Determination of the Branching Ratio of the Decay $\pi^0 \to e^+e^-$

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Employing the decay chain $K^+ \to \pi^+\pi^0$, $\pi^0 \to e^+e^-$ we have observed the decay $\pi^0 \to e^+e^-$. With a signal sample of $\approx$21 events we measure the branching ratio for $\pi^0 \to e^+e^-$ to be (6.9 $\pm$2.3 $\pm$ 0.6) $\times$ 10^{-8}, normalized to the decay $K^+ \to \pi^+\pi^0$, $\pi^0 \to e^+e^-\gamma$. This result is consistent with the unitarity lower bound and the published 90% confidence level upper limit of 13×10^{-8}.

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Measurement of the decay $\pi^0 \to e^+e^-$ (π^0_{ee}) has a checkered history. To lowest order in QED, a calculation of the ratio of the rate of this decay to that of the dominant decay of the π^0, $\pi^0 \to \gamma\gamma$ yields a lower limit of 4.7×10^{-8} [1], the"unitarity lower bound." Early measurements by Fischer *et al.* of $(22.3^{+24}_{-11}) \times 10^{-8}$ [2] and Frank *et al.* of $(17\pm7)\times10^{-8}$ [3] were large enough to suggest that the decay mechanism for this process was outside of the standard model [1]. A more recent measurement by the SINDRUM Collaboration at the Paul Scherrer Institute yielded an upper limit of 13×10^{-8} [4] which is now the value accepted by the Particle Data Group [5]. Employing the decay chain $K^+ \to \pi^+\pi^0$; $\pi^0 \to e^+e^-$ (K_{ee}) in an experiment at the Brookhaven Alternating Gradient Synchrotron (AGS), E851, we have made a new measurement of the rate of $\pi^0 \to e^+e^-$ normalized to $K^+ \to \pi^+\pi^0$; $\pi^0 \to e^+e^-\gamma$, Dalitz decays ($K_{\rm Dal}$).

The apparatus, described in previous publications [6] and shown in Fig. 1, resided in an unseparated beam of momentum 6 GeV/c containing about 10^7 K^+ per AGS pulse of about 1-s duration every 3 s, accompanied by 2×10^8 π^+ and protons. The detector consisted of a dipole spectrometer (M2) with two proportional chamber packages on either side (P1–P4). This system was capable of determining the momentum of trajectories, P, with a resolution of $\delta P/P \simeq 0.01P$ where P is in units of GeV/c and ranged from 0.6 to 4.0 GeV/c. Particle identification consisted of tandem Čerenkov counters (C1L, C2L; C1R, C2R) filled with hydrogen at atmospheric pressure, plus a Pb-scintillator shower counter 11 radiation lengths thick. Electrons were required to register in both Čerenkov counters and to have a signal in the shower counter whose amplitude was consistent with the measured energy (momentum) in the spectrometer. Pions were required to not register in either Čerenkov counter. The probability of π or e particle misidentification was less than 10^{-5}. Events selected were those having $\pi^+e^+e^-$ particle identification and particle trajectories consistent with having originated from a common vertex. The reader is referred to previous publications for details of data analysis [6,7].

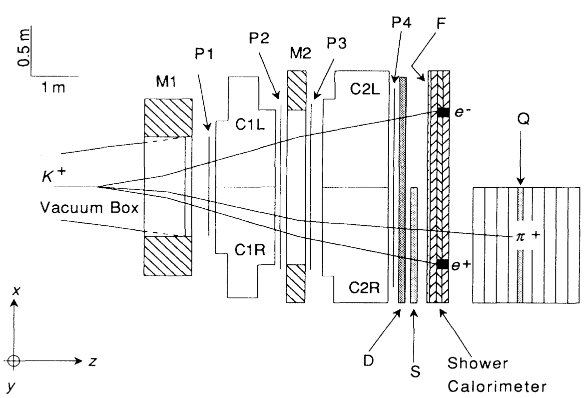

FIG. 1. Plan view of the apparatus showing spectrometer magnets M1-M2, the proportional chamber packages P1-P4, Čerenkov counters C1(L-R), C2(L-R), and scintillation hodoscopes F, D, S, Q.

