Measurement of the Parity of the Neutral Pion through the Decay $\pi^0 \to e^+e^-e^+e^-$

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Abstract

DRAFT

We present a new measurement of the double Dalitz decay $\pi^0 \to e^+e^-e^+e^-$. The angular distribution of the decay products is sensitive to the π^0 parity and any possible CP violating contributions to the decay. Some 30 511 candidate decays were observed in a sample of $K_L \to \pi^0\pi^0\pi^0$ decays in flight collected by the KTeV-E799 experiment at Fermi National Accelerator Laboratory. Both the momentum dependence and the CP properties of the $\pi^0\gamma^*\gamma^*$ vertex were extracted from the final state phase space distribution. We confirm the pseudoscalar π^0 parity, and place a limit on scalar contributions to the coupling of less than 3.3% assuming CPT conservation. We have also measured the branching ratio $B(\pi^0 \to e^+e^-e^+e^-) = (3.26 \pm 0.18) \times 10^{-5}$.

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The parity of the neutral pion has been measured indirectly by studying negative pions captured on deuterium [1, 2]. The observed reactions imply that the π^- is a pseudoscalar and that the parities of the π^- and the π^0 are the same. It has long been known that the decay $\pi^0 \to \gamma\gamma$ in principle offers a direct means of measuring the π^0 parity through the polarizations of the photons [3, 4]. Given that there are no available methods for measuring the polarization of a high-energy photon, this measurement has never been performed. However, it was soon noted that the decay $\pi^0 \to e^+e^-e^+e^-$, which proceeds through a two-photon intermediate state, is sensitive to the parity of the pion since the plane of a Dalitz pair is correlated with the polarization of the virtual photon [5, 6]. A 1962 study of 206 $\pi^0 \to e^+e^-e^+e^-$ events reported that the observed distribution of the e^+e^- planes was consistent with a pseudoscalar pion and disfavored a scalar pion at the level of 3.6 standard deviations [7]; this experiment also produced a measurement of the branching ratio of this decay, which remains the most precise result to date.

We report here a new measurement of $\pi^0 \to e^+e^-e^+e^-$ which makes use of three important improvements over the previous experiment: an increased statistical sample of 30,511 events, consideration of full $\mathcal{O}(\alpha^2)$ radiative corrections, and a proper treatment of the exchange contribution to the matrix element. With these advances, we have tested for a scalar contribution in the coupling with a sensitivity of a few percent. We have also measured for the first time the momentum dependence of the coupling in this decay mode. The precision is comparable to existing $\pi^0 \to e^+e^-\gamma$ results. In addition, we present a new measurement of the $\pi^0 \to e^+e^-e^+e^-$ branching ratio, taking into account radiative effects.

The coupling of the pion to two photons has the following general form [8]:

$$\begin{aligned} C_{\mu\nu\rho\sigma} \propto & f(x_1, x_2)[\cos\zeta\epsilon_{\mu\nu\rho\sigma} \\ & \qquad + \sin\zeta e^{i\delta} \left(g_{\mu\rho}g_{\nu\sigma} - g_{\mu\sigma}g_{\nu\rho}\right)], \end{aligned} \tag{1}$$

where the first term is the traditional pseudoscalar coupling and the second term introduces a scalar coupling with a mixing angle ζ and a phase difference δ. The momentum-dependent form factor, $f(x_1, x_2)$, has been studied in the decay $\pi^0 \to e^+e^-\gamma$ [9–11], where the quantity of interest has been the slope parameter a of the first-order Taylor expansion $f(x, 0) = 1 + ax$, with $x_i = q_i^2/M_{\pi^0}^2$. Here we use a form factor parametrizaton based on the model of D'Ambrosio, Isidori, and Portolés (DIP) [12], but with an additional constraint that ensures the coupling vanishes at large momenta [13]. In terms of the remaining free parameters, the form factor is:

$$f_{\rm DIP}(x_1, x_2; \alpha) = \frac{1 - \mu(1+\alpha)(x_1 + x_2)}{(1 - \mu x_1)(1 - \mu x_2)}, \tag{2}$$

where $\mu = M_{\pi^0}^2 / M_\rho^2 \approx 0.032$. In the limit of small x, this coincides with the Taylor expansion provided $a = -\mu\alpha$.

