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Direct e^+e^- Pair Production by 360 GeV/c π^- in Hydrogen

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We report on direct production of positron-electron pairs by 360-GeV/c pions incident on the Fermilab 30-in. hydrogen bubble chamber. These high-energy data are the first with liquid hydrogen, and are shown to be in agreement with quantum-electrodynamic calculations. For the region of four-momentum transfer considered, quantum electrodynamics predicts essentially equal contributions from production in the Coulomb field of the nucleus and the atomic electron.

We report the first high-energy experiment on direct production of electron-positron pairs using a liquid-hydrogen target. Previous experiments have been performed using nuclear emulsions,[1] and in a 200-GeV/c π^- experiment using the Fermilab 30-in. bubble chamber filled with a Ne-H mixture.[2] The emulsion experiments have suggested that the quantum-electrodynamic (QED) calculations predict a larger probability for pair production than is observed experimentally. The 200-GeV/c π^- Ne-H data are reported to be in good agreement with a QED calculation which uses only the leading diagram for pair production.

In our experiment, with a 360-GeV/c π^- beam and the Fermilab 30-in. bubble chamber filled with hydrogen, approximately 100 000 pictures have been scanned for three-prong candidates for direct pair production and all such candidates have been measured and reconstructed in space. Events are accepted as e^+e^- pairs if (i) one or both lepton candidates are identified by ionization in the bubble chamber *or* the pair has an opening angle consistent with zero degrees; (ii) the beam track is undeflected within the measuring resolution of ± 1 mrad; and (iii) no "lepton candidate" track in the event can be classified as a hadron either by ionization or by the presence of a secondary hadronic interaction on the track. In order to reject hadronic events further it is necessary to apply an upper limit in pair energy for later analysis. This was set at 2 GeV, and no attempt was made to decide on the disposition of ambiguous events above 2 GeV. Fiducial-volume restrictions were then applied for normalization purposes, resulting in 493 events which are accepted as direct e^+e^- pair production events with energy less than 2 GeV. It is also necessary to include a lower limit on the lepton momentum in order to minimize scanning and measuring biases. This cut, established at $p(\text{lepton}) \geq 5$ MeV/c, excludes 34 events, leaving 459 events with pair energy between 10 MeV and 2 GeV, and with each lepton having a momentum of ≥ 5 MeV/c. Of the events discarded with pair energy above 2 GeV, twelve were unambiguous e^+e^- pairs.

There is a possible background of pair production from bremsstrahlung photons. Such photon pairs originating in the liquid hydrogen, however, are less by the factor α^2 than the direct process under consideration. If the photon originates in the bubble-chamber front window or other high-Z material further upstream, then this background could be substantial as a result of the Z^2 dependence of the cross section. Since the angular distribution of bremsstrahlung photons is peaked at 0° relative to the beam, a subsequently produced e^+e^- pair might appear on film to originate on the π^- beam track. However, because of the 25 kG magnetic field the beam track will be sufficiently deflected at the center of the bubble chamber so as to result in nonoverlap with the photon produced pair. While some e^+e^- pairs of this type escaped detection at the scan phase of analysis, the improved resolution during measurement revealed six such events which were rejected. Therefore, we feel that this is not a significant background.

The possible background from electrons in the beam has been checked by scanning the beam track downstream of the pair vertex for secondary hadronic interactions. The detected rate of such secondary interactions is consistent with the known πp cross section. In addition, as reported in connection with another study from the same film,[3] the beam muon contamination was measured to be approximately 1%. A simple calculation using the known beam geometry shows the expected electron flux to be considerably less than the muon flux.

To calculate the direct pair production in hydrogen, we start with the QED expression for the "second order" process shown in Fig. 1, which is the dominant diagram [other diagrams are down by a factor of $(m_e/m_\pi)^2$]. In deriving the equations used we followed the treatment of Kel'ner[4] in making an approximation for the forward pair production. We used the s-wave hydrogen wave function to calculate the pair production amplitude from the nucleus and from the electron, where shielding effects have been included in each term. When the production is off of the nucleus the recoil energy is negligible and the final nuclear and

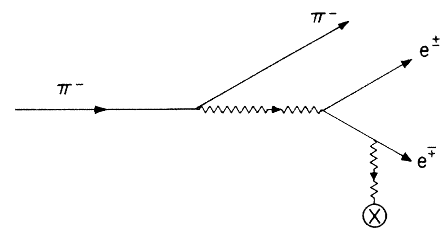

FIG. 1. Diagram for direct pair production.

