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Search for nucleon decay and $n - \bar{n}$ Oscillation in Soudan 2

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Abstract. We have studied multiprong contained events in the Soudan 2 detector in order to search for nucleon decay and neutron oscillation (and subsequent annihilation) into high multiplicity final states. The excellent spatial resolution of the Soudan 2 tracking calorimeter detector, together with its capability to identify slow proton tracks and stopping tracks through their higher ionization, enables us to analyze high multiplicity events in more detail than has been done previously. We have found no evidence for signal events above the (small) estimated background of multiprong events due to atmospheric neutrino interactions.

1 Introduction

The existence of baryon-number violating processes is a generic prediction of Grand Unified Theories that attempt to unify the fundamental forces. Such processes can lead to nucleon decay into a non baryonic system, with ΔB = 1, or even to neutron oscillation into an anti neutron, with ΔB = 2. No convincing experimental evidence for any of these processes has been reported, despite ever more sensitive searches using very large underground detectors(Groom, 2000).

Here we describe a new search for baryon-number violating processes using the 5.56 fiducial kiloton year (6.96 kTy total exposure) of the Soudan 2 iron tracking calorimeter (Allison, 1996). Detailed imaging of non-relativistic as well as of relativistic tracks enables efficient identification and (kinematic) analysis of events which have four or more final state ”prongs” (tracks/ showers). These high multiplicity final states are well suited to searching for neutron oscillation, since the resulting antineutron would collide with a baryon in the surrounding environment, and the subsequent $\bar{n}$ -N (where N = n or p) annihilation will usually yield a multipion final state.

Most multiprong final states contain several pions. Secondary scatterings of pions are likely, both within the (iron) nucleus where the pions were produced, and as (charged) pions traverse the iron sheets of the detector. These secondary scatterings will often alter the number of prongs of the observed event, as well as its visible energy and momentum, so that it becomes difficult and inefficient to isolate a specific multipion final state. Our simulations of events arising from atmospheric neutrino oscillations or nucleon decay or $\bar{n}$-n annihilation include a detailed model of intranuclear scattering (Mann, 1988) of final state pions. Because secondary scatterings can alter the number of visible prongs, and because of the small numbers of data events, we have carried out an analysis which is inclusive of several kinds of observed event topologies.

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2 Data Analysis

Data acquired during a detector exposure of 5.56 kTy was processed through our standard data reduction chain. Randomly interspersed with data events were simulated events induced by atmospheric neutrino interactions. This simulation of the major background was based upon the Bartol model of atmospheric neutrino fluxes, and took into account both elastic and inelastic neutrino scattering, as well as the detailed imaging properties of the Soudan 2 detector. These background ” ν MC events” were treated identically to real data events at each step of the data analysis chain.

Several systematic uncertainties must be considered when using these ν MC events as a measure of the background in our searches. Among these are normalization and solar cycle uncertainties in the atmospheric neutrino flux, possible effects of neutrino flavor oscillation upon the atmospheric muon neutrino flux, effects of poorly known partial cross sections for inelastic neutrino interactions at energies less than a few GeV, and uncertainties in intranuclear pion scattering effects in the final state.

Two important event parameters which were used in this analysis are E_{vis}, the summed total energy of the visible final state prongs, and P_{net}, the vector sum of their 3-momenta.

Electromagnetic showers were distinguished from muon and hadron tracks by their geometric structure.

3 Selections

The following topological selections were imposed upon all data events and simulated events: a) At least 4 prongs, including both prompt and remote prongs; b) No proton track; c) For $\bar{n}$-n candidates, no non-scattering track of length > 150 cm; d) For nucleon decay candidates, at least 3 of the prongs must be tracks, not showers.

Then the "signal" regions were defined by the following kinematic requirements. For nucleon decay candidates: $700 < E_{vis} < 1000\ MeV$ and $P_{net} < 400\ MeV/c$. For $\bar{n}$ annihilation events, $700 < E_{vis} < 1800\ MeV$ and $P_{net}/E_{vis} < 0.6$. These regions were chosen based upon detailed simulations of the physics of the processes being searched for, and represent compromises between high detection efficiency and good background rejection. These simulations are similar to those which we have done previously (Wall, 2000), and will be described elsewhere.