The π^0 decays used in this analysis are the result of $K_L \to \pi^0\pi^0\pi^0$ decays in flight collected by the KTeV-E799 experiment at Fermilab. The signal mode, denoted by $K_L \to \pi^0\pi^0\pi^0_{\rm DD}$, has a signature of four charged particles consistent with electrons and with a combined invariant mass comparable to the π^0 mass, plus four photons that are compatible with two additional π^0's. Furthermore, the eight–particle state has an invariant mass consistent with the K_L and total momentum in the direction of the kaon direction line of flight.

The branching ratio measurement makes use of a normalization mode in which two pions decay via $\pi^0 \to e^+e^-\gamma$ and the third $\pi^0 \to \gamma\gamma$. This mode, $K_L \to \pi^0\pi^0_{\rm D}\pi^0_{\rm D}$, has the same final state particles as the signal mode and is again identified by finding the proper combinations of particles to make three pions with a total momentum consistent with the kaon. The similarity of these modes is important for reducing systematic effects in the branching ratio measurement, but also allows each to be a background to the other.

Radiative corrections complicate the definition of the Dalitz decays in general. We define the signal mode $\pi^0 \to e^+e^-e^+e^-$ to be inclusive of radiative final states where the squared ratio of the invariant mass of the four electrons to the neutral pion mass $x_{4e} \equiv (M_{4e}/M_{\pi^0})^2$ is greater than 0.9, while events with $x_{4e} < 0.9$ are treated as $\pi^0 \to e^+e^-e^+e^-\gamma$. For normalization, the decay $\pi^0 \to e^+e^-\gamma$ is understood to include all radiative final states, for consistency with previous measurements of this decay [15].

Other final states of the $K_L \to \pi^0\pi^0\pi^0$ decay can become backgrounds to either the signal or normalization mode if one or more photons convert to an e^+e^- pair in the detector material: one $\pi^0 \to e^+e^-\gamma$ with two $\pi^0 \to \gamma\gamma$ and one conversion, or three $\pi^0 \to \gamma\gamma$ with two converted photons. These modes again have the same final state, but can be distinguished statistically since the externally produced pairs tend to have smaller invariant masses than the internal pairs.

The E799-II configuration of the KTeV experiment, designed to search for direct *CP* violation in rare kaon decays, received 800 GeV/c protons on a BeO target during three separate run periods in 1997 and 1999. A series of sweeper magnets and collimators produce two nearly parallel beams consisting mainly of neutral hadrons including K_L. An evacuated tank extending from 90 m to 158 m downstream of the target defines the fiducial kaon decay volume. The vacuum decay region ends at a Kevlar/Mylar vacuum window, which is followed by the KTeV detector.

This analysis relies on two core systems of the KTeV detector: the charged spectrometer and the electromagnetic calorimeter. These subsystems are described in some detail below; a full description of the apparatus can be found elsewhere [14].

The charged particle spectrometer system consists of four drift chambers, two upstream and two downstream of a large aperture dipole magnet which delivered a 205 MeV/c (150 MeV/c) kick in the horizontal plane during the 1997 (1999) run. The spectrometer is designed to measure charged particle positions to 100 μm transverse to the beam direction and momenta to 0.5 % for a 10 GeV/c electron.

Downstream of the spectrometer, positioned 186 m from the target, is the electromagnetic calorimeter. This device is composed of 3100 instrumented CsI crystals and measures 1.9 m $\times$ 1.9 m $\times$ 50 cm. Positions are measured to 1–2 mm while the energy resolution is 0.8 % for a 10 GeV photon or electron.

