Search for $\pi^0 \to \nu_\mu \bar{\nu}_\mu$ Decays in the LSND Detector

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(Received 30 October 2003; published 4 March 2004)

We observe a net beam excess of $8.7 \pm 6.3(\text{stat}) \pm 2.4(\text{syst})$ events, above 160 MeV, resulting from the charged-current reaction of ν_μ and/or $\bar{\nu}_\mu$ on C and H in the LSND detector. No beam-related muon background is expected in this energy regime. Within an analysis framework of $\pi^0 \to \nu_\mu \bar{\nu}_\mu$, we set a direct upper limit for this branching ratio of $\Gamma(\pi^0 \to \nu_\mu \bar{\nu}_\mu)/\Gamma(\pi^0 \to \text{all}) < 1.6 \times 10^{-6}$ at 90% confidence level.

DOI: 10.1103/PhysRevLett.92.091801 PACS numbers: 13.20.Cz, 14.40.Aq, 14.60.St

The observation of the decay $\pi^0 \to \nu\bar{\nu}$ would imply new interesting physics. The pion has zero spin and odd intrinsic parity (i.e., $J^P = 0^-$), and it is represented by a wave function which has the space transformation properties under inversion and rotation of a pseudoscalar. Momentum and angular momentum conservation require that the decay ν and $\bar{\nu}$ possess the same helicity. This decay provides an ideal laboratory to search for the pseudoscalar (P) weak interaction, because only the P interaction allows massless neutrinos and antineutrinos with the same helicity in the final state. Furthermore, if the neutrino mass is not zero and the Z^0 couples to the right-handed neutrino with standard weak-interaction strength, the branching ratio (BR) $B(\pi^0 \to \nu_\mu \bar{\nu}_\mu)$ has a maximum value of 5.4×10^{-14} at the ν_μ mass upper limit of $m(\nu_\mu) = 0.19\ \text{MeV}/c^2$ [1]. It is noteworthy that a BR of $\approx 10^{-14}$ for $\pi^0 \to \nu\nu\gamma$ within the standard model is allowed. Therefore, an observed BR $B(\pi^0 \to \nu_\mu \bar{\nu}_\mu) \gg 5 \times 10^{-14}$ would imply physics beyond the standard model.

To date limits have been set on $\pi^0 \to \nu\bar{\nu}$ derived from pion production in beam stops. An experimental upper limit, $\Gamma(\pi^0 \to \nu_\mu \bar{\nu}_\mu)/\Gamma(\pi^0 \to \text{all}) \leq 3.1 \times 10^{-6}$ at 90% confidence level (C.L.), was set by Hoffman [2] by using the data from several beam-dump experiments. Similar limits were obtained by Dorenbosch *et al.* [3]. An inclusive search for $\pi^0 \to \nu\bar{\nu}$ using $K^+ \to \pi^+\pi^0$ has set an upper limit of 8.3×10^{-7} (90% C.L.) [4].

The Liquid Scintillator Neutrino Detector (LSND) experiment was performed at the Los Alamos Neutron Scattering Center (LANSCE). An 800-MeV beam of protons incident on a predominantly water-copper target provided the source for the π^0. This energy is well below the kaon production threshold, and almost all pions are produced from p-nucleus interactions. The detector, located 30 m from the beam stop, contained 167 tons of dilute liquid scintillator which served as the active target. The liquid scintillator was viewed by 1220, 8 in.-diameter Hamamatsu photomultiplier tubes (PMTs) mounted inside the tank. An active shield with 292, 5 in.-diameter PMTs vetoed cosmic rays [5]. The readout and the data acquisition system are described in more detail elsewhere [6].

The π^0 production rate was calculated using the LSND beam Monte Carlo (MC) [7]. Figure 1 shows the neutrino spectrum resulting from the possible $\pi^0 \to \nu_\mu \bar{\nu}_\mu$ decay at the center of the LSND detector. Note that the peak between 70 and 80 MeV is due to multiple pion production [8]. For comparison, Fig. 1 also shows the ν_μ spectrum from the usual $\pi^+ \to \mu^+ \nu_\mu$ decay in flight (DIF) multiplied by 10. As the π^0 spectrum is expected to be very similar to that of the π^+, in these calculations the $\pi^+ \to e^+ \nu_e$ decay mode was used, where a lifetime of 8.4×10^{-16} s (π^0 lifetime) was assigned to the π^+. Assuming that all π^0's decay to two neutrinos, the neutrino flux is calculated to be $(6.5 \pm 1.6) \times 10^{14} \nu_\mu/\text{cm}^2$ at the center of the detector above the muon production threshold of 123 MeV for the entire running time of the LSND detector. The error estimate is based on the values quoted by Burman and Plischke [8].

