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Direct e^+e^- pair production by 300-GeV/c protons in neon*

R. J. Loveless, A. R. Erwin, E. H. Harvey, J. Mapp, and M. A. Thompson
Department of Physics, University of Wisconsin, Madison, Wisconsin 53706

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We report direct e^+e^- pair production by 300-GeV/c protons in the Fermilab 30-in. bubble chamber filled with 31% molar mixture of neon in hydrogen. We find 310 direct pairs for a cross section $\sigma = 12.0 \pm 0.6$ mb, in good agreement with quantum-electrodynamic calculations. Both the momentum distribution and the momentum asymmetry distributions of our direct pairs also agree well with theory.

We report the measurement of the direct pair cross section for 300-GeV/c protons in a hydrogen-neon mixture in the 30-in Fermilab bubble chamber. Direct electron-positron pair production, an electromagnetic process, occurs when an incident charged particle interacts with the Coulomb field of another charged particle. The production rate for this process can be computed from quantum electrodynamics by considering pair production from a virtual photon. The major uncertainty in this calculation concerns the effectiveness of the approximations due to electron screening, nuclear effects, and multiple scattering.

Recent emulsion experiments with high-energy muon and proton beams have found discrepancies from theoretical predictions. The cross section for 200-GeV/c protons was low by a factor of 5.[1] The cross section for 150-GeV/c muons was low by a factor of 4.[2] A third emulsion experiment reports a 200-GeV/c proton cross section of 6.7 ± 2.4 mb, compared to an expected 100 mb.[3] All these emulsion experiments have low statistics. On the other hand, bubble-chamber experiments in H_2-neon (Ref. 4) and H_2 (Ref. 5) with high energy π^- agree with theory and have good statistics. Since the quantum-electrodynamic predictions depend on the energy and spin of the incoming particle, it is important to measure accurately the direct pair production from high-energy protons.

39 242 frames were scanned for three-prong events in which the beam track remains undeflected, the electron and positron tracks are minimum ionizing, and both are collinear with the beam track. This scan also recorded γ conversions near the track for use in background studies.

All pair candidates were scanned by physicists and measured on standard film-plane machines. Track measurements were kept as short as possible, consistent with sufficient curvature to determine momenta to several percent, to avoid measuring past an invisible bremsstrahlung. In no case was a track measured past a visible kink.

In order to compute the cross section we must consider the following:

(a) Hadronic background. All frames with a visible upstream interaction were discarded because the resulting spray of tracks lowers the scanning efficiency and increases the number of γ conversions which can simulate a direct pair. In addition, the incident beam flux was low (usually 1 or 2 beam tracks/picture) to reduce multiple interactions in a picture.

(b) Beam flux. The number of beam tracks entering the chamber was counted every 25 frames throughout the exposure with a scanning efficiency of 0.98 ± 0.01. Using an hadronic absorption coefficient computed from this exposure[6] ($\mu = 0.003\,39 \pm 0.000\,16$), the beam flux can be scaled to the beginning of the fiducial volume and corrected for the beam length lost due to hadronic interactions. The total beam length available for direct pair production is $4.35 \pm 0.08 \times 10^6$ cm.

(c) Mixture densities. The density of the hydrogen-neon mixture must be obtained indirectly. The molar fraction of neon is 0.309, as determined from a chemical analysis of samples taken before and after the experiment. The static vapor pressure of the chamber during the experiment was 92.6 psi (absolute); from neon-hydrogen tables[7] this indicates a temperature of 28.5 °K in the saturated liquid. At this temperature a 0.309 molar mixture has a density of 0.249 g/cm^3. Since this mixture is 82.8% hydrogen by volume, the hydrogen density is 0.048 g/cm^3 and the neon density is 0.201 g/cm^3.

