Upper Limit on the Branching Ratio for the Decay $\pi^0 \to \nu\overline{\nu}$

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A sample of kinematically identified $K^+ \to \pi^+\pi^0$ decays obtained with the E949 detector was used to search for the helicity-suppressed decay $\pi^0 \to \nu\overline{\nu}$ resulting in an upper limit of 2.7×10^{-7} at 90% confidence level. The upper limit is also applicable to π^0 decays into unknown weakly interacting particles.

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We report on a search for the rare decay $\pi^0 \to \nu\overline{\nu}$ from the E949 experiment [1, 2, 3] at Brookhaven National Laboratory (BNL). The decay is forbidden by angular momentum conservation if neutrinos are purely massless left-handed particles. A finite neutrino mass as evidenced by recent oscillation measurements permits the decay to occur. If neutrinos, with mass m_ν less than half of the π^0 mass, couple to the Z^0 with standard weak-interaction strength, the theoretical branching ratio for the $\pi^0 \to \nu\overline{\nu}$ decay is given as $Br(\pi^0 \to \nu\overline{\nu}) = 3 \times 10^{-8}\ (m_\nu/m_{\pi^0})^2 \sqrt{1-4\,(m_\nu/m_{\pi^0})^2}$ for a single Dirac-neutrino type [4]. The experimental upper limit for the tau neutrino mass ($m_\nu < 18.2$ MeV/c^2 [5]) implies that $Br(\pi^0 \to \nu\overline{\nu}) < 5 \times 10^{-10}$; cosmological constraints on the neutrino masses [6] imply more stringent limits. The branching ratio for $\pi^0 \to \nu\nu$ in the case of massive Majorana neutrinos is a factor of two larger [7] than for Dirac neutrinos because the final state particles are identical. In addition to $\pi^0 \to \nu\overline{\nu}$, this search is sensitive to any decays of the form $\pi^0 \to$"nothing". The $\pi^0 \to$"nothing" decay can arise from several different physics processes beyond the standard model, including $\pi^0 \to \nu\overline{\nu}$ decay induced by helicity-flipping (chirality-changing) pseudoscalar interactions [8, 9], $\pi^0 \to \nu_1\overline{\nu}_2$ decay where ν_1 and ν_2 are neutrinos of different lepton flavor, and π^0 decays to other weakly interacting neutral states. Astrophysical limits on $\pi^0 \to \nu\overline{\nu}$ have also been adduced from constraints on the cooling of neutron stars through the pion-pole mechanism $\gamma\gamma \to \pi^0 \to \nu\overline{\nu}$ [10], although nuclear medium effects make this model-dependent [11].

The current upper limit [12] was set by the BNL E787 experiment with $Br(\pi^0 \to \nu\overline{\nu}) < 8.3 \times 10^{-7}$ at 90% confidence level (C.L.) to all possible $\nu\overline{\nu}$ states. A flavor specific search for the decay $\pi^0 \to \nu_\mu\overline{\nu}_\mu$ was performed by the LSND beam-dump experiment, with $Br(\pi^0 \to \nu_\mu\overline{\nu}_\mu) < 1.6 \times 10^{-6}$ (90%C.L.) [13].

E949 was designed to measure the rare kaon decay

$K^+ \to \pi^+\nu\overline{\nu}$ [14]. In that measurement, the decay $K^+ \to \pi^+\pi^0$ ($K_{\pi 2}$) is a major potential background and data is analyzed only with π^+ momenta above [2, 15] or below [16] the $K_{\pi 2}$ kinematic peak at 205 MeV/c. In the $\pi^0 \to \nu\overline{\nu}$ search, we tag a 205-MeV/c π^0 in the detector by the presence of a π^+ in the $K_{\pi 2}$ kinematic peak. The $\pi^0 \to \nu\overline{\nu}$ candidates are identified as $K_{\pi 2}$ events with no activity other than the K^+ and π^+ in the detector.