atomic states are taken to be identical with the initial state (elastic). When a pair is produced from the electron, however, the recoil is such that the electron can be left in an excited or even a free state (inelastic). These inelastic effects have been treated according to the method of Wheeler and Lamb.[5]

A straightforward calculation of the diagram shown in Fig. 1 yields an expression for $d\sigma/dW$ (where W is the total energy of the lepton pair), in terms of a three-dimensional integral[6] which must be done numerically. We display the separate elastic and inelastic (as defined above) contributions to the cross section as follows:

$$d\sigma = [Z^2|1 - F(q)|^2 + Z(1 - |F(q)|^2)]K. \quad (1)$$

The effects of shielding are determined by $F(q)$ which is defined as

$$F(q) = (1 + \tfrac{1}{4}a_0^2 q^2)^{-2}, \quad (2)$$

where q^2 is the square of the four-momentum of the virtual photon exchanged between one of the final leptons and the hydrogen atom, and a_0 is the Bohr radius. Z is the atomic number, and K is a complicated function of all four-momenta, except that K does not depend on either the target or its four-momentum. We have calculated the complete expression with and without shielding for the conditions of our experiment. The maximum effect of the shielding is less than 10% and reaches this value only near the 2-GeV limit of our data. From Eq. (1) it is clear that in the limit as q^2 goes to zero, the ratio of inelastic to elastic (or equivalently atomic electron to nuclear) pair production goes as $1/Z$. Thus for neon the inelastic contribution can at most be 10%, whereas in our case with hydrogen this limit is 50%. While no attempt was made to scan the film specifically for visible recoiling electrons, in fact in approximately 2% of the accepted events such recoil electrons were observed with momenta greater than 5 MeV/c.

The laboratory energy distribution ($W = E_+ + E_-$) of the pairs in our experiment is shown in Fig. 2.

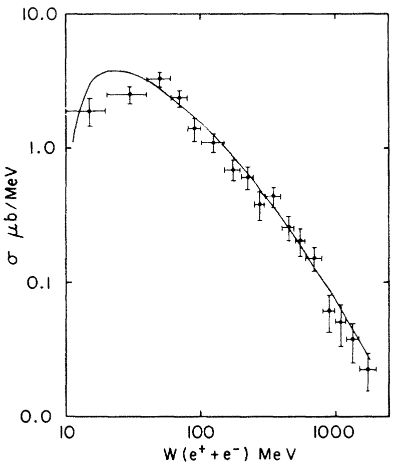

FIG. 2. Energy distribution of directly produced pairs. The smooth curve shows the results of QED calculation described in the text.

Within the limits 20 MeV $\leqslant W \leqslant$ 2 GeV, our data integrate to 494 ± 23 μb for direct pair production. There is approximately an 8% scale uncertainty in the normalization of the experimental data and this scale uncertainty is not reflected in the point-to-point errors shown in the figure. The solid curve is the result of the QED calculation, including shielding effects and including the restriction that both lepton momenta be $\geqslant$ 5 MeV/c. Possible discrepancies below 40 MeV are attributed to experimental cuts and subsequent resolution edge effects, in particular the restriction that both lepton momenta be $\geqslant$ 5 MeV/c. The agreement between the data and the theory shown in Fig. 2 is excellent.

We have defined an energy partition variable as $(E_+ - E_-)/(E_+ + E_-)$. For three different regions of $E_+ + E_-$, the cross section is plotted as a function of the absolute value of the energy partition in Figs. 3(a)–3(c). The solid curves shown in these figures are the result of the calculation from our QED approximation. The energy regions were chosen to yield approximately equal statistics while still showing the changing shape as a function of the pair energy. The agreement is again excellent. Although we have shown the cross section as a function of the absolute value of the partition variable, we have examined it from −1 to +1 and it is symmetric. This gives us confidence that we have considered all relevant forms of background. We have also examined the effective mass of the electron-positron pairs, and we find the distribution to be indistinguishable from photon pair production measurements; however, the widths of both distributions are overwhelmingly dominated by the measurement resolution.

