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Rapid Communications

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Two- and three-pion production by $\nu_\mu d$ reactions near threshold: The implications for nucleon-decay experiments

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We use ν_μ-deuteron reactions into exclusive multipion final states to determine the extent to which atmospheric ν interactions can imitate nucleon decay. For decays $N \rightarrow l^c\pi^c\pi^c$ $(l^c\pi^c\pi^c\pi^0)$, neutrinos induce background events at the rate 0.07 ± 0.06 (0.03 ± 0.02) per kiloton year. By requiring a multipion final state to be consistent with a ρ, ω, or η, a fivefold reduction of the background is obtained. Thus present-generation experiments are capable of searching for such decays at a lifetime level corresponding to many kiloton years of detector exposure.

A number of experiments searching for the decay of the nucleon have recently reported results.[1] Candidate decays into the modes $\mu^+\eta^0$ and/or μ^+K^0, and also $e^+\omega^0$ have been observed.[1,2] It is therefore imperative that background processes leading to multiparticle final states be well understood. The most abundant category of fully contained events recorded by nucleon-decay detectors are interactions of atmospheric neutrinos; these neutrinos are the decay remnants of muons and mesons which originate in collisions of energetic cosmic rays with nuclei of the upper atmosphere. In this Rapid Communication we inquire to what extent reactions induced by atmospheric ν_μ, $\bar{\nu}_\mu$, ν_e, and $\bar{\nu}_e$ can imitate nucleon decay $N \rightarrow l^\pm X^{\mp,0}$, where $l=e$ or μ, and $X \rightarrow \pi\pi$, $\pi\pi\pi$.

We have isolated samples of ν_μ-deuteron charged-current reactions near threshold in which two- or three-pion exclusive final states are produced. The data were obtained from exposures of the Argonne 12-foot deuterium-filled bubble chamber to the neutrino beam at the Zero Gradient Synchrotron. Details of the experimental arrangement, event processing, and analysis have been given in earlier publications.[3,4] Our data were obtained from analysis of all four-prong events and 60% of the five-prong events in 2.4×10^6 pictures. The total number of charged-current events recorded is 4000, the majority of which consist of the final states μ^-p, $\mu^-p\pi^+$, $\mu^-n\pi^+$, and $\mu^-p\pi^0$ (Ref. 3).

Scanning for events containing four and five visible charged particles in the final state yielded candidates for the following reactions:

$$\nu_\mu n \rightarrow \mu^- p \pi^+ \pi^- \ , \qquad (1)$$

$$\nu_\mu p \rightarrow \mu^- p \pi^+ \pi^+ \pi^- \ , \qquad (2)$$

$$\nu_\mu n \rightarrow \mu^- p \pi^+ \pi^- \pi^0 \ , \qquad (3)$$

$$\nu_\mu n \rightarrow \mu^- n \pi^+ \pi^+ \pi^- \ . \qquad (4)$$

Events which satisfied the three-constraint kinematical requirements of hypotheses (1) and (2) were assigned to these reactions. For events which failed the three-constraint fits, zero-constraint assignments to hypotheses (3) and (4) were attempted. In all cases, agreement was required with visual information on the photographs. These procedures yielded samples of 74 $\mu^-p\pi^+\pi^-$ events, 13 $\mu^-p\pi^+\pi^+\pi^-$ events, 15 $\mu^-p\pi^+\pi^-\pi^0$ events, and 9 $\mu^-n\pi^+\pi^+\pi^-$ events. In each sample, nearly half of the events contained a μ^-/π^- track ambiguity, and 10% contained a π^+/p track ambiguity. Following the procedure used in previous studies,[3,5] we resolved the ambiguity by assigning the negative (positive) track of higher momentum to be the muon (proton). Three events were found to be ambiguous between hypotheses (3) and (4) and were retained in both samples. We verified that these procedures do not significantly affect our results.

