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Search for the Direct Production of Positrons by 256- and 800-MeV Protons*

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The invariant cross sections for direct positron production in p-p collisions have been measured to be $E\,d^3\sigma/dp^3 = (-3\pm2)\times10^{-32}$ and $(-14\pm12)\times10^{-32}$ cm$^2/sr$ (GeV/c)^2 at 256 and 800 MeV, respectively. These results are consistent with zero ($e^+/\pi^+ \lesssim 3\times10^{-6}$ at 800 MeV) and are in marked contrast to results at higher energies.

Several experimental groups[1-4] have reported inclusive lepton production in hadron collisions with a ratio to inclusive pion production of order 10^{-4}, which is in excess of that expected from known weak and electromagnetic processes. Although most of the data have been obtained at very high energies, Kirz[5] has reported significant yields for incident proton momenta as low as 10 GeV/c. Attempts to explain direct leptons by the leptonic decays of vector mesons[6] (including the ψ) or of a new charged boson[7] require a threshold in energy; models which involve a continuum of lepton-pair masses[8] can predict single-lepton yields down to small energies. It is thus of considerable interest to establish whether a threshold exists for direct lepton production.

We report here the results of an experiment studying p-p collisions with protons of 256- and 800-MeV incident kinetic energy. At 800 MeV all leptons should be the result of pion decays and p-p bremsstrahlung, and at 256 MeV the only known lepton production mechanism is via p-p bremsstrahlung. We find no evidence for direct lepton production at either energy.

Figure 1 is a diagram of the apparatus located in the external proton beam at the Clinton P. Anderson Meson Physics Facility (LAMPF). A beam of approximately 10^9 protons/sec was incident on a liquid-hydrogen (LH_2) target 6.5 cm long. The beam intensity was monitored by a three-counter telescope and by an ionization chamber. A magnetic spectrometer detected positrons produced at 60° in the laboratory, corresponding to 93°

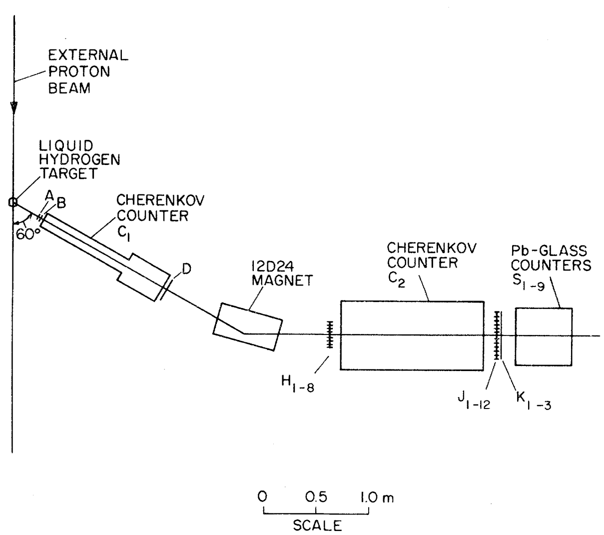

FIG. 1. The experimental apparatus.

(79°) in the p-p center-of-mass system at 800 (256) MeV. The acceptance of the spectrometer was $d\Omega dp = 0.6$ sr MeV/c at 800 MeV for momenta between 200 and 420 MeV/c. (The kinematic limit for positrons is 383 MeV/c.)

Counters B and D defined the solid angle of the spectrometer, while counter A defined the furthest point from the target at which a photon could create a positron event via pair production. Positrons were detected rather than electrons to avoid backgrounds from Compton scattering. Moderate momentum resolution (10%) was provided by two hodoscopes, H and J, following the 12D24 magnet. The hodoscope counters were made from Pilot 425 plastic and detected π's and e's via Cherenkov light but were insensitive to the high flux of scattered protons. Two isobutane-filled Cherenkov counters, C_1 and C_2, identified positrons; each was measured to have a positron efficiency of 98% and a pion efficiency of $\leq 10^{-4}$. An array of lead-glass shower counters provided redundant positron identification.

At 800 MeV, the major sources of positrons are roughly equal contributions from Dalitz decay of π^0's and pair conversion of π^0 decay photons. (The contribution from π^+ decays is negligible.) The material intrinsic to the apparatus, M_0, available to convert photons consisted primarily of the LH_2, the target walls, and counter A. M_0 corresponded to a $(5.50 \pm 0.08) \times 10^{-3}$ conversion probability for 200-MeV photons. The contribution from the LH_2 was held constant by monitoring the beam position to ± 1 mm throughout the experiment. The effective thickness of A was determined to be 0.78 ± 0.04 of its total thickness by taking the ratio of the pulse height corresponding to the discriminator threshold to the pulse height of two electrons which traversed the entire counter. To determine the positron yield from pair conversions in the apparatus, data were taken with one, two, and four radiators of 0.613-g/cm^2-thick Mylar placed between the target and counter A. The yield in each momentum bin after correction for empty-target rates, dE/dx, and radiative losses is well fitted by straight lines as a function of extra radiator. The slope and intercept of these straight lines are the positron yield per radiator, $\Delta N/\Delta M$, and the yield with no radiators added, N_0.

