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

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ABSTRACT

We report on direct production of positron-electron pairs from 360 GeV/c pions incident on the Fermilab 30 inch hydrogen bubble chamber. These high energy data are the first with liquid hydrogen, and are shown to be in agreement with QED calculations.

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-inch bubble chamber filled with a Ne-H mixture[2]. The emulsion experiments have suggested that the Quantum Electrodynamics (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 using the Fermilab 30-inch bubble chamber filled with hydrogen, approximately 100,000 pictures have been scanned for 3-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 <u>or</u> the pair has opening angle consistent with zero degrees; (ii) the beam track is undeflected within the measuring resolution of $\pm$ 1 mr; 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 further reject hadronic events 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 (lepton) $\gtrsim$ 5 MeV/c, excludes 34 events, leaving 459 events

with pair energy between 10 MeV and 2 GeV, and with each lepton having momentum $\geqslant$ 5 MeV/c. Of the events discarded with pair energy above 2 GeV, 12 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 due to the Z^2 dependence of the cross section. As 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, due to the 25 kilogauss magnetic field the beam track will be sufficiently deflected at the center of the bubble chamber so as to result in non-overlap 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 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 figure 1, which is the dominant diagram (other diagrams are down by a factor of $(\frac{m_e}{m_\pi})^2$). 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 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 straight forward calculation of the diagram shown in figure 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

$$d\sigma = \{Z^2|1 - F(q)|^2 + Z\,(1 - |F(q)|^2)\}\,K \qquad (1)$$

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

$$F(q) = [1 + \frac{a_o^2 q^2}{4}]^{-2} \quad , \qquad (2)$$

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_o 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.

The laboratory energy distribution ($W = E_+ + E_-$) of the pairs in our experiment is shown in Figure 2. Within the limits 20 MeV $\leq W \leq$ 2 GeV, our data integrates 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 $\geq$ 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 $\geq$ 5 MeV/c. The agreement between the data and the theory shown in Figure 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 Figures 3a through 3c. 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.

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 the fact that the inelastic contribution is conspicuously important, accounting, in fact, 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 are in good agreement with QED.

We would like to express our appreciation to our scanning and measuring staffs and to the staff at Fermilab, particularly the staff of the 30-inch bubble chamber. One of us (B.-L. Y) would like to thank Dr. Yung-Sue Tsai for a useful conversation.

References and Footnotes:

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9.) According to Ref. 7, the screening effect is important if $\gamma \lesssim 1$ and is not important for $\gamma \gtrsim 1$, where

$\gamma \equiv \frac{m_e W}{\alpha E_+ E_-} \left(1 + \frac{m_\pi^2}{E_1 E_2} \frac{E_+ E_-}{m_e^2}\right)$, E_1 and E_2 are the lab energies of the incoming and outgoing pions. γ is actually the minimum of the quantity $\sqrt{a_o^2 q^2}$ of Eq. (2). In our case the minimum value of γ ranges from 9.33 to 0.22.

Figure Captions

(1) Diagram for direct pair production.

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

(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.

