Measurement of $\pi^- p \to n e^+ e^-$ at 300 MeV/c and a search for scalar and vector bosons heavier than the π^0

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We report the results of an experimental study of the reaction $\pi^- p \to n e^+ e^-$ at 300 MeV/c over the range of e^+e^- effective mass from 140 to 160 MeV/c^2. The observed number of events is only one quarter of that expected from a calculation of inverse pion electroproduction. We see no evidence for the production of light Higgs bosons or any other particle that decays into e^+e^- in this mass region.

In an experiment designed to detect the rare decay $\pi^0 \to e^+e^-$ we have observed e^+e^- pairs from the interactions of 300-MeV/c π^- in hydrogen.[1] The e^+e^- pairs with effective masses (M) less than m_{π^0} result primarily from π^0 decays (including Dalitz decays and decays with photons converted by pair production and Compton scattering). Pairs with effective masses greater than m_{π^0} are expected from the reaction $\pi^- p \to n e^+ e^-$ (inverse pion electroproduction) and can also result from the production and decay of a scalar or vector boson heavier than a π^0. In this paper we compare the observed M^2 distribution with that expected from $\pi^- p \to n e^+ e^-$ and present upper limits for the production of such bosons.

The experiment and the data-analysis procedures have been described in detail elsewhere.[1] The magnetic spectrometer that was used to identify and momentum analyze the e^+ and e^- is shown in Fig. 1. The M^2 distribution for the region $19\,000 \leq M^2 \leq 25\,000$ (MeV/c^2)^2 that is shown in Fig. 2(a) contains 151 events. The M^2 in Fig. 2 is ~3% lower than the true square of the e^+e^- effective mass due to the energy losses suffered by the electrons and positrons in the hydrogen target and in the spectrometer. From studies of the distribution of the distance of closest approach for the e^+ and e^- trajectories we estimate that 17 ± 5 of these events are due to accidental coincidences. The experimentally determined M^2 distribution for accidental coincidences is shown in Fig. 2(b). From detailed Monte Carlo studies we expect 6 ± 3 events from π^0 decay to populate the M^2 region of Fig. 2, all in the lowest three bins. The remaining

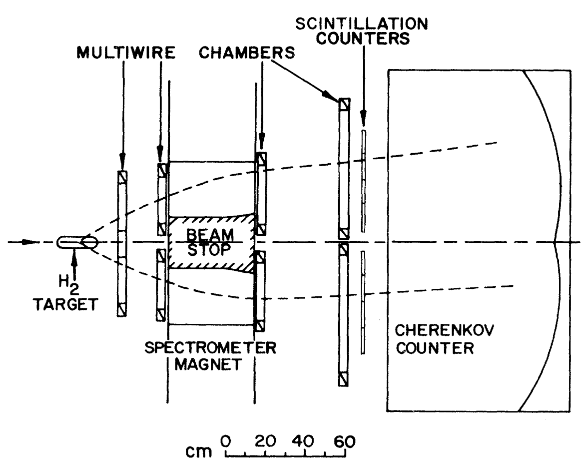

FIG. 1. Plan view of the apparatus to detect e^+e^- pairs. The π^- beam was incident from the left. Typical particle trajectories for a good event are shown by the dashed curves.