An intense beam of 22 GeV/c protons from the Alternating Gradient Synchrotron of BNL struck a platinum target over a 2.2 s interval (spill) every 5.4 s viewed by a beam line [17] with two stages of electrostatic mass separation. The typical K^+ beam intensity (with K^+:π^+ ratio of up to 4:1) at the entrance to the E949 detector was 1.3×10^7 per spill with momentum 710 MeV/c. After K^+'s were discriminated from π^+'s by Čerenkov and energy-loss counters, they came to rest in a scintillating-fiber target at the rate of 3.5×10^6 per spill. The time of the π^+ that emerged from the target was required to be at least 2 ns later than the time of the incoming K^+. This "delayed coincidence" requirement guaranteed that the π^+ originated from a K^+ decay at rest, not from a scattered beam particle. The momenta of the charged decay products were measured in a 1 T magnetic field by a drift chamber [18] surrounding the target. The kinetic energy and range were measured by a cylindrical array of plastic scintillators, the range stack (RS), outside of the drift chamber. The resolutions (rms) of the π^+ momentum (P_{π^+}), energy (E_{π^+}) and range (R_{π^+}) from $K_{\pi 2}$ were 1.1%, 2.9% and 2.9%, respectively. Waveform digitizers operating at 500 MHz [19] for the RS readout recorded the $\pi^+ \to \mu^+ \to e^+$ decay sequence to distinguish pions from muons. Photon detectors covered 4π sr solid angle to detect any photon or extra particle from K^+ decay. A new photon detection device, the barrel veto liner (BVL), was introduced just outside the RS and provided 2.3 radiation lengths to augment the E787 detector [20] configuration; with the addition of the BVL, a factor of three improvement in the π^0 detection inefficiency was expected by Monte Carlo (MC) simulations. Additional ancillary photon-detection systems [21] and an improved trigger system [22] were also introduced into the E949 detector. In 2002, the experiment collected $N_K = 1.8 \times 10^{12}$ kaons at rest in the target in 12 weeks.

The $\pi^0 \to \nu\overline{\nu}$ search started with the identification of $K_{\pi 2}$ decays using the π^+ kinematics ("$K_{\pi 2}$ tag") in the events collected by the $K^+ \to \pi^+\nu\overline{\nu}$ trigger [22]. Selection criteria (cuts) on the π^+ from the monochromatic two-body decay were set at $198 < P_{\pi^+} < 212$ MeV/c, $100 < E_{\pi^+} < 118$ MeV and $28 < R_{\pi^+} < 33$ cm, referred to as the "signal box". Potential non-$K_{\pi 2}$ backgrounds include $K^+ \to \mu^+\nu_\mu$ ($K_{\mu 2}$) decays and scattered beam pions. These were suppressed and their contribution to the total background was estimated using techniques similar to the $K^+ \to \pi^+\nu\overline{\nu}$ analysis [2]. The $K_{\mu 2}$ decays were suppressed with measurements of momentum, energy and range as well as with requirements on the observation of the $\pi^+ \to \mu^+ \to e^+$ decay sequence. Beam pion background was suppressed by the K^+/π^+ separation in the Čerenkov and energy-loss counters and by requiring the delayed coincidence in the target. Events with two beam particles entering the target, which can defeat the delayed coincidence requirement, were rejected by looking for activity in any of the beam counters at the time of the kaon decay. The expected numbers of non-$K_{\pi 2}$ background events are summarized in Table I. Ultimately, the search for $\pi^0 \to \nu\overline{\nu}$ was limited by the detection inefficiency for the π^0 decay photons (20–225 MeV) from $K_{\pi 2}$ decay.

TABLE I: The number of background and candidate events.

Total non-$K_{\pi 2}$ background	$3.12^{+1.33}_{-0.99}$
• $K^+ \to \mu^+\nu_\mu$ ($K_{\mu 2}$)	$0.37^{+0.07}_{-0.06}$
• π^+ beam	$0.03^{+0.01}_{-0.01}$
• Two beam particles	$2.72^{+1.26}_{-0.92}$
Number of $\pi^0 \to \nu\overline{\nu}$ candidates (N)	99

