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[14]The lightest member of this family of particles is *expected* to be singly charged. The weak decay of this particle could be explained by a nonzero mixing angle between the heavy quark and the light quarks or by conventional beta decay (see Cahn, Ref. 4) if the neutral particle turns out to be the lightest one. In the latter case, the charged particle will live long enough to be detected with full sensitivity unless the mass splitting is anomalously large ($\gtrsim 50$ MeV/c^2).

Search for Direct Electron Production in *p-p* and *p*-Be Collisions at 12 GeV/*c*

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We have made a systematic search for direct e^+ and e^- production in p-p and p-Be collisions at 12 GeV/c incident proton momentum. Data were collected at c.m. angles of 20°, 35°, 63°, and 84°. We find no evidence for the previously reported rise in the ratio e/π at low momentum transfer. The data are consistent with zero direct electron production from other than previously known sources.

Leptons produced directly in hadron-hadron collisions have been the subject of intense study in recent years.[1] The approximately constant e/π ratio of 10^{-4} observed at center-of-mass energy $\sqrt{s} > 20$ GeV and transverse momentum $P_T > 1$ GeV/c has been explained by a fit which includes a signficant amount of charmed-particle production.[2] However, the reported rise in this ratio for $P_T < 1$ GeV/c observed at both the CERN intersecting storage rings[3] with $\sqrt{s} = 53$ GeV and at the Brookhaven National Laboratory alternating-gradient synchrotron[4] with $\sqrt{s}$ as low as 4.5 GeV cannot be explained in the same way. Indeed, some experiments near or below charm threshold have reported null results.[5-7] We report here the results of a systematic search for direct e^+ and e^- production in proton-proton and proton-beryllium collisions at four c.m. angles (20°, 35°, 63°, 84°) in this region of momentum transfer and at an incident proton momentum of 12 GeV/c ($\sqrt{s} = 4.9$ GeV). These data partially overlap those of Ref. 4 but have been obtained by a different technique.

The experiment was performed using the external proton beam of the zero-gradient synchrotron (ZGS) at Argonne National Laboratory. A schematic diagram of the experimental setup is shown in Fig. 1. Secondary particles produced in a target of hydrogen or beryllium at positions *T*1, *T*2, *T*3, or *T*4 were selected by a two-stage spectrometer viewing targets at position *T*2. Different production angles were investigated by moving the target upstream or downstream to positions *T*1, *T*3, or *T*4 and then restoring secondary particles of the desired momentum to the spectrometer axis by a septum magnet *M*1. Data were obtained with a 0.40-cm-long beryllium target at all four production angles and from a 10-cm-long liquid hydrogen target at position *T*2, corresponding to a 35° c.m. production angle.

The spectrometer was evacuated except in the target region, which was filled with helium at atmospheric pressure. The momentum bite of the spectrometer was set at 3% by a collimator at the intermediate focus. The spectrometer subtended a solid angle from 0.05 to 1 msr for the

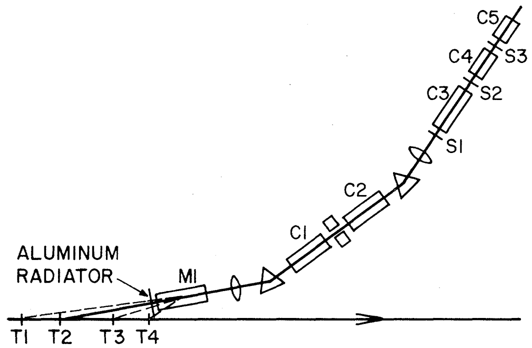

FIG. 1. Schematic layout of the experiment (not to scale).

extreme upstream and downstream positions of the target, respectively.

Particles passing through the spectrometer were detected by a coincidence of three scintillation counters, S1, S2, and S3. Electrons or positrons were identified by coincident pulses from at least two of three 2-m-long threshold Cherenkov counters C1, C2, C3 and by their characteristic pulse height in a lead-glass shower counter C5. Pions were identified in a high-pressure threshold Cherenkov counter C4. The overall electron detection efficiency was always greater than 90% while the hadron rejection ratio was greater than 10^6:1. Background in the electron signal was negligible except for the highest momentum positrons at small production angles where protons comprised up to 98% of the secondary particles. The pulse-height spectrum in the lead-glass shower counter was used to make the appropriate background subtraction in this case. The incident proton intensity was determined by an ionization chamber situated in the primary beam.

The primary source of electrons passing through the spectrometer was pair production by photons from the decay of secondary π^0 mesons. These were subtracted from the observed yield by an extrapolation method.[5] Five additional aluminum radiators, up to 0.06 radiation length, were placed in the spectrometer upstream of $M1$ and the measured e/π yields extrapolated to zero radiator and target thickness. The primary beam intensity was typically 3×10^{11} protons per ZGS pulse, resulting in high statistical accuracy: At low secondary momenta, we determined e/π to better than 1% for each radiator.