4 Results

Fig 1 shows the distribution of the 16 data events, and Fig 2 shows the corresponding distribution for ν MC events for a much larger exposure. (There is also a small background which we subtract from the data due to neutrons originating in the rock walls of the cavern.(Wall, 2000)

For nucleon decay, we find no candidate events and 0.3 (normalized) ν background MC events. The average estimated detection efficiency for various lepton plus 3 pion final states is (3±1.5)%, corresponding to a 90% CL lower limit on nucleon lifetime / branching ratio of 6×10^{31} yr. For multiparticle final states with fewer pions, the estimated efficiency rises to (20± 10)%, and the limit for tau/B becomes 4×10^{32} yr.

For neutron oscillation, the estimated detection efficiency is (18±2)%. Fig 1 shows that there are 5 events in the selected region, and our preliminary estimate of the ν MC background shown in Fig 2 is also approximately 5 events after normalization. Thus we have no evidence for a signal due to n oscillation.

5 Data Candidate Events

Calorimeter views of two (of the five) data events which are in the selected $\bar{n} - n$ kinematical region of Fig 1 are shown in Figs 3 and 4. These two events are only slightly outside of the kinematic acceptance region which we had chosen (a priori) for nucleon decay. We have therefore analyzed these two events with particular care.

The four-track event in Fig 3 has E_{vis} of about 1100 MeV if each track is either a pion or a muon. If one of the visible tracks was in fact an electron, E_{vis} would be about 1000 MeV, which is the edge of our acceptance region for nucleon decay. However, detailed track shape measurements disfavor the electron hypothesis.

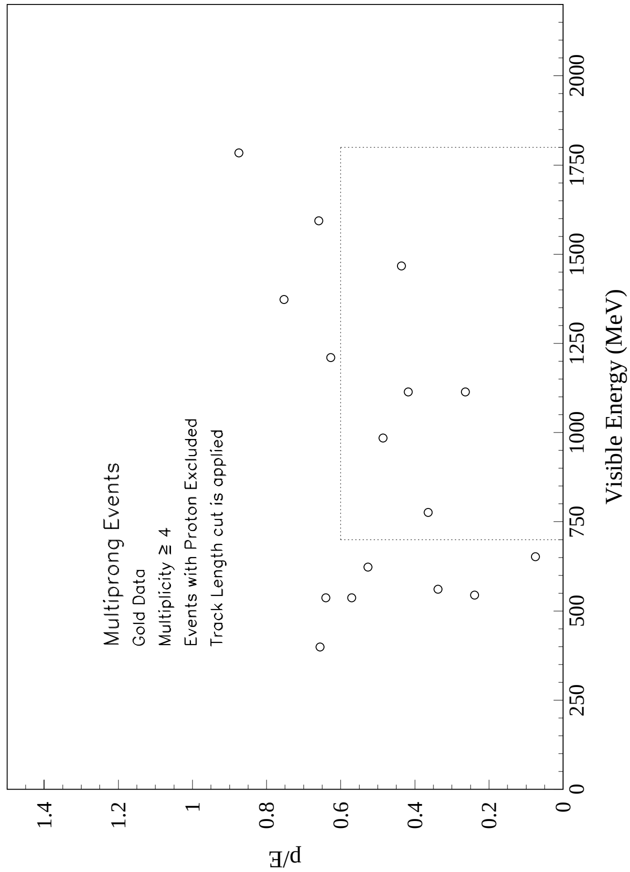

Fig. 1. Data candidate $\bar{n} - n$ events after topology cuts.

The event shown in Fig 4 has three tracks and two showers. Two of the tracks undergo large angular deflections in flight. We analyzed this event as a possible example of p goes to $\mu^+ K^0_S + \pi^0$. However, its P_{net} is 469 MeV/c, assuming that the scatterings of the two tracks are elastic. This is above our proton decay acceptance limit of 400 MeV/c If the scatterings are inelastic, P_{net} will be even larger.