The Dalitz decay of the π^0 has been well studied experimentally [8] as well as theoretically [9]. For $K_{\rm Dal}$ decays and other decay modes under investigation, i.e., K_{ee} , $K^+ \to \pi^+\pi^0$, $\pi^0 \to e^+e^-e^+e^-$ ($K_{\rm DDal}$), and direct $K^+ \to \pi^+e^+e^-$ ($K_{\pi ee}$), the observed final state charged particles are the same. Hence it was natural to use the $K_{\rm Dal}$ mode to verify our understanding of the detector and for it to serve as a normalization for the measurement of other decays. To wit, for any decay mode K_i the branching ratio is

$$B(K_i) = (N_i/N_{\rm Dal})B(K_{\rm Dal})R. \qquad (1)$$

Here $N_{\rm Dal}$ refers to the number of experimentally observed $K_{\rm Dal}$ events in the normalization sample, N_i to the number of K_i decays, and R to the ratio of the net experimental acceptance of the $K_{\rm Dal}$ normalization sample to that of K_i as determined by Monte Carlo calculation.

Figure 2 shows the e^+e^- invariant mass (M_{ee}) distribu-

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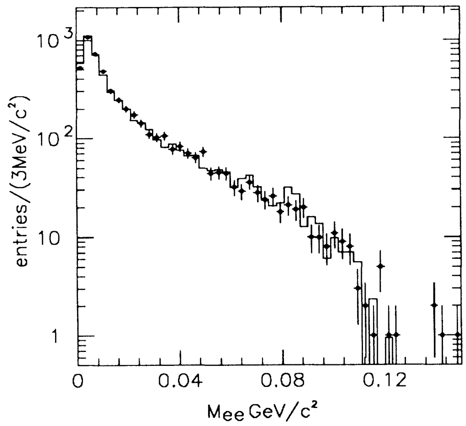

FIG. 2. M_{ee} distribution for Dalitz data and Monte Carlo simulation (histogram) for $0.400 < M_{\pi ee} < 0.450$ GeV/c^2.

tion of events with πee invariant mass $0.400 < M_{\pi ee} < 0.450$ GeV/c^2 [10]. The histogram is the Monte Carlo simulation of Dalitz decays including radiative corrections [11], the accepted π^0 form factor of $a = 0.033$ [5,12], and a correction due to a 1% contamination in the data sample from $K^+ \to \pi^0\mu^+\nu; \pi^0 \to e^+e^-\gamma$. The value of χ^2 comparing data and simulation is 73 for 49 degrees of freedom. For the normalization sample of Dalitz decays we selected events from this distribution with $M_{ee} < 0.05$ GeV/c^2, so chosen to be away from the region of the Dalitz decay spectrum which is affected significantly by radiative corrections [11] or uncertainties in the form factor of the π^0. This resulted in $N_{\rm Dal} = (1.05 \pm 0.02) \times 10^6$ data events for normalization.

Figure 3(a) displays $M_{\pi ee}$ vs M_{ee} for events which in addition to the above selection criteria were required to have the reconstructed K^+ momentum vector be consistent with having originated at the production target. One sees a clear band of $K_{\pi ee}$ events with $M_{ee} > 0.15$ GeV/c^2. Employing the approximately 820 events in the signal region of Fig. 3(a) with $M_{ee} > 0.15$ GeV/c^2 and $0.474 < M_{\pi ee} < 0.504$ GeV/c^2 in the above described manner yielded new measurements of the $K_{\pi ee}$ branching ratio and its form factor [13] both consistent with the previous measurement [7]. Using the number of events in the region from $0.450 < M_{\pi ee} < 0.474$ GeV/c^2 and $M_{ee} > 0.150$ GeV/c^2 we estimate the background in the signal region to be $\approx$0.009 event per (MeV/c^2)^2.

Figure 3(b) displays the $M_{\pi ee}$ distribution for events in Fig. 3(a); Fig. 3(c) shows the M_{ee} distribution. The histograms in these two figures are results of a Monte Carlo calculation with the Dalitz decay events in this region ($K_{\text{Dal-hi}}$), the $K_{\rm DDal}$ events, and the $K_{\pi ee}$ events normalized as described above. For $K_{\pi ee}$ we used our newly measured $K_{\pi ee}$ branching ratio and form factor [13]. The values of χ^2 for these two plots are 108 and 139 for 79 and 89 degrees of freedom, respectively.