The single event sensitivity for the $\pi^0 \to \nu\overline{\nu}$ branching ratio Br is given by

$$SES(\pi^0 \to \nu\overline{\nu}) = \frac{1}{N_K Br(K_{\pi 2}) A_{K_{\pi 2}} \cdot C_{dis} C_{acc}} = \frac{1}{N_{\pi^0}} \cdot \frac{1}{C_{dis} C_{acc}} \qquad (1)$$

where $Br(K_{\pi 2})$ is the branching ratio of the $K_{\pi 2}$ decay, $A_{K_{\pi 2}}$ is the acceptance of the $K_{\pi 2}$ tag, and N_{π^0} is the number of π^0's collected by the $K_{\pi 2}$ tag. A correction factor C_{dis} was introduced to compensate for the loss of $K_{\pi 2}$ events from the tagged sample due to the misreconstruction of the π^+ track by overlapping γ's and $e^\pm$'s from the predominant π^0 decays, which do not occur in the $\pi^0 \to \nu\overline{\nu}$ events. The factor was obtained from two sets of data produced by MC simulations; one was from normal $K_{\pi 2}$ decays, and the other was from $K_{\pi 2}$ decays where the $\pi^0 \to \nu\overline{\nu}$ decay was forced. The difference in the efficiency of the π^+ reconstruction was used to estimate the correction factor, $C_{dis} = 1.14 \pm 0.01$. The correction factor C_{acc} takes into account signal losses due to accidental activity in coincidence with the $\pi^0 \to \nu\overline{\nu}$ decay. This factor was obtained from the loss observed in a pure sample of $K_{\mu 2}$ decays (after all activity of the muons were removed) by imposing the cut for hermetic photon detection (HPD).

The sensitivity to $\pi^0 \to \nu\overline{\nu}$ was maximized by optimizing the parameters for the HPD cut in order to achieve the greatest rejection against the π^0 decay products ($\gamma\gamma$, $e^+e^-\gamma$) while minimizing the acceptance loss ($1 - C_{acc}$) due to accidentals. The HPD parameters consisted of timing windows and energy thresholds of more than 20 sub-detectors: typically ± 10 ns and 1 MeV. A uniformly sampled 1/3 portion of the data ("1/3 sample") was used

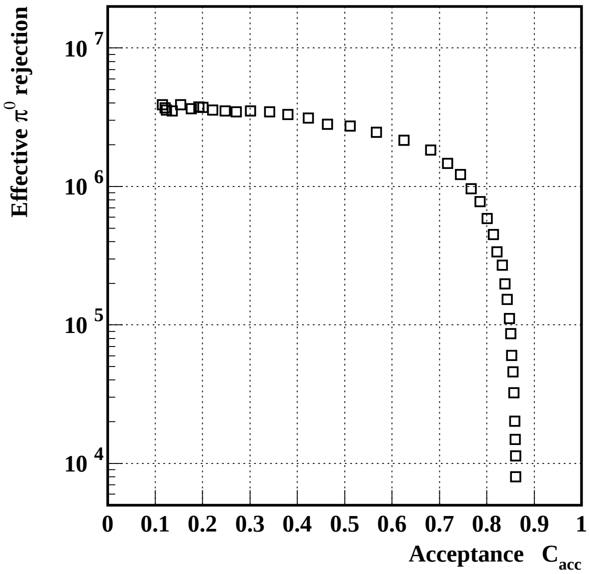

FIG. 1: Effective π^0 rejection (defined as π^0 rejection $\times$ C_{acc}) vs acceptance C_{acc} of the HPD cut as measured on the 2/3 sample. The saturated curve at 4×10^6 indicates the limit of the E949 π^0 detection efficiency.

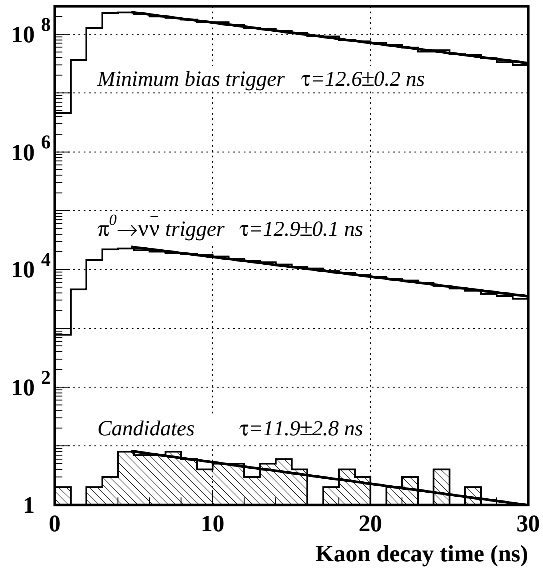

FIG. 2: Kaon decay-time distribution with various levels of the HPD cut described in the text. All the other cuts except the offline delayed-coincidence cut were imposed. The distribution was not distorted by the HPD cut confirming that the sample was dominated by kaon decays. The depletion of events near time zero was due to trigger requirements to suppress single beam particle backgrounds. Decay-time fits were performed for each plot in a time range of [4ns:30ns]; no evidence of two-beam background was found.