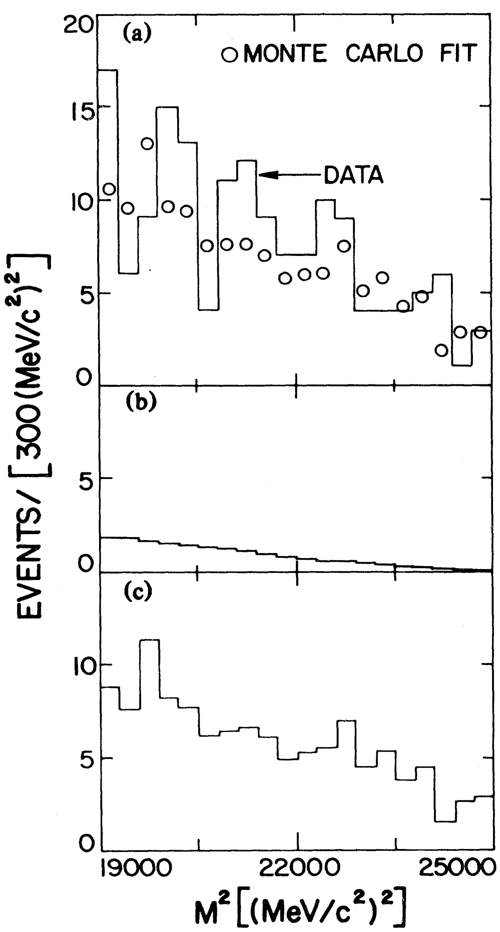

FIG. 2. (a) M^2 distribution for the data and for the Monte Carlo fit. (b) Contribution from accidental coincidences. (c) Contribution from $\pi^- p \to n e^+ e^-$.

events are due to $\pi^- p \rightarrow ne^+e^-$ and to the production of any boson in this mass range decaying into e^+e^-.

We compare the observed M^2 distribution with that expected from the theoretical treatment of inverse pion electroproduction by Dombey and Read[2] in which the amplitudes are calculated using PCAC (partial conservation of axial-vector current). The shape of this distribution as calculated by a Monte Carlo simulation of the experiment is shown in Fig. 2(c). A fitting program determined the strength of the $\pi^- p \rightarrow ne^+e^-$ signal that led to a least-squares fit to the M^2 distribution for the data (excluding accidentals and π^0 decays). The fit shown in Fig. 2(a) includes fixed contributions from accidentals and π^0 decay modes. The agreement between the data and the Monte Carlo is quite good; we obtain a χ^2 of 21 for 19 degrees of freedom. The observed average total energy of the e^+e^- pair is 314.5 MeV, which is in excellent agreement with the result of the Monte Carlo calculation.

While the shape of the distributions agree, the theory predicts we should observe many more events. The theoretical cross section, using the model of Ref. 2, for $19\,000 \leq M^2 \leq 25\,000$ (MeV/c^2)^2 and $0° \leq \theta^* \leq 30°$, where θ^* is the virtual-photon angle in the π-p c.m. system, is

$$\Delta\sigma^T = \int_{M^2=19\,000}^{25\,000} \int_{\phi=0}^{2\pi} \int_{\theta^*=0}^{30°} \frac{d^2\sigma}{dM^2 d\Omega} dM^2 d\Omega = 10.9 \text{ nb} . \tag{1}$$

The acceptance of our apparatus falls slowly with increasing M^2 over the range given above but is strongly peaked at $\theta^* = 0°$ as shown in Fig. 3. The average θ^* for our data is 9.7°. The experimentally determined cross section is obtained from the equation

$$N_E = N_{\pi^-} N_p \int\int \frac{d^2\sigma^E}{dM^2 d\Omega} \eta(M^2, \Omega)\, dM^2 d\Omega \ , \tag{2}$$

where N_E is the number of observed $\pi^- p \rightarrow ne^+e^-$ events, N_{π^-} is the number of incident π^-, N_p is the number of target protons/cm^2, and $\eta(M^2, \Omega)$ is the apparatus detection efficiency as a function of M^2 and Ω. The integral in Eq. (2) is evaluated using the Monte Carlo simulation program.

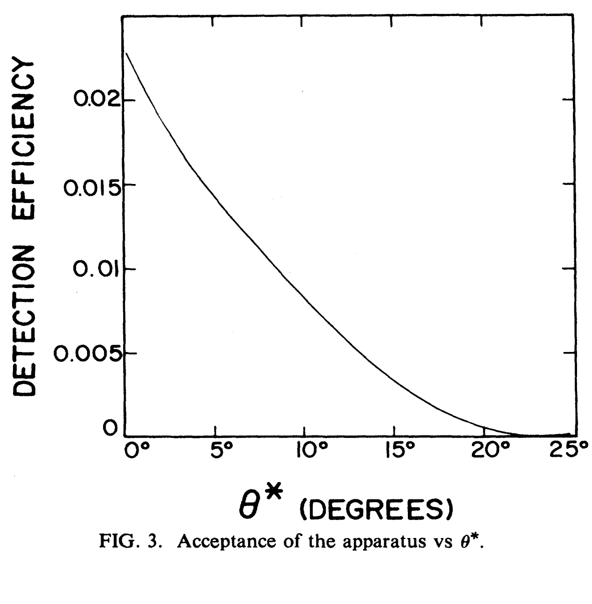

FIG. 3. Acceptance of the apparatus vs θ^*.

