator Laboratory. This is the highest muon energy available from the present accelerators. We may point out that in order to get the same value of γ from a proton beam, we would have to use $E_p \approx 1.5$ TeV, which is at the present time only possible through colliding-beam experiments. For direct electron production we have already stressed[2] the uncertainty, the unreliability, and the contradicting results of the previously performed experiments with cosmic-ray muons. We have also pointed out the scarcity of such muon experiments from accelerator beams at high energy. In the past there have been a number of experiments with electron beams[6-12] at low energies, but for high-energy electrons one has to correct for bremsstrahlung pairs, which is a very dominant process, and this correction increases with the increase of the electron energy. Direct electron pairs cannot easily be distinguished from the bremsstrahlung pairs, hence muon particles at high energy would be ideal for the present studies, which we shall describe as follows.

We exposed a small stack of 15 pellicles of G-5 emulsion of dimensions 10 cm × 15 cm × 600 μm to a monoenergetic beam of 150-GeV positive muons parallel to the emulsion plane. The contamination of the pions in the muon beam was very small. At a distance of 0.5 cm from the edge of the plate we picked up a track parallel to the primary beam at about halfway up from the bottom of the pellicle and followed it with others along the x motion of a Koristka microscope stage at an average speed of about 15 cm/h. For careful studies at such a high energy, we kept our scanning speed slow. 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. We followed a total of 150 m of track length. All the apparent knock-on electrons which did not satisfy the energy-angle relationship for a two-