In Fig. 1 we show the shape of the ν_μ flux spectrum for our experiment (solid curve), normalized to the flux calculated for atmospheric ν_μ's[6,7] (dashed curve) in the interval $0.6 \leq E_\nu \leq 2.0$ GeV. This comparison provides energy-dependent weights which, when applied on an event-by-event basis, convert our event distributions into ones appropriate for atmospheric ν_μ events.

Previous results from this experiment[3,5] show that the excitation function $\sigma(E_\nu)$ for any specific final state rises rapidly from its kinematic threshold, but exhibits milder E_ν variation at higher energies; in addition, excitation functions for two- and three-pion neutrino reactions, $\sigma_{\pi\pi(\pi)}$, have relatively high E_ν thresholds. Hence, convolution of $\sigma_{\pi\pi(\pi)}$ with the rapidly falling atmospheric ν flux yields event rates lower by an order of magnitude than rates for quasielastic or single-pion events. Final states with $n_\pi \geq 4$ are suppressed by an additional order of magnitude and are neglected here. We also note that two- and three-pion events have net

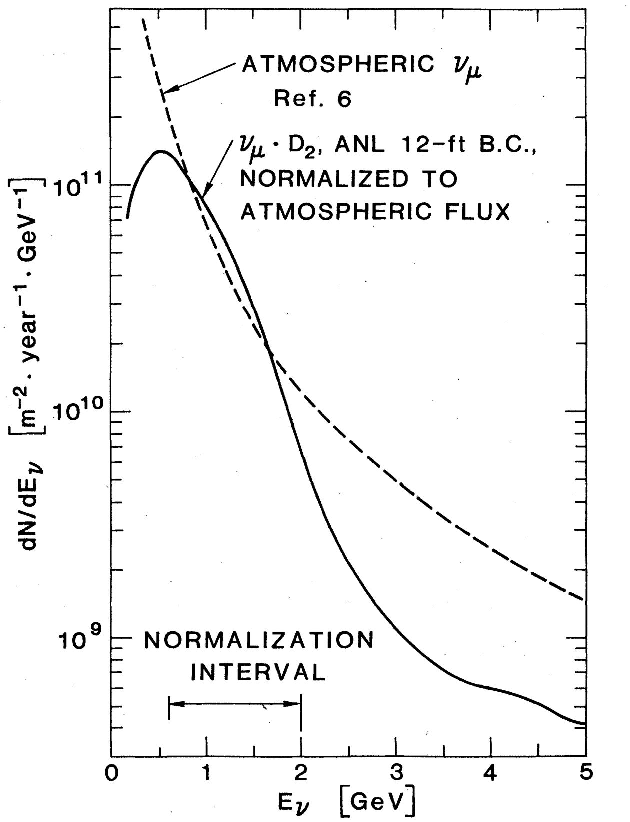

FIG. 1. Neutrino flux for our experiment (solid curve), normalized to the atmospheric ν_μ flux (dashed curve) in the interval $0.6 \leq E_\nu \leq 2.0$ GeV.