(d) Scanning efficiency. The single-scan efficiency is 0.94 ± 0.03; it was computed by double scanning approximately 25% of the film. We find no evidence that this efficiency depends on the direct pair momentum between the limits of 5 and 5000 MeV/c. Above 5000 MeV/c the scanning efficiency for direct pairs decreases because the tracks do not spiral in the chamber, and it is difficult to separate direct pairs from hadronic three-prong interactions. Hence all candidates above 5000 MeV/c were discarded. This removes less than 1% of the expected direct pairs. At low energies the scanning efficiency drops, and a δ ray

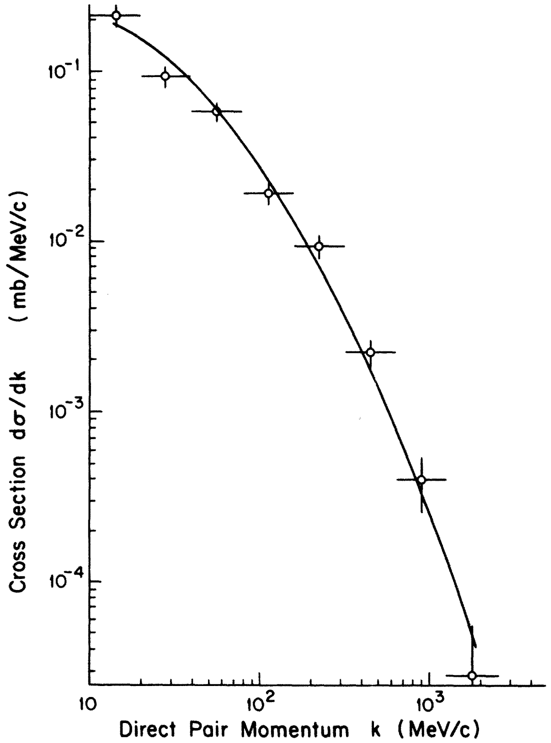

FIG. 1. The differential cross section, $d\sigma/dk$, as a function of the direct pair momenta k. The solid curve represents the predicted value from a QED calculation by Ternovskii.

can simulate an asymmetric pair. Thus we require that the total momentum of the pair be above 5 MeV/c and the momentum of each track be above 2 MeV/c.

(e) γ background. During the experiment the accelerator was operating at 300 GeV/c so the 300-GeV/c proton beam should have no leptonic or pionic background. γ background can come only from upstream interactions, most of which have been removed by (a). By observing γ conversions as a function of momentum and distance from a beam track, we estimate that the number of background γ's converting within 1 mm of a beam track is 2 for the complete data sample. These background γ's typically have momenta large relative to most direct pairs and constitute a serious background above 5 GeV/c because of the low pair rate at such momenta. We expect most of our background γ's between 500 and 5000 MeV/c.

We chose to compare our experiment with a QED calculation of Ternovskii,[8] who uses a Thomas-Fermi model for the nucleus and assumes a "second-order" process, where the incident particle is considered free. The cross section for spin-$\frac{1}{2}$ particles can be written

$$\frac{d^2\sigma}{d\omega dk}=\alpha^2 Z(Z+1)\, LB(\omega,k), \qquad (1)$$

where α is the fine-structure constant, k is the total momentum of the pair, ω is the difference in electron and positron momenta divided by k, Z is the charge of the nucleus, L is a screening factor, and B is a complicated function which includes not only ω and k but also the mass and energy of the incoming particle. This theory contains no free parameters. Since direct pair production occurs from the Coulomb field of the orbital electrons as well as the nucleus, the expected Z^2 dependence becomes $Z(Z+1)$. For the neon this implies that 9% of the direct pairs come from interactions with the Coulomb field of an electron.