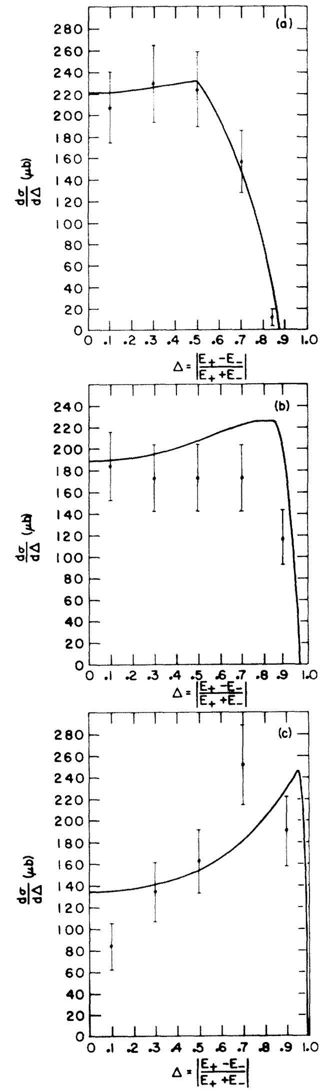

FIG. 3. Distribution in the partition variable $|(E_+ - E_-)/(E_+ + E_-)|$ for (a) 20 MeV $< E_+ + E_- <$ 80 MeV, (b) 80 MeV $< E_+ + E_- <$ 300 MeV, and (c) 300 MeV $< E_+ + E_- <$ 2 GeV. The smooth curves indicate the results of the QED calculations described in the text.

The theoretical calculation used by Fortney *et al.*[2] for comparison with the 200-GeV/c Ne-H data was based upon an expression due to Ternovskii.[7] That expression uses a Thomas-Fermi wave function, and is intended to be applicable to heavier nuclei. However, we have also used this expression with the Z dependence given by $Z(Z+1)$ to account for pair production off of the electron and the proton, and applied it to our data. This calculation also agrees with our data and differs from the more exact QED calculation by at most a few percent. It is interesting to note that although the general considerations of Ternovskii[7] and Wright[8] suggest that the screening effect may be important,[9] in this experiment for pair energies less than 2 GeV the screening effect is small [see Eq. (1)]. Finally, we emphasize that the inelastic contribution is conspicuously important, accounting for almost one-half of the cross section for direct pair production. In conclusion, direct pair production from 360-GeV/c π^-p interactions for pair energies between 40 and 2000 MeV is in good agreement with QED.

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$$\gamma \equiv \frac{m_e W}{\alpha E_+ E_-}\left(1+\frac{m_\pi^2}{E_1 E_2}\frac{E_+E_-}{m_e^2}\right),$$

with E_1 and E_2 the lab energies of the incoming and outgoing pions. γ is actually the minimum of the quantity $(a_0^2 q^2)^{1/2}$ of Eq (2). In our case the minimum value of γ ranges from 9.33 to 0.22.

Radiative Decays of $\psi(3095)$ and $\psi(3684)$†

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We present the inclusive photon spectra observed in $\psi(3095)$ and $\psi(3684)$ decays. The decay $\psi(3684) \to \gamma\chi(3415)$ is observed with a branching fraction of 0.075 ± 0.026. Evidence is presented for three intermediate states in the decay sequence $\psi(3684) \to \gamma\gamma\psi(3095)$ with masses of 3504, 3543, and 3455 or 3340 MeV.

States of even charge conjugation intermediate in mass to $\psi(3095)$ ($\equiv \psi$) and $\psi(3684)$ ($\equiv \psi'$) have been observed in radiative decays of $\psi(3684)$ by their hadronic decays[1,2] and by their decays to $\gamma\psi$.[3,4] There is also evidence from DESY for a state below the ψ.[5] We present here the inclusive photon spectra from 142 000 ψ and 309 000 ψ' events observed in the Stanford Linear Accelerator Center—Lawrence Berkeley Laboratory magnetic detector at SPEAR; the detector and its trigger criteria have been described previously.[6] We also present results on intermediate states in $\psi' \to \gamma\gamma\psi$ decays based on a data sample three times larger than for our previous Letter.[3]

Photons are detected by their conversion to electron-positron pairs in material near the interaction region. The effective converter consists of the vacuum pipe, two scintillation counters, and two proportional chambers, a total of 0.052 radiation length of material located 8 to 22 cm from the beam axis. The conversion products are tracked through the 4-kG magnetic field by