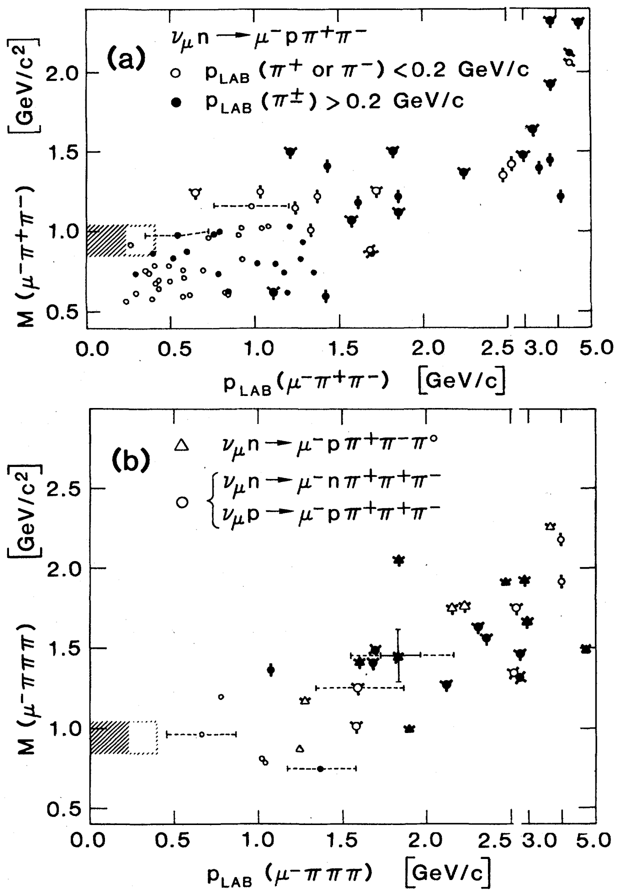

FIG. 2. Invariant mass vs net momentum of the $\mu^-\pi\pi(\pi)$ system in the threshold region $0.6 \leq E_\nu \leq 5.0$ GeV. Three different symbol sizes, accompanied by zero, two, or three beads, illustrate event weighting used to match the E_ν distribution of atmospheric ν's. Solid symbols denote events with all pions above detection threshold of 200 MeV/c; open symbols denote events with at least one pion below the threshold. Shaded regions show momentum smearing due to Fermi motion; with inclusion of resolution effects, nucleon decay should populate the larger bordered regions. (a) Reaction (1). (b) Reactions (2), (3), and (4).

final-state momenta typically 1 GeV higher than net momenta of final states $\mu^- p$ or $\mu^- N\pi$. These differences suggest that multipion neutrino reactions are less likely to be a source of background for nucleon decays.

The extent to which neutrino reactions imitate nucleon decay depends in part on the properties of the nucleon-decay detectors. In order to detect a multiparticle final state, a detector must be able to count the particles, to determine their identity (e, μ, π, or γ), and to measure their momenta. The present-generation detectors have several limitations: Electric charge is not measured, and only hadrons with momenta exceeding a characteristic minimum of ~ 200 MeV/c are detected. The minimum is set by the Cherenkov threshold in water or by the thickness of the iron plates in tracking calorimeters. Final-state nucleons in the neutrino interactions will usually be undetected. In our analysis, we consider charged-pion thresholds at zero momentum and at 200 MeV/c.

For the neutrino reactions (1)–(4), a typical nucleon-decay experiment will therefore detect the lepton and pions, and the net momentum will approximate the neutrino momentum. On the other hand, for nucleon decays, the momentum of the lepton will balance the sum of momenta of the hadrons. To exploit this basic difference, we display in Fig. 2 the invariant mass of the $\mu^-\pi\pi(\pi)$ system plotted against the magnitude of the $\mu^-\pi\pi(\pi)$ total momentum. Nucleon decays will then populate the bordered areas, with $\mu^-\pi\pi(\pi)$ mass values within 10% of m_N and net momentum below 400 MeV/c.

Neutrino events for which all charged-pion momenta exceed 200 MeV/c are denoted by solid symbols; open symbols denote events with one or more pions below 200 MeV/c. In order to indicate the relative frequency of occurrence corresponding to the atmospheric ν flux, events are depicted using small symbols (0.6 to 1.9 GeV in E_ν), medium symbols with bead pairs (1.9 to 2.5 GeV), or large symbols with bead triplets (2.5 to 5.0 GeV) according to their flux weights. The uncertainties due to the bubble-chamber resolution are negligible when all final-state mesons are charged; a typical error for the $\mu^-\pi^+\pi^-\pi^0$ final state is shown in Fig. 2(b). For detectors whose media are predominantly oxygen or iron nuclei, the net momentum will be smeared due to Fermi motion. The magnitude of this effect in oxygen[8] is shown by the dashed bars on representative ν events and by shaded portions of areas which define nucleon decays.

Figure 2(a) show that, from 135.3 weighted events of reaction (1) having $E_\nu < 5$ GeV, only 1.8 events have $l\pi\pi$ kinematics consistent with nucleon decay, and only 1.0 will have both pions above the 200-MeV/c detection threshold.