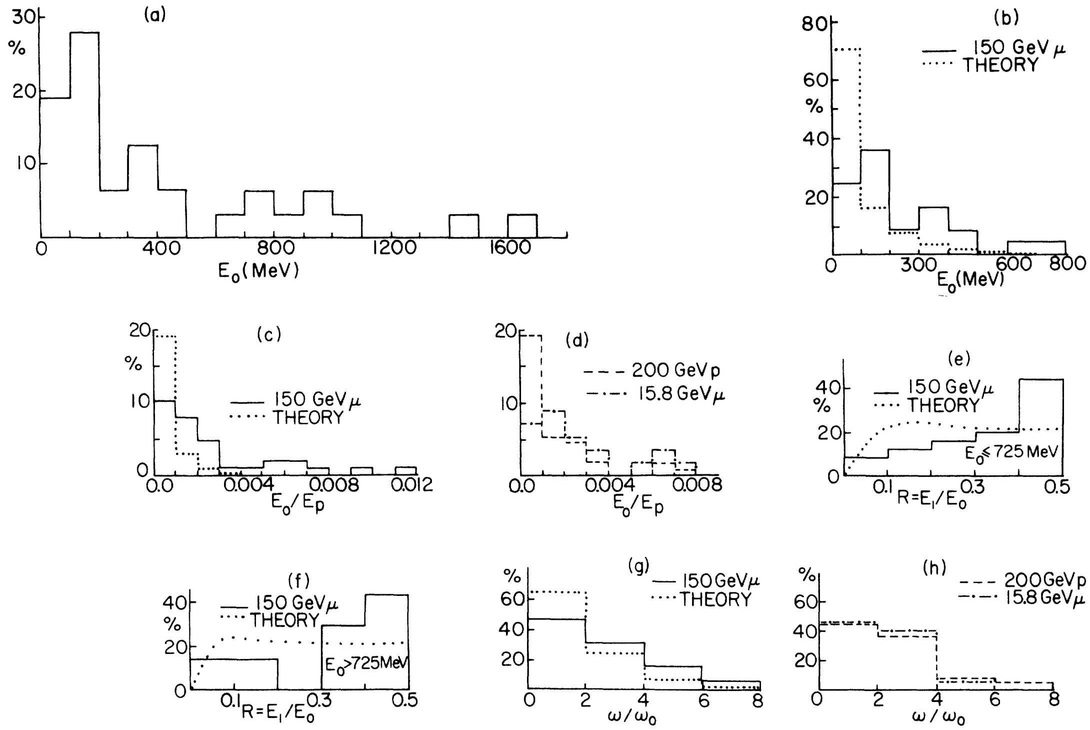

FIG. 1. *(Continued on following page)*

body process were examined very carefully for a second low-energy track for a possible electron trident. The stringent criteria for eliminating spurious events and for accepting events for electron-positron pairs were followed as discussed earlier.[1,2] Thus, after careful separation of electron pairs from the other three-pronged events (i.e., inelastic and bremsstrahlung events, etc.), we found 35 direct electron-positron pairs. The scanning efficiency was 98%. Thus, the mean free path for electron-pair production in nuclear emulsion for 150-GeV muons was $\lambda_{\text{pair}} = 4.26 \pm 0.7$ m, with $\sigma_{\text{pair}} = 29.8 \pm 4.8$ mb. For 200-GeV protons ($\gamma \approx 200$) $\lambda_{\text{pair}} = 17.8 \pm 2.9$ m and $\sigma_{\text{pair}} = 7.1 \pm 1.1$ mb, while for 15.8-GeV/c ($\gamma \approx 149$) muons $\lambda_{\text{pair}} = 14.0 \pm 3.1$ m and $\sigma_{\text{pair}} = 9.0 \pm 1.9$ mb. The energy of the electron tracks was measured by multiple Coulomb scattering.[2] The reliability of the method was checked by measuring the known momenta from an angle of emission of knock-on electrons[13] having a spectrum of momenta representative of those measured for pairs. 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 are excluded from our discussion throughout this paper. In Fig. 1(a) is shown the experimental histogram of the total energy transferred to the electron pairs with scattering measurement errors ~12%. The energy values were corrected for all other observed experimental errors.[1] In the energy distribution of the electron pairs about 75% of the events are produced with $E_0 \leqslant 725$ MeV, where $E_0 = E_1 + E_2$ is the total energy of the electron pair ($E_1 < E_2$): $E_0 < mc^2\gamma \approx 725$ MeV. In Fig. 1(b) the histogram shows the electron-pair energy up to 800 MeV, with $\langle E_T \rangle = 217$ MeV, and this is compared with the theoretical histogram given by the modified Bhabha theory[6] for $2mc^2 < E_0 < \gamma mc^2$, where $\gamma \approx 1420$ 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 does not fit well with the observed data, especially for the low-energy values. The total cross section calculated by this theory for the range $E_0 \leqslant 725$ MeV is ~94 mb, which is about 4 times larger than the experimental value observed for the same range of E_0. In order to facilitate further comparison with the theory, we plot in Fig. 1(c) the fractional transfer of primary energy to the electron pair, i.e., $R = E_0/E_p$, where $E_p = 150$ GeV. We notice that the data do not agree with the theory, while the experimental observation of R for 150-GeV muons in Fig. 1(c) does agree within the statistical errors with our experimental data observed for 200-GeV protons and 15.8-GeV/c muons shown in Fig. 1(d).