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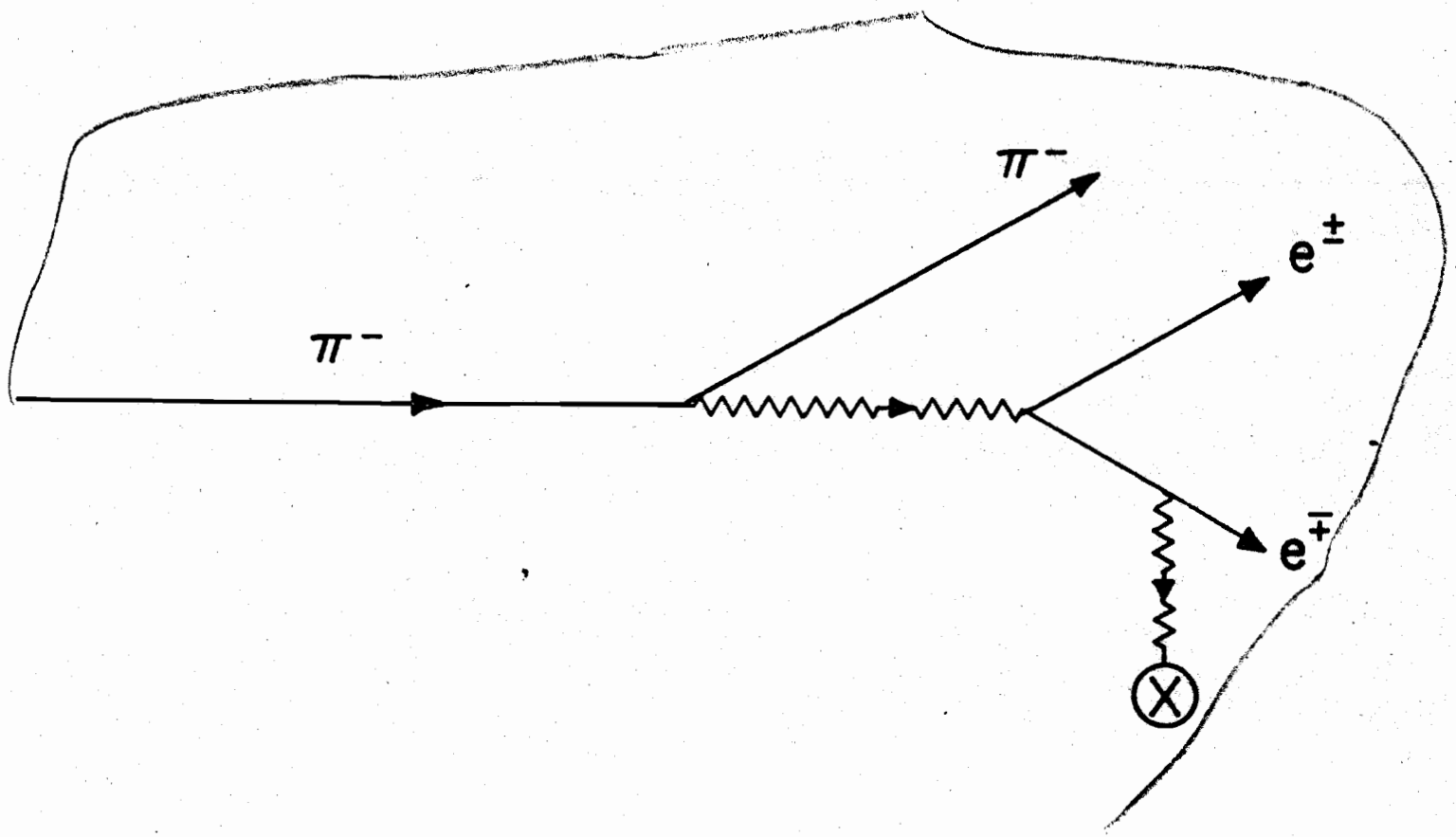