TABLE I. Atmospheric neutrino interaction rates per kiloton year in a nucleon-decay detector of isoscalar medium.

Neutrino reactions	Neutrino event rate	Candidate nucleon-decay channel	Neutrino background for nucleon decay (rate per kiloton year) $\pi^\pm$ threshold: 200 MeV/c	$\pi^\pm$ threshold: 0 MeV/c
$\overset{(-)}{\nu}_l N \to l^c(N)\pi^c\pi^c$	5.8 ± 4.7	$N \to l^c\pi^c\pi^c$	0.07 ± 0.06	0.08 ± 0.06
$\overset{(-)}{\nu}_l N \to l^c(N)\pi^c\pi^c\pi^c$	2.6 ± 1.9	$N \to l^c\pi^c\pi^c\pi^c$	0.03 ± 0.02	0.03 ± 0.02
$\overset{(-)}{\nu}_l N \to l^c(N)\pi^c\pi^c\pi^0$	2.7 ± 2.1	$N \to l^c\pi^c\pi^c\pi^0$	0.03 ± 0.02	0.03 ± 0.02
$\overset{(-)}{\nu}_l N \to \overset{(-)}{\nu}_l(N)\pi^c\pi^c\pi^c$	0.17 ± 0.13	$N \to$ "l^c"$\pi^c\pi^c$	0.002 ± 0.002	. . .
ρ^0: $600 < M(\pi^c\pi^c) < 900$ MeV/c^2				
$\overset{(-)}{\nu}_l N \to l^2(N)[\pi^c\pi^c]$	0.9 ± 0.7	$N \to l^c[\pi^c\pi^c]$	0.01 ± 0.01	0.01 ± 0.01
ω^0: $600 < M(\pi^c\pi^c\pi^0) < 900$ MeV/c				
$\overset{(-)}{\nu}_l N \to l^c(N)[\pi^c\pi^c\pi^0]$	0.9 ± 0.8	$N \to l^c[\pi^c\pi^c\pi^0]$	0.01 ± 0.01	0.01 ± 0.01
η^0: $M(\pi^c\pi^c\pi^0) < 700$ MeV/c				
$\overset{(-)}{\nu}_l N \to l^c(N)[\pi^c\pi^c\pi^0]$	0.5 ± 0.4	$N \to l^c[\pi^c\pi^c\pi^0]$	Not detected: $\pi^\pm$ below threshold	0.005 ± 0.005
$M(\gamma\gamma) \sim M(\eta^0)$				
$\overset{(-)}{\nu}_l N \to l^c(N)[\gamma\gamma]$	0.4 ± 0.4	$N \to l^c[\gamma\gamma]$	0.004 ± 0.004	0.004 ± 0.004

Similarly, Fig. 2(b) shows that, from 107.9 weighted events in three-pion channels, less than one has $l\pi\pi\pi$ variables consistent with nucleon decay. We note that events from lower-energy neutrinos ($E_\nu < 2$ GeV) are more likely to mimic nucleon decay than are events from energetic neutrinos.

To relate the distributions in Fig. 2 to atmospheric neutrino event rates per kiloton year in a nucleon-decay experiment, we scale our data using the event-rate calculation of Battistoni *et al.*[6,9] The reaction rates for the various neutrino species into $\pi\pi$ and $\pi\pi\pi$ channels are obtained from our ν_μ results using the predicted inelastic charged-current ratio $\bar{\nu}_\mu/\nu_\mu = \frac{1}{3}$, and a flux ratio $(\nu_e + \bar{\nu}_e)/(\nu_\mu + \bar{\nu}_\mu) = \frac{1}{2}$. For example, from the scaled number of events in reaction (1), we obtain rates for $\nu_l n \to l^- p\pi^+\pi^-$ and $\bar{\nu}_l p \to l^+ n\pi^+\pi^-$. An additional factor ($2.1 \pm 0.5$) is applied to account for "look-alike" channels $\nu_l p \to l^- n\pi^+\pi^+$ and $\bar{\nu}_l n \to l^+ p\pi^-\pi^-$, yielding rates for detected configurations $\nu_l N \to l^c(N)\pi^c\pi^c$. Our rate estimates are summarized in Table I. For candidate nucleon decays into two-pion modes as observed in a detector with 200-MeV/c $\pi^\pm$ threshold, we find 0.07 ± 0.06 background events per kiloton year; we find 0.06 ± 0.03 background events per kiloton year for the three-pion modes.[10]