In this integral, $\eta(M^2, \Omega)$ is weighted by the double-differential cross section. Assuming that the relatively gentle variation of this cross section over the small regions of θ^* and M^2 to which we were sensitive is correctly described by the theory, we find $\langle \eta(M^2, \Omega) \rangle = (1.39 \pm 0.05) \times 10^{-3}$.

Using the observed number of $\pi^- p \rightarrow ne^+e^-$ events (128 ± 13), $N_{\pi^-} = (3.23 \pm 0.16) \times 10^{13}$, and $N_p = 1.05 \times 10^{24}$/cm^2, we obtain

$$\Delta\sigma^E = \int\int \frac{d^2\sigma^E}{dM^2 d\Omega} dM^2 d\Omega = 2.7 \pm 0.3 \text{ nb} \ . \tag{3}$$

Thus the ratio of measured to theoretical cross section is 0.25 ± 0.03.

We have investigated whether other data also disagree with the theory. There have been two previous measurements of $\pi^- p \rightarrow ne^+e^-$, one[3] at 275 MeV and the other[4] at 164 MeV. In both cases we have used the model of Ref. 2 to calculate $d^2\sigma/d\Omega_1 d\Omega_2$, where Ω_1 (Ω_2) is the laboratory solid angle for the electron (positron). A Monte Carlo program simulated the acceptance of the appropriate apparatus. For each experiment we reproduced the published distributions in cosθ^*, M^2, and other kinematic variables. At 275 MeV accepted events had $\theta_1, \theta_2 \simeq 90°$ and $E_{e^+}, E_{e^-} > 40$ MeV. The theoretical result is $d^2\sigma/d\Omega_1 d\Omega_2 = 2.5$ nb/sr^2, to be compared with an experimental value of 3.4 ± 1.0 nb/sr^2. At 164 MeV the calculation yields $d^2\sigma/d\Omega_1 d\Omega_2 = 3.0$ nb/sr^2 while the experimental result is $5.1^{+1.1}_{-1.4}$ nb/sr^2, for $\theta_1, \theta_2 \simeq 70°$ and $E_{e^+}, E_{e^-} > 50$ MeV. Thus the model of Dombey and Read is able to reproduce adequately the other $\pi^- p \rightarrow ne^+e^-$ data. The major difference between our data and those of Refs. 3 and 4 is that only forward, nearly real, virtual photons contribute in our experiment while the others can detect a much wider range of virtual-photon masses and angles. The typical M^2 for our experiment is much smaller than that in Ref. 3 [$50\,000 < M^2 < 120\,000$ (MeV/c^2)^2] and in Ref. 4 [$30\,000 < M^2 < 75\,000$ (MeV/c^2)^2]. The 275-MeV experiment has also been compared to another theoretical approach in which the amplitudes are evaluated via dispersion relations.[5] The agreement is excellent.

The theory can also be compared with data for the reaction $\pi^- p \rightarrow n\gamma$ and its inverse,[6] which corresponds to our reaction with $M^2 = 0$ and a laboratory photon energy of 340 MeV. The best of these data are shown in Fig. 4 along with the calculation of Dombey and Read. The calculation appears to adequately reproduce the θ^* dependence for $\theta^* \geq 45°$ although it is $\sim 20\%$ too high in absolute normalization. However, the experimental results do not agree well with each other forward of 45° in the π-p c.m. system, and there are no data forward of 30°, which is just the region populated by our data. For comparison, we extrapolate our result to $M^2 = 0$, giving a value

$$\frac{d\sigma}{d\Omega}(\gamma n \rightarrow \pi^- p) = 5.8 \pm 0.7 \ \mu\text{b/sr}$$

for $\theta^* = 10°$. This value is consistent with a linear extrapolation of existing data from larger θ^*. However, theoretical calculations[8] indicate that the cross section should increase **substantially as θ^* decreases below 30°.** ***Note added in proof.*** **We have plotted our events divided by the acceptance given in Fig. 3 versus θ^* and find**

$$\frac{d\sigma}{d\Omega}(\theta^* = 0) \Big/ \frac{d\sigma}{d\Omega}(\theta^* = 20°) = 0.55 \pm 0.25 \ .$$