Charged tracks are identified as electrons if they have a momentum greater than 2 GeV/c and point to a cluster in the calorimeter with comparable energy. Specifically, the ratio E/p is required to be in the range 0.93 to 1.07. In addition, there must be exactly four tracks, two of each charge, that extrapolate to a common vertex that lies within one of the two beams and has a z–position between 97 m and 157 m. Note that all π^0's are assumed to decay instantaneously since even at a typical energy of 30 GeV the decay length is only 6 μm, well below the vertex resolution of 10 cm.

Photons are then identified by clusters that are not associated with tracks and have an energy greater than 2 GeV. There must be exactly four photons. The momentum of a photon is calculated assuming it originated at the charged-track vertex.

To verify that the event is due to a kaon decay, the combined momentum of the eight particle state is calculated. The invariant mass is required to fall between 480 MeV/c^2 and 515 MeV/c^2 while the square of the component of the momentum transverse to the kaon direction, p_T^2, must be less than 800 MeV^2/c^2.

The only remaining background is from $K_L \to \pi^0\pi^0\pi^0$, primarily from $K_L \to \pi^0\pi^0\pi^0_{\rm D}$ with an external conversion in material. The photon must convert upstream of the first chamber in order for four tracks to be reconstructed. The material in this region sums to

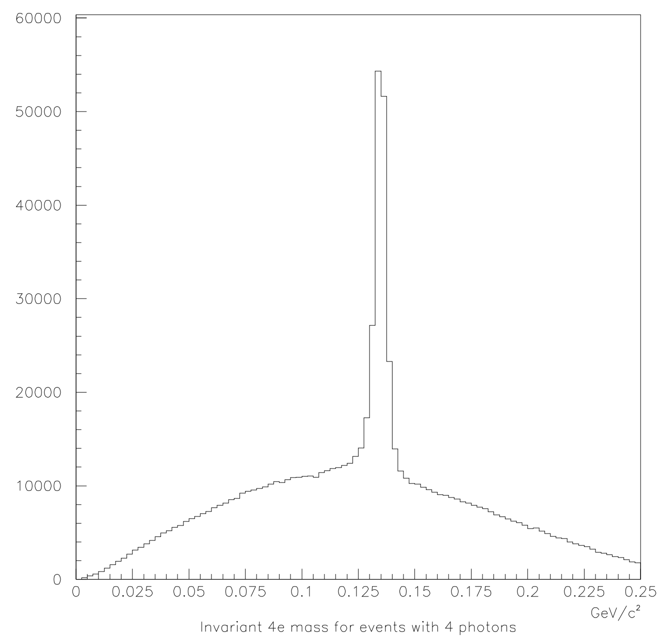

FIG. 1: Invariant $e^+e^-e^+e^-$ mass for events identified as $K_L \to \pi^0\pi^0\pi^0_{\rm DD}$ and $K_L \to \pi^0\pi^0_{\rm D}\pi^0_{\rm D}$.

2.8×10^{-3} radiation lengths. With five photons available, the probability of one converting is 1.08 %, close to the single–Dalitz branching ratio. The distinguishing characteristic of these events is the small value of the e^+e^- invariant mass, or similarly, the small value of the opening angle of the pair. A cut requiring a track separation at the first drift chamber greater than 2 mm removes all but 0.26 % of the remaining background while preserving 78 % of the signal.

The final selection criterion separates $K_L \to \pi^0\pi^0\pi^0_{\rm DD}$ from $K_L \to \pi^0\pi^0_{\rm D}\pi^0_{\rm D}$ events. This is accomplished by a χ^2 formed of the three reconstructed π^0 masses. This serves to identify the best pairing of particles for a given decay hypothesis, as well as to select the more likely hypothesis of the two. The event is tagged as the mode with the smaller χ^2, which is further required to be less than 12 (with three degrees of freedom). While this technique is accurate to better than 99.5 %, misclassification of events between these two samples is the largest source of background after all cuts.