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Figure 1

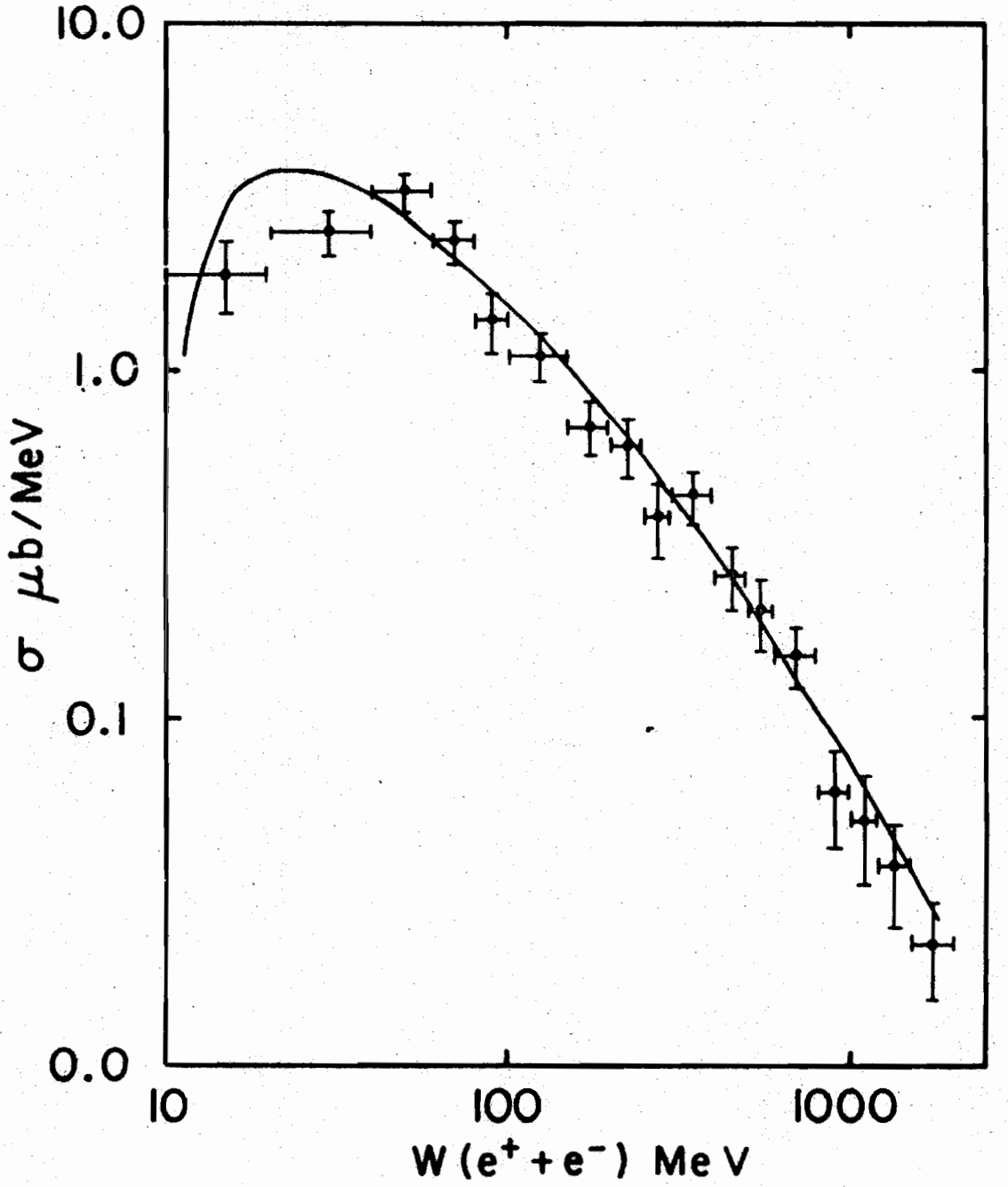

Figure 2

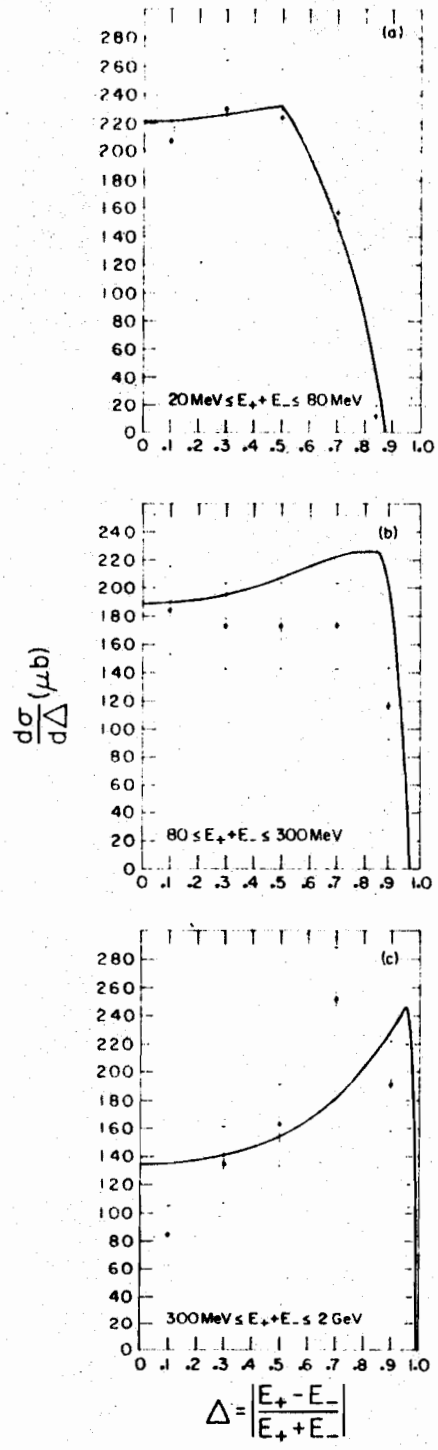

Figure 3