For $M_{ee} < 0.150$ GeV/c^2 Fig. 3(a) is dominated by $K_{\text{Dal-hi}}$ and $K_{\rm DDal}$ decays. These events have $M_{\pi ee}$ less than the kaon mass (M_K) due to the undetected photon or e^+e^- pair. As the momentum of these missing particles approaches zero, however, $M_{\pi ee}$ approaches M_K. These events are the dominant background to K_{ee}, but their effect can be reduced by requiring the events to have come from the production target and by selecting events with high values of $M_{\pi ee}$. The requirement that the three tracks come from a common vertex removes the background from photon conversions in the material downstream of the evacuated decay volume.

Figure 4 is a series of M_{ee} distributions in the M_{ee} region of the π^0 mass with $M_{\pi ee} < 0.504$ GeV/c^2 and successively higher cuts on the lower bound of $M_{\pi ee}$. In each, the solid histogram is a normalized composite of Monte Carlo simulations of $K_{\text{Dal-hi}}$, $K_{\rm DDal}$, and $K_{\pi ee}$ decays without inclusion of the K_{ee} process. The dashed histogram is the same including our best fit value of the K_{ee} branching ratio. Cutting at $M_{\pi ee} > 0.49$ GeV/c^2, Fig. 4(c) optimizes the statistical significance of the signal. For this figure the χ^2 value obtained by comparing the simulation with data reduces from 35 without the in-

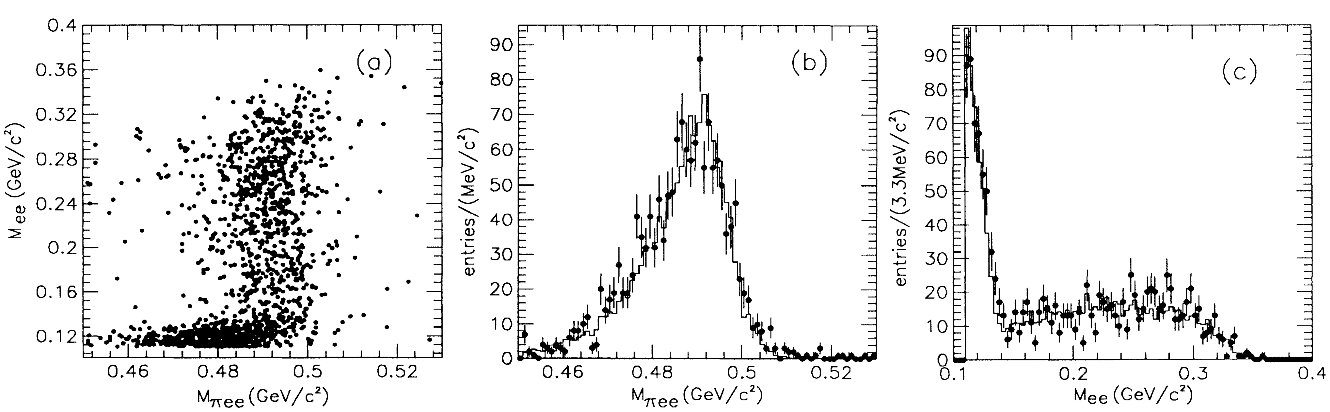

FIG. 3. (a) Scatter plot of $M_{\pi ee}$ vs M_{ee} for selected events. (b) $M_{\pi ee}$ and (c) M_{ee} distribution of these events with Monte Carlo simulation (histograms).