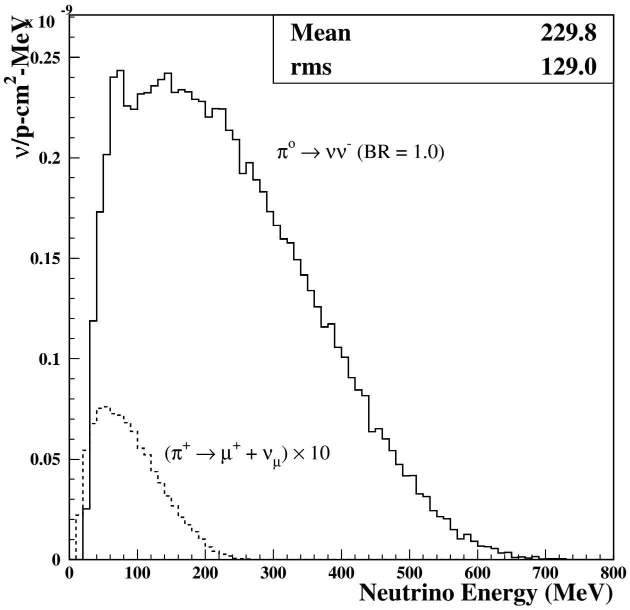

FIG. 1. The neutrino energy spectrum resulting from the possible $\pi^0 \rightarrow \nu_\mu \bar{\nu}_\mu$ decay at the beam stop and as seen at the center of the LSND detector. The dashed curve shows the energy spectrum of neutrinos from π^+ DIF.

The results presented here were obtained during the 1993–1998 LSND operation periods. A total of 28 896 Coulombs of protons were incident on the beam stop. The dominant interactions inside the LSND detector were $\nu_\mu + ^{12}C \rightarrow \mu^- + p + X$, $\bar{\nu}_\mu + ^{12}C \rightarrow \mu^+ + n + X$, and $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$. The flux-averaged cross sections for these reactions are estimated to be $(3.0 \pm 0.6) \times 10^{-38}$, $(0.60 \pm 0.12) \times 10^{-38}$, and $(0.20 \pm 0.01) \times 10^{-38}$ cm^2, respectively, from a Fermi-gas model (FGM) of Gaisser and O'Connell [9]. The estimated errors are from the uncertainties for the FGM calculations quoted by Vogel [10]. The μ in each of the above reactions usually decays and produces a Michel electron. The $\pi^0 \rightarrow \nu_\mu \bar{\nu}_\mu$ search focused on identifying high-energy, muonlike beam-excess events in the energy range between 160 and 600 MeV electron equivalent (MeVee). The lower cut of 160 MeVee is obtained because the end-point energy of muon neutrinos is about 280 MeV and the muon production threshold is 123 MeV. This cut, therefore, insures that beam-related background μ events are negligible [11]. The upper energy cut was chosen because the end-point energy of the neutrinos is about 730 MeV and the muon production threshold is 123 MeV.

The majority of the triggers (99%) were cosmic ray induced and were classified as through-going muons, electrons from stopping muon decays, recoil protons from neutron collisions, and $^{12}B_{\mathrm{g.s.}}$ decay resulting from μ^- capture on ^{12}C. In order to minimize the background induced by cosmic rays, a Michel electron was selected for the current event that satisfied an energy cut of $20 < E < 55$ MeV. The reconstructed electron vertex was required to be inside a fiducial volume 35 cm from the face of the PMTs. The particle identification parameter, χ_l', from Ref. [12] was used to select electrons and was required to satisfy $-1.5 < \chi_l' < 0.5$, where the allowed range is chosen by maximizing the selection efficiency divided by the square root of the beam-off background. A veto cut of less than four hits was applied to reduce cosmic rays. Events with future activity within 9 μs ($\approx 4\mu$ lifetimes) or with a bottom veto counter hit were rejected in order to further eliminate cosmic-ray muon events. Furthermore, no veto hit was allowed within 30 ns of the trigger time. These cuts and their associated efficiencies for the selection of primary electrons are summarized in Table I. A second set of cuts was applied to isolate parent muons. These cuts are similar to those of Ref. [11]. Muons were required to have a decay time of less than 9 μs. An energy cut between 160 and 600 MeV was chosen to eliminate possible muons from beam-related π^+ DIF. A spatial μ-e correlation distance cut of less than 100 cm was applied. The muon vertex was required to be within a fiducial volume of 35 cm from the face of the PMT. A veto cut of less than two hits was applied to further reduce cosmic rays. These cuts and their corresponding efficiencies are summarized in Table II.