The final event sample contains 30,511 signal candidates with a 0.6 % residual background and 141,251 normalization mode candidates with 0.5 % background. The branching ratio is proportional to the ratio of the number of reconstructed signal mode events to normalization mode events.

The ratio of observed events must be corrected by the ratio of acceptances, which has been determined using a detailed Monte Carlo simulation of the beam distribution and detector response. This double ratio is directly related to the branching ratio B_{eeee} of the $\pi^0 \to e^+e^-e^+e^-$ mode normalized to the square of the branching ratio $B_{ee\gamma}$ of the $\pi^0 \to e^+e^-\gamma$ mode:

$$\frac{B_{eeee} \cdot B_{\gamma\gamma}}{B_{ee\gamma}^2} = \frac{N\left(K_L \to \pi^0\pi^0\pi^0_{\mathrm{DD}}\right)}{N\left(K_L \to \pi^0\pi^0_{\mathrm{D}}\pi^0_{\mathrm{D}}\right)} \cdot \frac{\epsilon\left(K_L \to \pi^0\pi^0_{\mathrm{D}}\pi^0_{\mathrm{D}}\right)}{\epsilon\left(K_L \to \pi^0\pi^0\pi^0_{\mathrm{DD}}\right)}, \tag{3}$$

where N is the number of events and ϵ is the combined geometric acceptance and detection efficiency for a given mode.

The statistical error on the ratio is 0.62%. Systematic errors on the efficiencies were determined through data studies as well as variations in the parameters of the Monte Carlo simulation. Because the final state particles in the signal and normalization mode are the same, detector-related quantities substantially cancel in the ratio, which is generally insensitive to the details of the simulation. The dominant systematic errors came from variation of the analysis cuts (0.21%) and Monte Carlo simulation statistics (0.25%). The largest systematic errors from the detector simulation were uncertainties in the amount of material in the spectrometer (0.15%), uncertainty in the background levels in the two samples (0.15%), and modeling of the drift chamber resolutions (0.11%). The total systematic error on the relative branching ratio is 0.41%.

The final result for the ratio of decay rates is:

$$\frac{B_{eeee} \cdot B_{\gamma\gamma}}{B_{ee\gamma}^2} = 0.2245 \pm 0.0014_{\mathrm{stat}} \pm 0.0009_{\mathrm{syst}}. \tag{4}$$

The $\pi^0 \to e^+e^-e^+e^-$ branching ratio can be calculated from the double ratio to be $B_{eeee} = (3.26 \pm 0.18) \times 10^{-5}$, where the error is dominated by the uncertainty in the $\pi^0 \to e^+e^-\gamma$ branching ratio [16]. These rates should be scaled up by a factor of 1.06??? to find the branching ratio $B_{eeee(\gamma)}$ for a definition of the $\pi^0 \to e^+e^-e^+e^-$ decay inclusive of all radiative final states.

The parameters of the $\pi^0\gamma^*\gamma^*$ form factor are found by minimizing a likelihood function composed of the differential decay rate in terms of the five phase-space variables, where the pairing of the four electrons is chosen to minimize the product x_1x_2. The likelihood itself, however, is calculated from the full matrix element including the exchange diagrams and $\mathcal{O}(\alpha^2)$ radiative corrections. Acceptance-dependent effects are included as a normalization factor calculated from Monte Carlo simulations. The fit parameters are the DIP α parameter