The contribution from Dalitz decay is similar to the conversion of $(5.85 \pm 0.03) \times 10^{-3}$ of the photons. A Monte Carlo calculation which simulates the apparatus and the details of Dalitz decay and pair production is used to determine η, the relative detection efficiency for positrons from these two processes. Combining the above information, the positron yield in excess of that due to π^0 decay is given by

$$N_{e^+} = N_0 - \frac{\Delta N}{\Delta M} M_0 \left\{ 1 + \frac{\eta}{2} \frac{\Gamma(\pi^0 \to e^+ e^- \gamma)}{\Gamma(\pi^0 \to \gamma\gamma)} \right\}.$$

Even though we explicitly assume that all photons come from π^0 decay, the analysis technique will subtract out positrons originating from any photon source with internal conversion coefficient similar to that of the π^0. We estimate that $< 10\%$ of the photon flux is from p-p bremsstrahlung, but we are not able to exclude an anomalously large production of single photons. Electron-positron pairs could be detected by studying the pulse-height distributions in the A and B counters. However, since the pair detection efficiency is very sensitive to the details of the pair production mechanisms (both Dalitz decay and photon conversion), eliminating pairs would not improve our analysis.

The results for the direct positron yield as a function of momentum are shown in Fig. 2. The error bars represent the statistical errors and the uncertainties in the radiative corrections. Combining all of the data from $p_\perp = 175$ to 310 MeV/c yields an invariant cross section of $E\,d^3\sigma/dp^3 = (-14 \pm 12) \times 10^{-32}$ cm^2/sr (GeV/c)^2 at 800 MeV. The observed positron yields with no radiators added correspond to an invariant cross section which falls exponentially from $\sim 10^{-28}$ to 10^{-31}

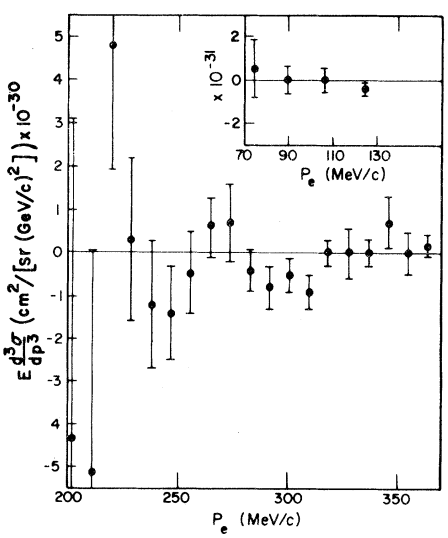

FIG. 2. Direct positron yields at 800 MeV as a function of the positron momentum. The inset shows the yields at 256 MeV.

$cm^2/sr\ (GeV/c)^2$ over this momentum interval.

There are, in addition, errors due to uncertainties in the amount of material available for photon conversion, in the value of the Dalitz ratio and the pair cross section, and in η. These errors contribute an uncertainty of $\pm 10\times 10^{-32}$ $cm^2/sr\ (GeV/c)^2$, and there is an overall normalization uncertainty of 20%.

Since p-p collisions at 256 MeV are below threshold for π^0 production, the observed positrons come primarily from π^0 production in the target walls. Photons from these π^0's convert in the available material, and when the target is full, an additional number convert in the LH_2. Thus there will be a difference between target-full and target-empty yields even if no positrons are produced in the hydrogen. The photon flux was measured directly at 110° by a lead-glass shower counter and has been extrapolated to 60° using the expected angular distributions of p-p bremsstrahlung.[9] The internal-conversion coefficient for these photons is calculated using the prescription of Kroll and Wada.[10] The net direct positron cross section is obtained by subtracting the bremsstrahlung yield from the data, corrected for conversions in the hydrogen. The results are shown in Fig. 2. The momentum range included is from 65 MeV/c (the lower limit of the spectrometer acceptance) to 136 MeV/c (the kinematic limit at this energy). The weighted average invariant cross section is $E\,d^3\sigma/dp^3 = (-3\pm 2)\times 10^{-32}$ cm^2/sr $(GeV/c)^2$ at 256 MeV. The contribution of all systematic errors is less than 20% of the statistical error.