The ratio of direct electron production to pion production R_D has been extracted from the observed ratio R_0 by a fit with the quadratic form

$$R_0=(R_D+R_Et)(1+\alpha t),$$

where R_E is the ratio for external production per radiation length t. α incorporates the effects of the exponential photon and pion attenuation, electron energy straggling, and photon production from π^0's produced by charge exchange of secondary π^+ and π^- in the target and external radiator, all of which are small and proportional to t. Except for the last, these effects are easily calculable and agree with the measured values of α at the higher secondary momenta where the tertiary π^0 production is negligible. t is the radiation length of the external aluminum radiator and other material in the upstream region of the spectrometer, plus one-half the thickness of the target and other material in the primary beam (since photons produced in the target pass through one-half target thickness, on average). The target thickness was 0.012 radiation length of either beryllium or hydrogen. Radiation lengths were determined by careful weighing and chemical analysis of both the beryllium target and aluminum radiators.

With the beryllium target removed from the primary beam, the observed secondary particle rates in the spectrometer were reduced to 2% at the largest production angle, and 15% at the smallest. When the liquid hydrogen target was emptied the rates dropped to 15%, arising mainly from the target windows. Because of the difficulties of making a subtraction, we have included this additional material in the beam as part of the target. The estimate of our systematic errors includes a factor to reflect the uncertainty in this procedure.

Multiple Coulomb scattering of the secondary electrons and pions was significant only at the lowest secondary momenta and at the two smaller production angles where the angular acceptance of the beam was smallest. This process was manifest as an apparent reduction in the measured pion production rate as the external radiator thickness was increased. In principle, the data can be corrected for this effect. However, since those data points with nonnegligible multiple-scattering corrections also have very large external production rates (R_E) they have been dropped from the analysis except to the extent that they provide a consistency check on the external production rate. We have eliminated those data points with $R_E>25\times10^{-4}$ per 0.01 radiation length, where R_E is defined by $(e^++e^-)/(\pi^++\pi^-)$.

The main component in R_D is electrons from Dalitz decay of π^0 mesons. This effect may be calculated to first order by computing the quantity $(\frac{1}{2}R\times\frac{9}{7})R_E$ where R is the Dalitz-decay branching ratio (taken to be[8] 0.011 96), the factor $\frac{9}{7}$ is the ratio between radiation length and conversion length for pair production, and the factor $\frac{1}{2}$ is included because the two-photon π^0 decay is primarily responsible for R_E. This method assumes that the kinematics of the electrons from the internal conversion of the virtual photon in Dalitz decay are the same as those of the electrons produced by external conversion of real photons.

More precise values for the Dalitz contribution were determined by Monte Carlo calculation. The Monte Carlo calculation simulated electron production by both external and internal conversion (Dalitz decay) into the acceptance of the spectrometer. The π^0-production cross sections were derived from a Sanford-Wang parametrization of π^+ and π^- cross sections in p-Be collisions previously measured at the ZGS[9] and the assumption that the π^0 cross section is the average of the π^+ and π^- cross sections. This assumption is justified by the results of a bubble chamber experiment at this primary energy[10] (which also showed that at least 98% of all secondary photons originate from π^0 decay).

Dalitz decay was simulated using the virtual-photon mass spectrum and angular distributions given by Joseph.[8] The calculation took account of the partial screening effect in the Bethe-Heitler pair production[11] and also determined the contribution of Compton scattering to the e^- production.

The data for the external conversion rates (R_E) are shown in Fig. 2. The agreement between the data and the calculations gives us confidence in our treatment of external photon conversion.

Our results for direct electron production (R_D) are shown in Fig. 3(a) after subtraction of the Dalitz decay and Compton scattering contributions.

Dalitz decays of η and ω mesons also contribute to the direct-electron signal. However, their production rates are less than 2%[10] and (7 ± 1)%[12] of π^0 production, respectively. To first order, the η and ω Dalitz decays have the same branching ratio as the π^0 Dalitz decay. For this reason, our π^0 Dalitz subtraction, taken to be proportional to the external conversion rate R_E, also corrects approximately for electrons from these other Da-

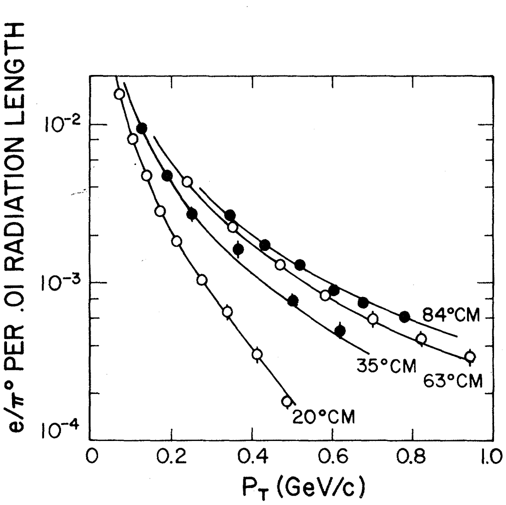

FIG. 2. Ratio of external electron production (R_E) per 0.01 radiation length of added aluminum radiator vs momentum transfer P_T. The lines are the results of a Monte Carlo calculation.