The bubble chamber contains a mixture of hydrogen and neon so direct pairs will be produced by both atoms. The theoretical estimate for the total cross section is obtained by integrating Eq. (1)

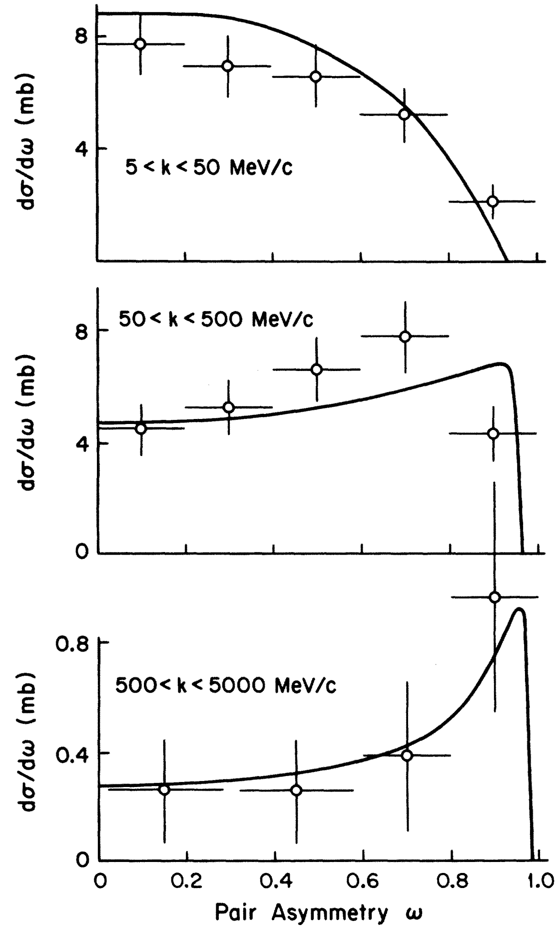

FIG. 2. The differential cross section, $d\sigma/d\omega$, as a function of direct pair asymmetry $\omega=|p_+-p_-|/(p_++p_-)$ for three ranges of direct pair momenta. The solid curves are theoretical predictions from QED.

numerically over the total momentum k and the pair asymmetry ω. The limits of integration correspond to the experimental constraints, namely, each track is greater than 2 MeV/c and the total momentum varies from 5 to 5000 MeV/c. To show the correspondence between theory and experiment most clearly, we compute the theoretical absorption coefficient for direct pair production by 300-GeV/c protons,

$$\mu = \left(\frac{\rho_{\mathrm{Ne}} \sigma_{\mathrm{Ne}}}{A_{\mathrm{Ne}}} + \frac{\rho_{\mathrm{H}_2} \sigma_{\mathrm{H}_2}}{A_{\mathrm{H}_2}} \right) A_0$$
$$= 0.73 \times 10^{-4} \text{ pairs/cm} ,$$

from theory and compare it directly with the measured quantity. Approximately 96% of all direct pairs come from neon interactions.

The final data sample contains 310 observed pairs. After correcting for scanning efficiency and background, the experimental absorption coefficient for direct pair production is $0.75 \pm 0.04 \times 10^{-4}$ pairs/cm. In more familiar terms, the direct pair cross section for neon is $\sigma_{\mathrm{Ne}} = 12.0 \pm 0.6$ mb. This can be compared to the hadronic absorption cross section for 300-GeV/c protons on neon, which is approximately 360 mb as measured in the same exposure. We note that 26 ($8 \pm 2\%$) of the direct pairs have visible low-momentum (< 5 MeV/c) electron recoils, which is consistent with the expectation that 9% of the pairs are produced by the Coulomb field of an electron that subsequently recoils.

Figure 1 shows the differential cross section, $d\sigma/dk$, as a function of the total momentum of the direct pair. The solid curve represents the theoretical estimate obtained by integrating Eq. (1) over ω. Figure 2 shows the cross section, $d\sigma/d\omega$, as a function of the pair asymmetry ω for three different ranges of pair momentum k. The solid curves represent the theoretical estimate from integrating Eq. (1) over the appropriate values of k. We point out that the experimental data are not normalized but represent an absolute count of direct pairs. Both plots show good agreement with prediction.

We conclude that our observed rate of direct pair production is in good agreement with Ternovskii's calculation. Both the asymmetry distributions and the momentum distribution agree with the theory.

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[6] The absorption coefficient is defined as

$$\mu = -\frac{1}{x} \ln(1 - N/N_0),$$

where x is the beam length, N_0 is the number of beam tracks, and N is the number of interactions.

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