The 256- and 800-MeV data are thus consistent with no direct lepton production. In Fig. 3 the 95%-confidence-level cross-section limits are compared with previous data. The high-energy data fall on a smooth curve as a function of $p_\perp$, while our data fall two orders of magnitude below that curve. The π^+ invariant production cross section at 800 MeV fits smoothly onto a universal curve, shown in Fig. 3, connecting the higher-energy pion data when plotted as a function of $p_\perp$.[11,12] This is true despite the difference between the production mechanism at this energy and that dominant at higher energies, so the e^+/π^+ ratio still provides a useful comparison. Using this universal curve for the pion yield, we obtain $e^+/\pi^+ < 3\times 10^{-6}$ (95% confidence) at 800 MeV.

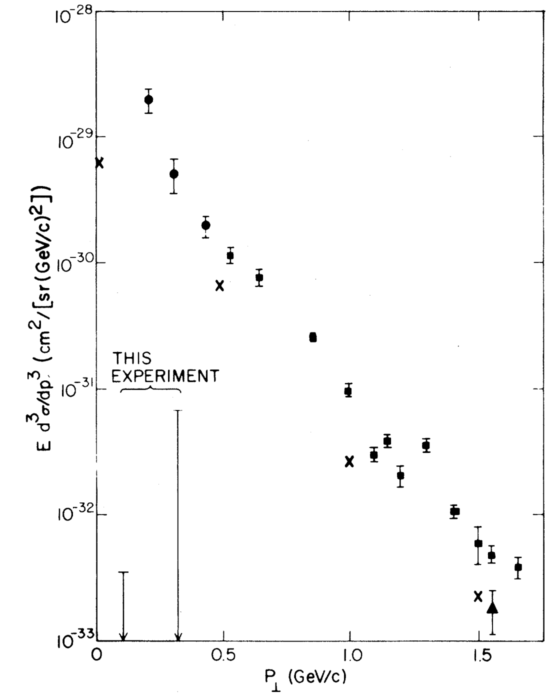

FIG. 3. The invariant cross section for direct lepton production and for π^+ production as a function of $p_\perp$. Lepton data are shown for $\sqrt{s} = 52.7$ GeV, $\theta^* = 30°$ (circles, Ref. 1); $\sqrt{s} = 52.7$ GeV, $\theta^* = 90°$ (squares, Ref. 2); and $\sqrt{s} = 24$ GeV, $\theta^* = 90°$ (triangles, Ref. 3). The π^+ invariant cross section ($\times 10^{-4}$) at $\theta^* = 90°$ is indicated by crosses. The results from this experiment at both 256 and 800 MeV are also plotted. The pion cross section is independent of $\sqrt{s}$.

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Detection of π-μ Coulomb Bound States*

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We have observed atoms consisting of a pion and a muon produced in the decay $K_L{}^0 \to (\pi\mu)_{\rm atom}\nu$. This represents the first observations of an atom composed of two unstable particles and of an atomic decay of an elementary particle.

We report herewith the detection of hydrogen-like atoms consisting of a negative (or positive) pion and a positive (or negative) muon in a Coulomb bound state. These pion-muon atoms are formed when the π and μ from the decay $K_L{}^0 \to \pi\mu\nu$ have sufficiently small relative momentum to bind. We have observed these atoms, produced at relativistic velocities, in the course of an experimental program at the Brookhaven National Laboratory alternating-gradient synchrotron.

The basic properties of these atoms are calculable by the formalism used to describe the hydrogen atom. The reduced mass of the system is 60.2 MeV/c^2, its Bohr radius is 4.5×10^{-11} cm, and the binding energy of the $1S_{1/2}$ state is 1.6 keV. To our knowledge, the first calculation of the branching ratio $R = [K_L{}^0 \to (\pi\mu)_{\rm atom} + \nu]/(K_L{}^0 \to {\rm all})$ was carried out by Nemenov,[1] who found that $R \sim 10^{-7}$, with the precise value depending upon the form factors of $K_L{}^0$ decay. We will present our results on R in a subsequent paper; only the evidence related to the detection of these atoms is discussed herein.

The prime motivations for the experiment are twofold. Firstly, the value R is proportional to the square of the π-μ wave function at very small distances and so an anomaly in its value may be indicative of an anomaly in the π-μ interaction. Secondly, by passage of the atoms through a magnetic field at high velocity ($\gamma \sim 10$) the $2S$ states should be depopulated through Stark mixing with the $2P$ states and consequent decay to the $1S$ states. The extent of this depopulation will be highly dependent upon the vacuum polarization shift (Lamb shift) of the $2S$ states relative to the $2P$ states and may, if measured with some accuracy, lead to a determination of the pion charge radius.

The $K_L{}^0$ particles which give rise to our "atomic beam" are produced by a 30-GeV proton beam striking a 10-cm beryllium target (see Fig. 1). A large vacuum tank and a connecting evacuated beam channel lead out to the detection equipment. A 4-ft steel collimator prevents any direct line of sight from the detector system to the target. This is to prevent background particles, in par-