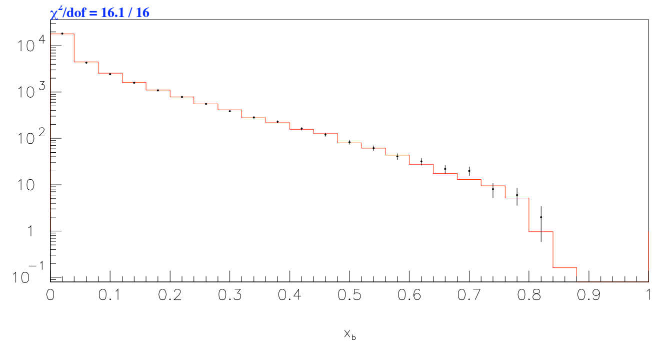

FIG. 2: Distribution of the kinematic variables x_1 and x_2 for signal event candidates.

and the (complex) ratio of the scalar to the pseudoscalar coupling, parametrized as $\tan\zeta e^{i\delta} = \kappa + i\eta$. The shape of the minimum of the likelihood function indicates that these three parameters are uncorrelated.

Systematic error sources on α and κ are similar to those for the branching ratio measurement. The dominant error is due to variation of cuts, resulting in a total systematic error of 0.9 and 0.011 on α and κ respectively. For the η parameter, the primary uncertainty results from the resolution on the angle ϕ between the two lepton pairs, which produces an effective dilution of the angular distribution. The distribution of this angle has the form $d\Gamma/d\phi \sim 1 + A\cos 2\phi + B\sin 2\phi$, where the cosine term corresponds to a pseudoscalar coupling and the sine term to a scalar coupling. Along the η axis, we have $A \sim 1 - 2\eta^2$ and $B \sim 0$. The finite resolution on ϕ has the effect of reducing the observed amplitude A, which in turn is seen by the fitter as a larger value of η, particularly for small values of η. This behavior was studied with Monte Carlo simulation and a correction was calculated. The uncertainty on this correction results in error of 0.031, which dominates the error on η.

The distributions of x_1, x_2, are shown in Fig. 2. The ϕ distribution is shown in Fig. 3. It is clear that the pseudoscalar coupling dominates, as expected, with no evidence for a scalar component.

The final results for the three parameters are $\alpha = 1.3 \pm 1.4$, $\kappa = -0.011 \pm 0.014$, and $\eta = 0.051 \pm 0.031$. The DIP α parameter is related to the standard slope parameter by $a = -0.032\alpha$, yielding $a = -0.040 \pm 0.040$. This result is in agreement with recent direct measurements.

The pseudoscalar and scalar coupling parameters κ and η are transformed into limits on the pseudoscalar-scalar mixing angle ζ under two hypotheses. If CPT violation is allowed,

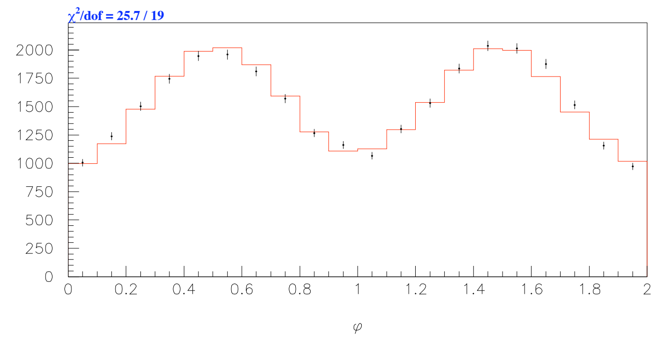

FIG. 3: Distribution of the angle ϕ/π between the planes of the two e^+e^- pairs. The observed $\cos 2\phi$ dependence indicates negative π^0 parity; $\sin 2\phi$ dependence would indicate positive parity.

then the limit is set by the uncertainties in η, resulting in $\zeta < 5.7°$ at the 90% confidence level. If instead, *CPT* conservation is enforced, η must be zero, and the limit derives from the uncertainties on κ, resulting in $\zeta < 1.9°$, at the same confidence level. These limits on ζ limit the magnitude of the scalar component of the coupling, relative to the pseudoscalar component, to less than 10.0% in the presence of *CPT* violation, and less than 3.3% if *CPT* is assumed conserved. We therefore confirm the negative parity of the neutral pion.

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