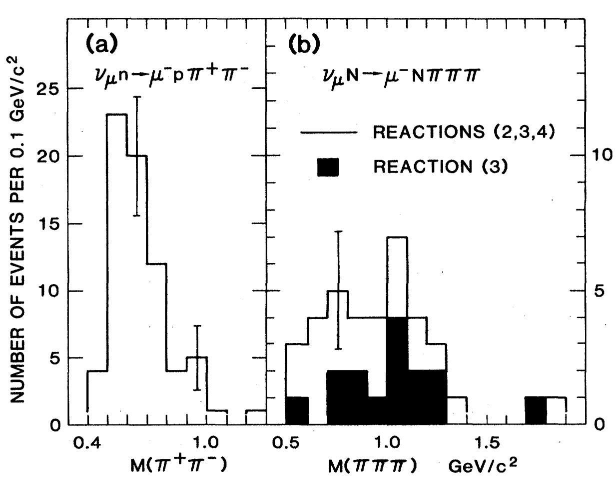

FIG. 3. Invariant-mass distributions (a) $M(\pi^+\pi^-)$ from reaction (1), and (b) $M(\pi\pi\pi)$ from reactions (2), (3), and (4). $M(\pi^+\pi^-\pi^0)$ is shown by the solid area.

Our data samples can also be used to determine whether neutral-current events $\nu N \to \nu(N)\pi^c\pi^c\pi^c$ can simulate $N \to$ "l^c"$\pi^c\pi^c$ in a detector that confuses a charged pion with a lepton. For this purpose, we ignored the muon tracks in our data, and assigned each pion in turn as a muon. The resulting rate of candidate nucleon decays is less than one event per 100 kiloton years.

More stringent limits results when the multipion system comes from a meson resonance. Figure 3 shows the unweighted effective-mass distribution of the meson system for the different reactions; no evidence for significant resonance production is observed. The neutrino background for nucleon decay with ρ^0, ω^0, or η^0 in the final state have been estimated using weighted number of events in the corresponding mass intervals of Fig. 3. These rates are also given in Table I.

Other background configurations that could imitate nucleon decay were investigated. A candidate $N \to l^c\pi^c\pi^c$ decay results when a three-pion neutrino final state has one charged pion below momentum threshold. This configuration contributes 0.02 ± 0.02 counts. Background topologies that arise when reactions $\overset{(-)}{\nu}_l p \to l^\mp p\pi^\pm$ or $\nu_l n \to l^- p\pi^+\pi^-$ have final-state protons sufficiently fast to imitate pions contribute less than 0.01 events per kiloton year and have been neglected.

We conclude that in a detector exposure of ten kiloton years, observation of a few events in which a charged lepton plus two or three pions has invariant mass near the nucleon mass and net momentum below 400 MeV/c can provide conclusive evidence for nucleon decay.

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[9]These calculations agree with observations from 18 contained neutrino events collected thus far by the Mont Blanc detector [E. Iarocci, talk at the Fifth Workshop on Grand Unification, Providence, Rhode Island, 1984 (unpublished)].

[10]We do not measure effects of rescattering in nuclei heavier than deuterium. Comparison of our deuterium data with results from the Gargamelle heavy-liquid bubble chamber shows that rescattering does not substantially alter neutrino final states. See, for example, M. Pohl *et al.*, Lett. Nuovo Cimento **24**, 540 (1979).