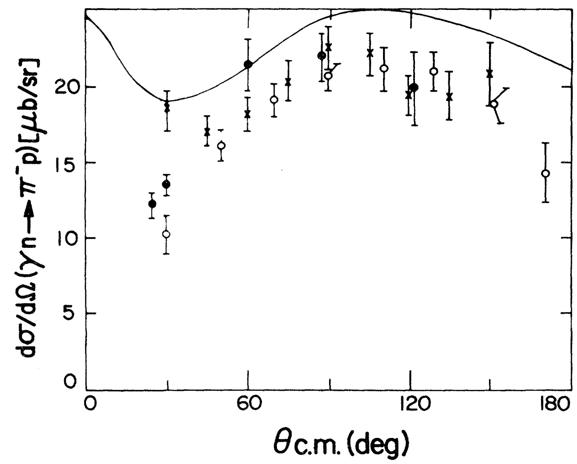

FIG. 4. Differential cross section for $\gamma n \to \pi^- p$ for a photon energy of 340 MeV in the laboratory. The data are from: ● Tran *et al.*; × Fujii *et al.*; ○ Benz *et al.* (Ref. 7). The solid curve is the calculation of Dombey and Read (Ref. 2) for $M^2=0$.

This is additional evidence that the cross section for $\pi^- p \to n e^+ e^-$ decreases at small angles. The corresponding angular distribution for events with smaller M agrees with the known distribution for $\pi^- p \to n\pi^0$.

In addition to the study of $\pi^- p \to n e^+ e^-$, we have looked for structure in our data that would indicate the presence of a particle in this mass range decaying into an e^+e^- pair. For example, this reaction has been suggested as a possible means to search for light scalar Higgs bosons.[9] Other particles that could produce an enhancement in the M^2 distribution are the spin-1 partner of the Goldstone fermion that occurs in some supersymmetric theories,[10] and the axion.[11]

We see no statistically significant evidence for an enhancement in the M^2 distribution. The resolution in M^2 is calculated to be $\simeq 1500$ $(\text{MeV}/c^2)^2$ full width at half maximum from Monte Carlo studies.[1] A boson with narrow width that decayed into an e^+e^- pair would then produce an enhancement spanning several bins in Fig. 2. We obtain an upper limit for the production of any particle X^0 which decays into e^+e^-, of

$$\frac{d\sigma}{dt}(\pi^- p \to X^0 n)\frac{\Gamma(X^0 \to e^+e^-)}{\Gamma(X^0 \to \text{all})} < 3.5\times 10^{-32}\ \text{cm}^2/\text{GeV}^2 \quad (90\%\ \text{C.L.})$$

for $140 \le M_{X^0} \le 160$ MeV/c^2. To obtain this limit, we have assumed that the shape of the differential cross section is similar to that for $\pi^- p \to \pi^0 n$, and that the X^0 lifetime is shorter than $\sim 10^{-9}$ sec. For Higgs bosons with masses between 135 and 200 MeV/c^2, the dominant decay channel is expected to be e^+e^- and the lifetime should be less than 10^{-10} sec. An estimate of the production cross section[9] is given as

$$\frac{d\sigma}{dt}(\pi^- p \to H^0 n) \simeq \frac{G_F m_\pi^2}{s|p_\pi^{\text{c.m.}}|^2} = 1.2\times 10^{-33}\ \text{cm}^2/\text{GeV}^2 ,$$

where $p_\pi^{\text{c.m.}}$ is the pion momentum and s is the total energy in the $\pi^- p$ c.m. system. Our sensitivity is not adequate to test this prediction for Higgs bosons.

In conclusion, we have examined the distribution of the square of the e^+e^- effective mass for the reaction $\pi^- p \to n e^+ e^-$ at 300 MeV/c. The shape of the distribution is in agreement with that expected from theoretical calculations but we observe fewer events than predicted. This could be because the cross section for forward $\gamma n \to \pi^- p$ is significantly smaller than previously thought. We see no evidence for the production of Higgs bosons or any exotic bosons with masses between 140 and 160 MeV/c which decay into e^+e^-.

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