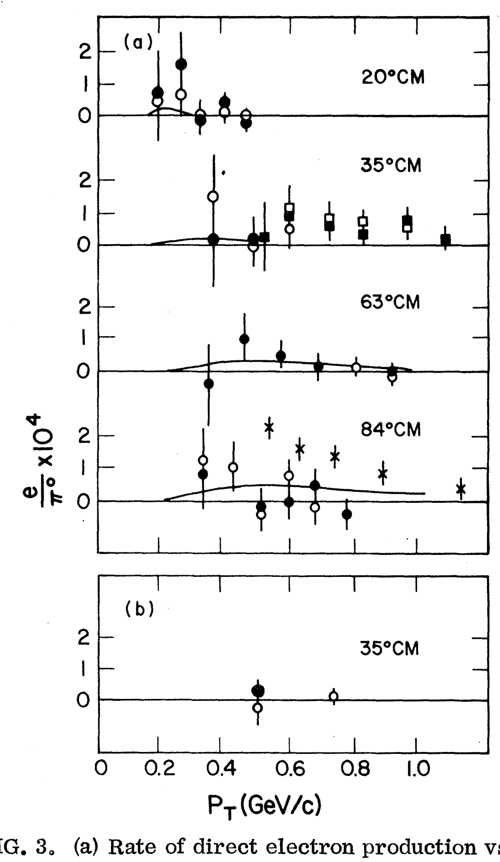

FIG. 3. (a) Rate of direct electron production vs momentum transfer P_T. Solid data points are for e^-, open points for e^+. Circles and squares represent data from beryllium and hydrogen targets, respectively. The crosses are the data of Ref. 4. The lines are estimates of the vector-meson contribution. (b) Production rate of single electrons or of electrons accompanied by an additional wide-angle electron.

litz decays.

The solid lines in Fig. 3(a) are estimates of the direct-electron rates from e^+e^- decays of the vector mesons with cross sections taken from published data[12] and using the known e^+e^- branching fractions.[13] These estimates are accurate to within a factor of 2. K_{e3} decays yield at most a contribution of 2×10^{-5} to R_D at the lowest momentum transfer, falling rapidly at higher momentum transfer. The decay $\pi\rightarrow e\nu$ makes a negligible contribution.

The data from Ref. 4 are also shown in Fig. 3(a). In order to compare the data, we have adjusted those results by interpolation between 10 and 15 GeV/c incident momentum and also converted them to the ratio e^+/π^0 rather than e^+/π^- using the relative π^+ and π^- production rates measured in this experiment.

For a portion of the run at 35° c.m., the magnet $M1$ was replaced by a 2-m-long Cherenkov counter filled with ethylene at atmospheric pressure. An electron traversing the counter produced approximately 15 photoelectrons. By observing the pulse-height spectrum in this counter in coincidence with single electrons observed in the spectrometer we were able to detect the presence or absence of any additional electron originating in the interaction provided that the pair opening angle was small ($\lesssim 0.05$ rad). The beam intensity was reduced to $\sim 3\times10^9$ protons per pulse to minimize accidental coincidences and pulse pile-up in the counter. For a given run, the pulse-height spectrum from the Cherenkov counter was fitted to determine the number of events with only one electron in the counter. The resulting (single e)/π ratio was again a function of added radiation length, because of multiple scattering of the second electron in an electron pair. The slope, however, was typically 5% of that observed from all events. Electrons from small-angle pairs were subtracted by extrapolating to zero radiation length. This subtraction introduced very little uncertainty because of the small slopes. The e/π ratios remaining after subtraction are shown in Fig. 3(b). These data using the upstream Cherenkov counter agree with those data using all electrons and provide an important check of the extrapolation method used with the bulk of the data.

The results of this experiment may be summarized as follows:

(1) We observe no evidence for a rise in e/π at progressively lower momentum transfers. This is in disagreement with the results of Ref. 4. We have no explanation of this disagreement.

(2) The data are consistent with zero direct electron production at an incident momentum of 12 GeV/c, other than from well-known sources. At 84° c.m., the averaged e/π ratio is $(-0.30\pm0.20)\times10^{-4}$ while we obtain $(0.07\pm0.08)\times10^{-4}$ as the average over all data points. A continuum pair spectrum could be accomodated by the data where the pair masses are less than approximately 100 MeV/c^2 and with a total integrated rate less than 0.25×10^{-4} of the total π^0 rate.

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