as a training sample exclusively for tuning the parameters. To avoid bias, this sample was not used for the signal search reported below, nor for the background measurements shown in Table I. After the parameter space was explored to set the HPD parameters, the cut was imposed on the remaining 2/3 portion of the data ("2/3 sample", $N_{\pi^0} = 3.02 \times 10^9$) for evaluation. The effective rejection (defined as 'π^0 rejection$\times C_{acc}$') as a function of C_{acc} for various levels of the cut is shown in Figure 1. The HPD cut position optimized on the 1/3 sample was set at a value of $C_{acc} = 0.117 \pm 0.002(stat) \pm 0.003(sys)$. A total of 99 events were observed in the signal box with the final HPD cut.

Some properties of the 99 events observed in the signal box are shown in Figures 2 and 3. The decay time distribution in Figure 2 is consistent with the known kaon lifetime and does not show any evidence of large contamination by two-beam background, which would tend to flatten the distribution of the surviving events. The π^+ momentum distribution in Figure 3 does not show evidence of a significant contamination by beam pions or from $K_{\mu 2}$ decays.

The primary reasons for failure to detect photons from π^0 decay in $K_{\pi 2}$ events are sampling fluctuations in the electromagnetic shower of low energy photons around 20 MeV and photonuclear interactions of high energy photons with undetected products, such as neutrons. While the effects of electromagnetic interactions can be estimated well, there are presently very large uncertainties associated with the detailed modeling of detection inefficiencies due to photonuclear processes. Therefore, since the overall background contribution from $\pi^0 \to \gamma\gamma$ decays in which both photons go undetected is difficult to estimate reliably, we treated all 99 observed events as $\pi^0 \to \nu\overline{\nu}$ candidates to set an upper limit. Using Poisson statistics, the number of signal events was limited to be < 113 at 90% C.L. when 99 events were observed. Subtracting the non-$K_{\pi 2}$ background of approximately three events, the 90% C.L. upper limit of the $Br(\pi^0 \to \nu\overline{\nu})$ was obtained as :

$$Br(\pi^0 \to \nu\overline{\nu}) \ < \ \frac{110}{3.02 \times 10^9} \cdot \frac{1}{1.14 \times 0.117} \tag{2}$$

$$= 2.7 \times 10^{-7} \tag{3}$$

The result is three times better than the previous best result [12]. The upper limit obtained above is sensitive to any hypothetical weakly-interacting particles, whose masses are less than half of the π^0 mass; other decays of the kind $X^0 \to$ "nothing" (e.g. η, $K_{L,S}$ [7], and B^0 [23]) are experimentally more difficult to measure.

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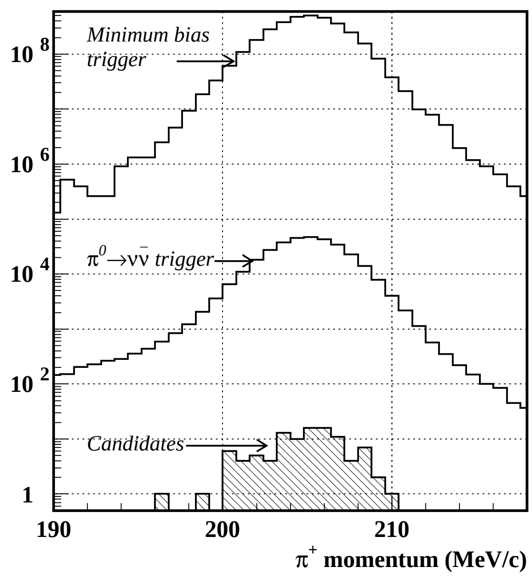

FIG. 3: The $K_{\pi 2}$ π^+ momentum distribution with various levels of the HPD cut. All the other cuts except for the signal box cuts were imposed.

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