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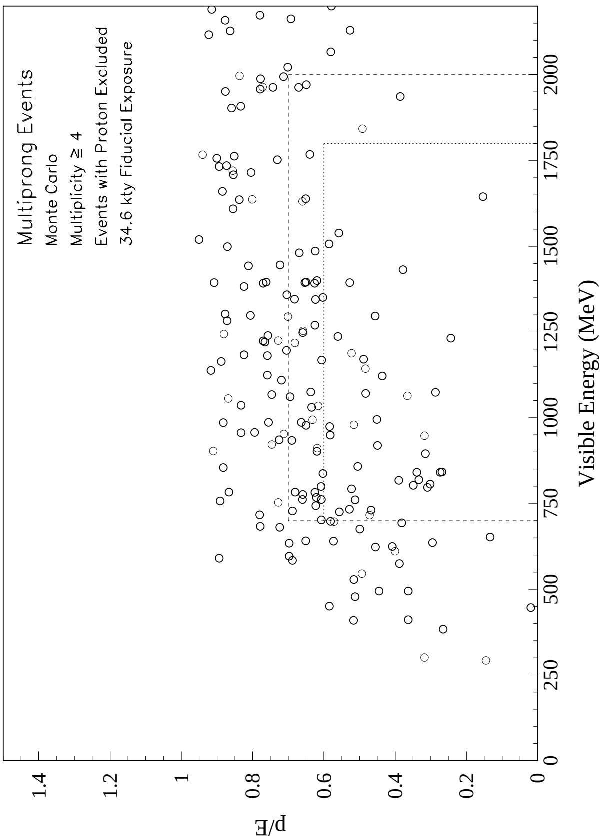

Fig. 2. Monte Carlo neutrino events after $\bar{n} - n$ topology cuts.

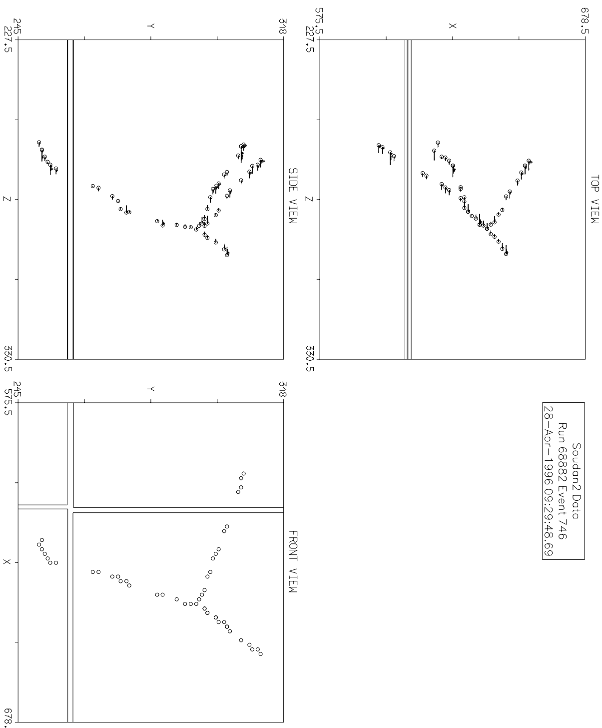

Fig. 3. Data Event. Axes are in centimeters.

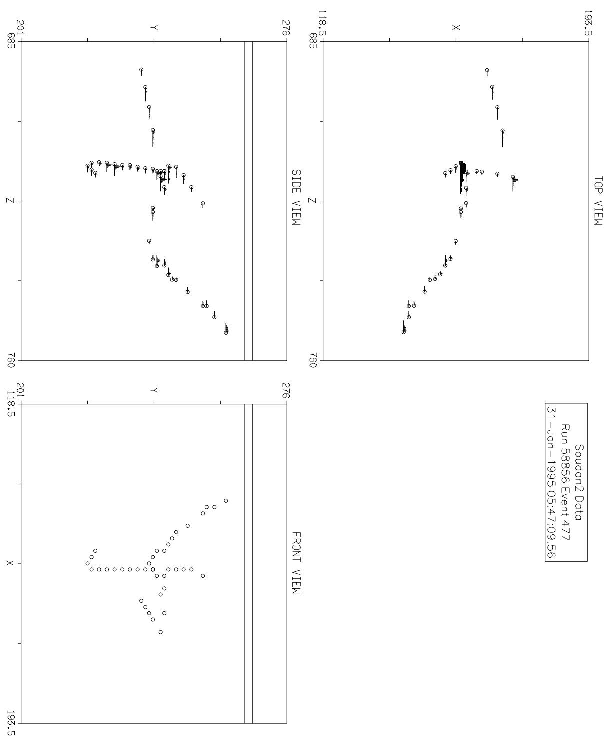

Fig. 4. Data Event. Axes are in centimeters.