The overall efficiency of these cuts was 0.15 ± 0.01, which resulted in a total of 38 beam-on events and 473

TABLE I. Selection criteria and corresponding efficiency for the primary Michel electron.

Selection Criteria		Efficiency
Veto live time		0.76 ± 0.02
Data acquisition live time		0.96 ± 0.02
	Analysis efficiency	
Electron energy	$20 < E < 55$ MeV	0.98 ± 0.02
Fiducial volume	$D > 35$ cm	0.88 ± 0.02
Particle identification	$-1.5 < \chi_l' < 0.5$	0.84 ± 0.01
Shield and crack hits	< 4	0.98 ± 0.01
Future time gate	$\Delta t_{\mathrm{future}} > 9$ μs	0.99 ± 0.01
In-time veto gate	$\Delta t_{\mathrm{veto}}^{\mathrm{best}} > 30$ ns	0.97 ± 0.01
Total in-time cuts		0.50 ± 0.03

TABLE II. Selection criteria and corresponding efficiency for the parent muon.

Selection criteria		Efficiency
Muon decay time	$0.7 < \tau_\mu < 9$ μs	0.74 ± 0.01
Uncaptured μ^-	$\cdots$	0.97 ± 0.01
Past energy	$160 < E < 600$ MeV	0.64 ± 0.01
Spatial correlation	< 100 cm	0.99 ± 0.01
Fiducial volume	> 35 cm	0.75 ± 0.01
Shield and crack hits	< 2	0.87 ± 0.01
Total past cuts		0.30 ± 0.01

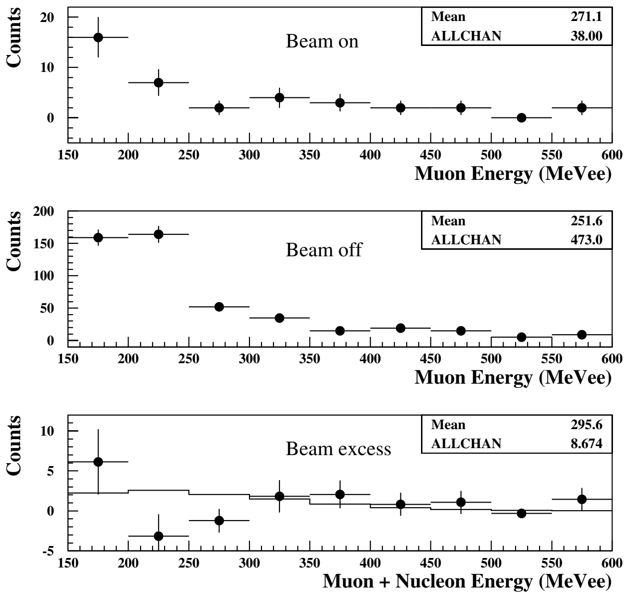

FIG. 2. The visible energy distribution for beam-on, beam-off, and beam-excess events. The solid line represents the MC calculation.

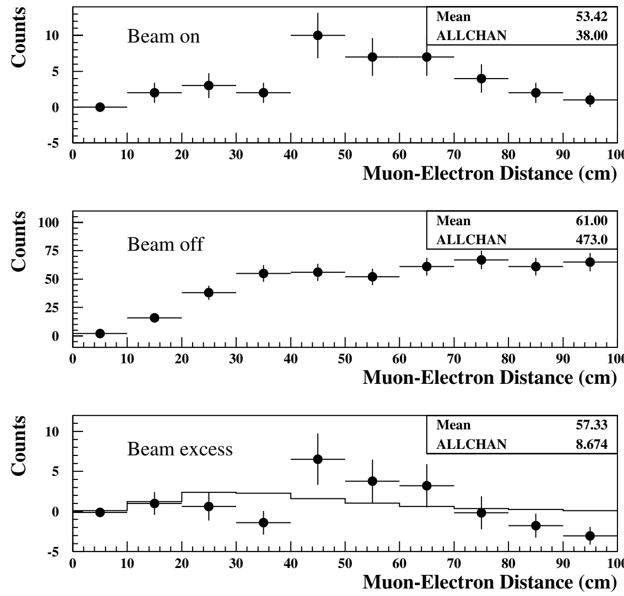

FIG. 3. Distance between muon and electron for beam-on, beam-off, and beam-excess events. The solid line represents the MC calculation.

beam-off events. After applying the duty factor ratio of 0.062 ± 0.005, the normalized number of beam-off events was $29.3 \pm 1.3 \pm 2.4$, resulting in a beam excess of $8.7 \pm 6.3 \pm 2.4$ events. Figure 2 shows the visible energy distribution for beam-on, beam-off, and beam-excess events. Also shown in the beam-excess figure is the area normalized GEANT-3.21 MC calculation. The calculation uses the neutrino spectrum of Fig. 1 and generates muons and knockout protons based on the Fermi-gas model of Ref. [9].