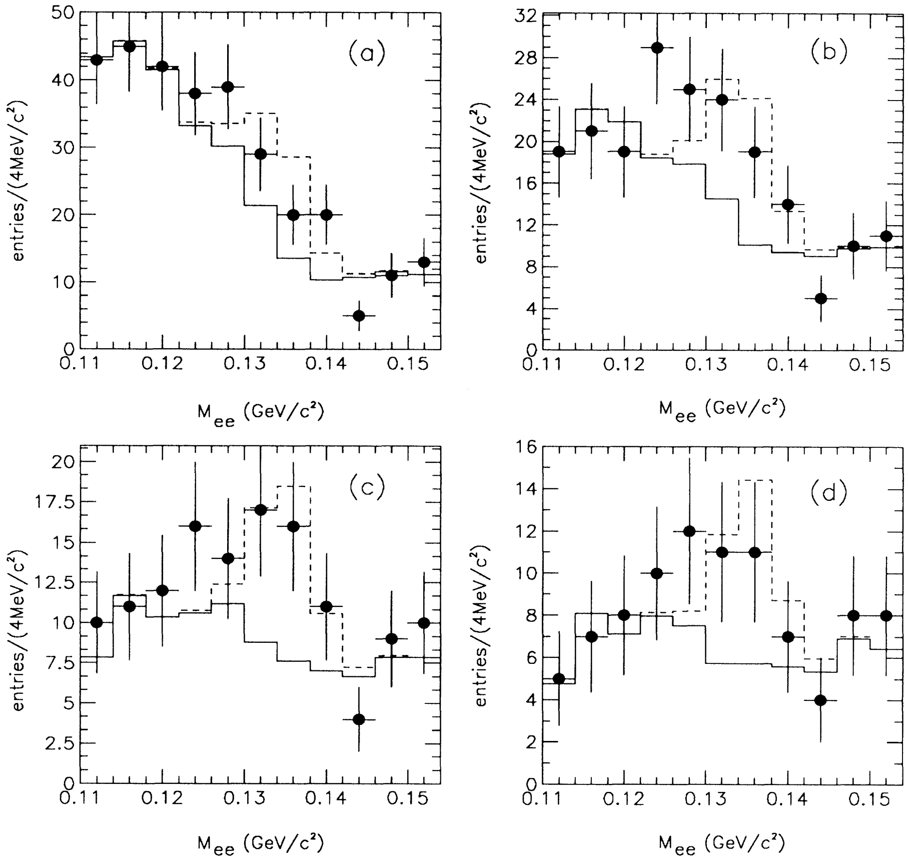

FIG. 4. A series of M_{ee} distributions in the M_{ee} region of the π^0 with $M_{\pi ee} < 0.504$ GeV/c^2. (a) $M_{\pi ee} > 0.483$ GeV/c^2, (b) $M_{\pi ee} > 0.487$ GeV/c^2, (c) $M_{\pi ee} > 0.490$ GeV/c^2, (d) $M_{\pi ee} > 0.492$ GeV/c^2. The solid histogram is the Monte Carlo simulation with no K_{ee}. The dashed histogram includes K_{ee}.

clusion of Monte Carlo K_{ee} to 12 with the inclusion, for 10 degrees of freedom.

In searching for the π^0_{ee} decay , we employed a peak finding algorithm which used three input components: the solid histogram Monte Carlo mass spectra of Fig. 4(c), a Monte Carlo M_{ee} spectrum for a short lived neutral particle, X^0, of mass M_{X^0} decaying to e^+e^-, and the data (with error bars) shown in Fig. 4(c). The algorithm sought to maximize the likelihood of the fit of the sum of the two Monte Carlo M_{ee} spectra to the data spectrum by varying the number of events in the X^0 peak, N_{X^0}, and its central mass, M_{X^0}. The result of this analysis was N_{X^0}=21 ± 7 at M_{X^0}=(0.134 ± 0.001) GeV/c^2. M_{X^0} was thus found to be consistent with the mass of the π^0. This result is not significantly changed by radiative corrections [14] to the M_{X^0} spectrum.

Assuming these surplus events correspond to the decay chain, $K^+ \to \pi^+\pi^0$; $\pi^0 \to e^+e^-$, we measure the branching ratio using the technique described above. In Eq. (1) the number of events for this mode, N_{ee}, is 21 ± 7; $N_{\rm Dal} = (1.05 \pm 0.02) \times 10^6$; and $R = 0.286 \pm 0.005$. The quoted uncertainties are statistical only; systematic uncertainties are discussed below. Since the observation of π^0_{ee} and Dalitz decays of the π^0 both involve π^0 mesons resulting from $K^+_{\pi2}$ decays, the $K^+_{\pi2}$ branching ratio does not affect Eq. (1). For the quantity labeled $B(K_{\rm Dal})$ we thus use the π^0 Dalitz decay branching ratio $(1.198 \pm 0.032) \times 10^{-2}$ [5]. Evaluating Eq. (1) with these numbers results in $B(\pi^0_{ee}) = (6.9 \pm 2.3) \times 10^{-8}$. The analysis was repeated for the other plots in Fig. 4 and the results were found to be consistent with this value.