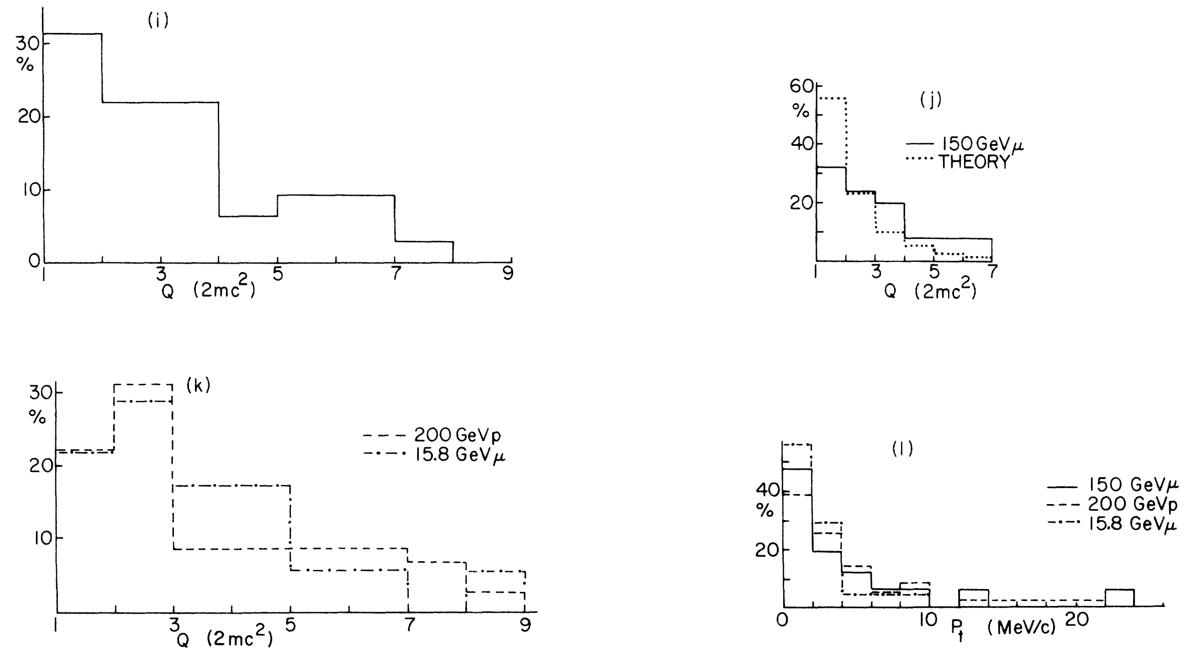

FIG. 1. (a) Energy distribution of the electron pairs. (b) Energy distribution of the electron pairs with $E_0 < 725$ MeV, and the theoretical curve given by Ref. 6. All the theoretical curves are normalized to the experimental data in these figures. (c) Fractional transfer of primary energy to pairs. (d) Experimental normalized data for the 200-GeV proton and 15.8-GeV/c muon. (e) and (f) are experimental and theoretical distributions for $R = E_1/E_0$ for $E_0 \leq 725$ MeV, respectively, where $E_1 < E_2$. (g) Angular divergence ω for electron pairs in terms of Borsellino's angle ω_0. The theoretical curve is given by Ref. 15. (h) ω/ω_0 for the normalized 200-GeV proton and 15.8-GeV/c muon beams. (i) Invariant-mass (Q) distribution for all events in units of $2mc^2$. (j) Experimental and theoretical invariant-mass (Q) distribution for pairs with $E_0 \leq 725$ MeV, in units of $2mc^2$. (k) Experimental normalized distributions for 200-GeV protons and 15.8-GeV/c muons. (l) Net p_t distribution of electron pairs from 200-GeV protons, 15.8-GeV/c muons, and 150-GeV muons.