Figure 3 shows the spatial correlation between the muons and the Michel electrons for the beam-off, beam-on, and beam-excess events. The MC calculation is shown as the solid line on the beam-excess histogram. Figure 4 shows the time correlation between the muons and the Michel electrons for the beam-on, the beam-off, and the beam-excess events. The usual decay-at-rest muon lifetime curves, $e^{t/2.12\ \mu\text{s}}$, are superimposed for comparison. Note the choice of 2.12 μs for the muon lifetime is because the detected muons are a mixture of μ^- and μ^+.

The upper limit to the BR for the $\pi^0 \to \nu_\mu \bar{\nu}_\mu$ decay is calculated using the values for the neutrino reaction cross section $[(3.8 \pm 0.8) \times 10^{-38}\ \text{cm}^2]$, the neutrino flux $[(6.5 \pm 1.6) \times 10^{14} \nu/\text{cm}^2]$, the total number of target atoms $[(3.7 \pm 0.1) \times 10^{30}]$, and the overall efficiency (0.15 ± 0.01). If the small excess is due to $\pi^0 \to \nu_\mu \bar{\nu}_\mu$ decay, then the corresponding BR is $\Gamma(\pi^0 \to \nu_\mu \bar{\nu}_\mu)/\Gamma(\pi^0 \to \text{all}) = [6.4 \pm 4.6(\text{stat}) \pm 3.3(\text{syst})] \times 10^{-7}$, which corresponds to an upper limit of $\Gamma(\pi^0 \to \nu_\mu \bar{\nu}_\mu)/\Gamma(\pi^0 \to \text{all}) < 1.6 \times 10^{-6}$ at 90% C.L.

In summary, a beam excess of $8.7 \pm 6.3(\text{stat}) \pm 2.4(\text{syst})$ events is observed above an energy of 160 MeV, where no beam-related background is expected. Within the framework of $\pi^0 \to \nu\bar{\nu}$, a direct upper limit for this BR of 1.6×10^{-6} at 90% C.L. is obtained.

We are grateful to the administrative and technical staff members of LANSCE for their support during this experiment. We also gratefully acknowledge Dr. Cyrus Hoffman, Dr. Peter Herczeg, and Dr. Lon Chang Liu for enlightening discussions. This work was supported in part by the U.S. Department of Energy.

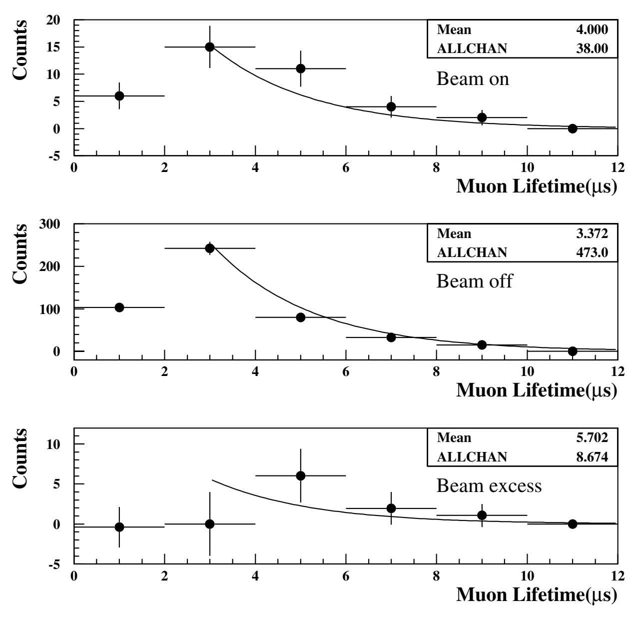

FIG. 4. Muon lifetime for beam-on, beam-off, and beam-excess events. The superimposed solid curves represent the expected $e^{-t/2.12\ \mu\text{s}}$ exponential decay of muons at rest.

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