The systematic uncertainties in the measurement are mainly due to uncertainties in the ratio of the experimental acceptances of the two decays $K_{\rm Dal}$ and K_{ee}, R. Since the particles detected in the two modes are the same, the fractional uncertainty in R, $\delta R/R$, due to uncertainties in detector efficiencies and acceptance are significantly smaller than the fractional uncertainties in these quantities themselves. Because of differences in the distribution of kinematic variables for the two decays, however, there exist differences in the track populations in different parts of the detector. This gives rise to a $\delta R/R$ which we estimate to be ±0.068. Another systematic uncertainty arises from uncertainty in parameters of beam elements. This affects the target requirement which is made for the $\pi^0 \to e^+e^-$ sample but not for the Dalitz sample. We estimate $\delta R/R$ from this effect to be ± 0.038. The number of direct $K_{\pi ee}$ events in the K_{ee} sample depends on the value of the $K_{\pi ee}$ branching ratio and form factor, λ. Using the measured uncertainties in these quantities, we estimate the uncertainty in N_{ee} to be ± 0.8 event. Adding these uncertainties in quadrature yields a systematic uncertainty in $B(\pi^0_{ee})$ of 0.6×10^{-8}. Other uncertainties such as those due to uncertainties in the number of background events, or the form factors for Dalitz or double Dalitz decays, are sufficiently smaller than those mentioned as to be inconsequential.

Our final result is thus $B(\pi^0_{ee}) = (6.9 \pm 2.3 \pm 0.6) \times 10^{-8}$, where the first uncertainty is statistical and the second systematic. Applying the bremsstrahlung radiative correction as prescribed in Ref. [14] to our simulation of π^0_{ee} increases this branching ratio to $(8.0 \pm 2.6 \pm 0.6) \times 10^{-8}$. These results are consistent with the unitarity bound and also the published 90% confidence level upper limit of 13×10^{-8} [4].

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[1] L. Bergström, Z. Phys. C **14**, 129 (1982).
[2] J. Fischer *et al.*, Phy. Lett. **73B**, 364 (1978).
[3] J. Frank *et al.*, Phys. Rev. D **28**, 423 (1983).
[4] C. Niebuhr *et al.*, Phys. Rev. D **40**, 2796 (1989).
[5] Particle Data Group, K. Hikasa *et al.*, Phys. Rev. D **45**, S1 (1992).
[6] N. J. Baker *et al.*, Phys. Rev. Lett. **59**, 2832 (1987); C. Campagnari *et al.*, Phys. Rev. Lett. **61**, 2062 (1988); A. M. Lee *et al.*, Phys. Rev. Lett. **64**, 165 (1990).
[7] C. J. Alliegro *et al.*, Phys. Rev. Lett. **68**, 278 (1992).
[8] F. Farzanpay *et al.*, Phys. Lett. B **278**, 413 (1992), and references therein.
[9] M. Lambin and J. Pestieau, Phys. Rev. D **31**, 211 (1985); D. Beder, Phys. Rev. D **34**, 2071 (1986); G. Tupper, Phys. Rev. D **35**, 1726 (1987), and references therein.
[10] The upper limit avoids $K_{\pi ee}$ decays. The lower limit reduces contamination from $K^+ \to \pi^0 \mu^+ \nu$, $\pi^0 \to e^+ e^- \gamma$, and eliminates $K^+ \to \pi^+ \pi^0 \pi^0$, $\pi^0 \to e^+ e^- \gamma$.
[11] K. O. Mikaelian and J. Smith, Phys. Rev. D **5**, 1763 (1972).
[12] H. Behrend, Z. Phys. C **49**, 401 (1991).
[13] A. Deshpande *et al.*, "A New Measurement of the Branching Ratio and Form Factor of the Decay $K^+ \to \pi^+ e^+ e^-$" (to be published).
[14] L. Bergström, Z. Phys. C **20**, 135 (1983).