In Figs. 1(e) and 1(f) are shown the experimental histograms of the imbalance ratio $R = E_1/E_0$ for $E_0 \leq 725$ MeV and $E_0 > 725$ MeV, respectively. The theoretical curves were calculated from Eq. (31) of Bethe and Heitler[14] for $\langle E_0 \rangle = 217$ and 1105 MeV, respectively. In Fig. 1(g) we evaluated the angular divergence ω of the electron pair in terms of Borsellino's characteristic angle[15] $\omega_0 = E_0 mc^2/E_1E_2$. The calculated error[13] in the space angle is less than 5%. The theoretical curve is calculated from Eq. (14) of Ref. 15 in which we used from our experiments the overall average value $\langle E_0 \rangle = 411$ MeV and the imbalance ratio $R = 0.33$. The theoretical curve gives approximately the shape of the experimental data. Similarly, in Fig. 1(h) is shown ω/ω_0 for the experimental data of the 200-GeV proton and 15.8-GeV/c muon which also agrees with the data of the 150-GeV muon. The average $\langle \omega/\omega_0 \rangle$ are 2.45 ± 0.36, 2.30 ± 0.54, and 2.39 ± 0.41 for the 150-GeV muon, the 15.8-GeV/c muons, and the 200-GeV protons, respectively. In Fig. 1(i) are shown the experimental data for the invariant-mass $Q = (E_0^2 - p^2)^{1/2}$ distribution for the electron pairs in units of $2mc^2$ in the center-of-mass system of the electron and positron, where p is the total momentum of the pair, $\langle Q \rangle = 3.22 \pm 0.54$ MeV for the present experiment, and for the 15.8-GeV muon and the 200-GeV proton, $\langle Q \rangle = 4.3 \pm 1.0$ MeV and 4.8 ± 0.8 MeV, respectively. For events with $E_0 \leq 725$ MeV, the values of Q are plotted in Fig. 1(j). For these events, the average value of the energy observed for the electron pairs is $\langle E_0 \rangle = 217$ MeV. The theoretical curve was fitted to this distribution for this average value of E_0. We see that the theoretical value is much larger as compared to the observed data for small Q values. In Fig. 1(h) are shown the observed Q values for the 200-GeV protons and the 15.8-GeV/c muons for the entire range of their observed energies. The distributions in Figs. 1(i) and 1(k) are approximately identical within their statistical errors. In Fig. 1(l) is shown the p_t distribution of each electron pair for 150-GeV and 15.8-GeV/c muons and for 200-GeV protons. All these three distributions are identical within their statistical errors. The values for $\langle p_t \rangle_{\text{pair}}$ are 4.05 ± 0.6 MeV/c, 4.9 ± 0.8 MeV/c, and 3.6 ± 0.8 MeV/c for 150-GeV, 200-GeV, and 15.8-GeV/c

beams, respectively. More than 50% of the events fall in the region of $p_t < 4$ MeV/c, with an upper limit $p_t \sim 25$ MeV/c. In order to see if the mass of the incoming particle has any indirect effect in the production cross section of electron pairs in the same target, we plotted in Fig. 2 the mean free path λ (cm) against γ ($=E/m$) for our data along with the data of other investigators[6-12] using nuclear emulsions. We find that all electron data can be represented by the relation $\lambda = a(E/m)^b = a(\gamma)^b$, where $a = (12.22 \pm 2.24)$, and $b = -(0.329 \pm 0.021)$. Data points for muons are at higher values of λ, and they have practically the same slope as the electron data. The proton data point is at a higher value than those for both electrons and muons.

In conclusion, we can say that our results from three experiments with different energies and different primary particles have repeatedly indicated that the theory is in serious trouble and should be looked into very carefully. At such high energies perhaps one needs to use the nuclear form factor $F(q_N^2)$ corrections in the theories.

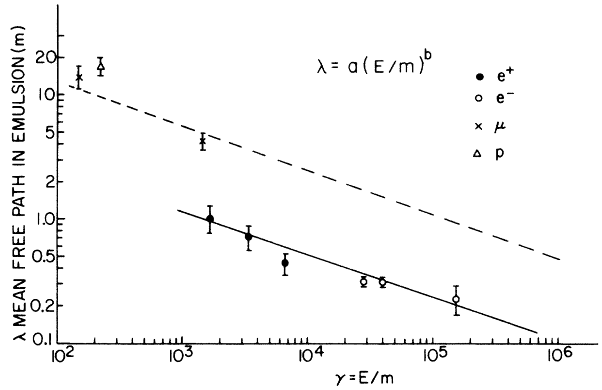

FIG. 2. Electron-pair mean free paths in nuclear emulsions as a function of $\gamma(\approx E/M)$ for electrons (Refs. 6–12), protons (Ref. 1), and muons (Ref. 2). Electrons are represented by a linear relation. $\lambda = a(\gamma)^b$, where $b = -0.329 \pm 0.021$, $a = 12.22 \pm 2.24$.

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