Calculation of Atmospheric Neutrino-Induced Backgrounds in a Nucleon-Decay Search

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We have developed an extensive model of atmospheric ν interactions which provide the backgrounds to nucleon-decay experiments. We report results from a 417-live-day exposure of the Irvine-Michigan-Brookhaven detector. During this time 401 contained events were observed at a rate and with characteristics consistent with atmospheric ν interactions. We have calculated the expected backgrounds to a variety of two- and three-body decay modes and have set lower limits on many nucleon partial lifetimes.

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It has been experimentally shown that the nucleon partial lifetimes for a wide variety of decay modes are longer than order of 10^{31} years.[1] Further progress in the search for nucleon decay in any detector is limited by the lack of knowledge of the backgrounds produced by the interactions of atmospherically produced ν's. Several groups[2,3] have studied atmospheric ν interactions as a background to nucleon decay. One such approach is to use cross sections derived from theoretical models; the other leans more heavily on experimental observations. These studies are of limited use because they are either based on crude simplifications of this very complex problem, or are based on data that has various systematic or statistical uncertainties. The ideal solution is to expose each detector to a large number of ν interactions. Another possible solution is to model such interactions theoretically using the available knowledge of ν interactions in the energy range of interest ($\sim$0.25–5 GeV). Such a model has to provide not only the correct overall rate of ν interactions, but also the correct distribution in many specific kinematical regions of interest where a signal from nucleon decay might be found. The uncertainties in such a model put basic limits on the ability to detect nucleon decay using these techniques.

We report initial results from a detailed simulation of atmospheric ν interactions in the Irvine-Michigan-Brookhaven (IMB) detector, which is an 8000-metric-ton ring-imaging water Cherenkov detector designed to search for nucleon decay.[3] The ν simulation corresponds to about 12 years of detector live time. The data reported here correspond to 417 live days of detector operation with a fiducial volume of 3.3 ktonne. Therefore, it is possible to make a quantitative comparison of the results of the calculation with a large sample of atmospheric ν interactions.

There are four major factors entering the calculation of the ν background in proton-decay detectors: (i) detailed information about the atmospheric ν flux and spectrum at a given experimental site; (ii) complete information about the ν interactions, including cross sections and kinematical distributions for all possible final states; (iii) information about nuclear interactions of the final particles in the complex nuclei in which the interaction occurs as well as in the detector medium; and (iv) a complete simulation of the response of the detector to the interactions. We will discuss each of these components separately.

The flux, composition, and energy distribution of atmospheric ν's have been extensively calculated by many authors.[4] We have adopted the results of the latest and most detailed calculations by Gaisser *et al.* which were done specifically for the site of the IMB detector.

Low-energy ν interactions ($E_\nu \leq 5$ GeV) are not understood in detail because of various experimental difficulties. There have been only a few bubble-chamber experiments dedicated to looking at low-energy ν interactions. The data from these experiments provide information for only a small number of possible final states. The quasielastic and single-pion processes that dominate at low energies have been extensively stud-

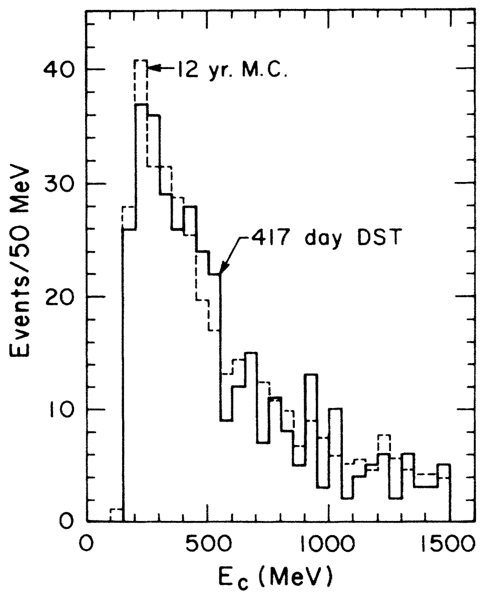

FIG. 1. E_C distributions for the 417-day data (solid line) and the 12-yr ν simulation (dashed line) normalized to 417 days.

ied for both ν types and for both charged and neutral current interactions, and the absolute cross sections and kinematical details of these processes are sufficiently well known. Some measurements have been done for double-pion production, but for more than two pions the data are very meager.

To describe low-energy ν scattering, we consider both charged- and neutral-current weak interactions. This includes the quasielastic process, single-pion production, and multiple-pion (2,3) production.[5] We have used the standard description of quasielastic ν interactions.[6]

Out of the many theoretical models describing single-pion production by the weak current[7] we have adopted the model of Fogli and Nardulli (FN) because of its good agreement with the experimental data. Briefly, the model includes pion production by both $I=\frac{1}{2}$ ($P11,S11,D13$) and $I=\frac{3}{2}$ ($P33$) resonances as well as by nonresonant Born background terms. Our parametrization of both quasielastic and single-pion production follows that of FN and is taken mostly from electroproduction experiments. The FN model has been reformulated, independently of the original authors, to suit our use of Monte Carlo techniques. We have checked that our formulation of the model also agrees very well with existing ν data in absolute cross sections and kinematical distributions (Q^2 and hadronic invariant mass).

Since there is no convincing evidence for resonance dominance in weak multiple-pion production, we have based our model of two- and three-pion production on

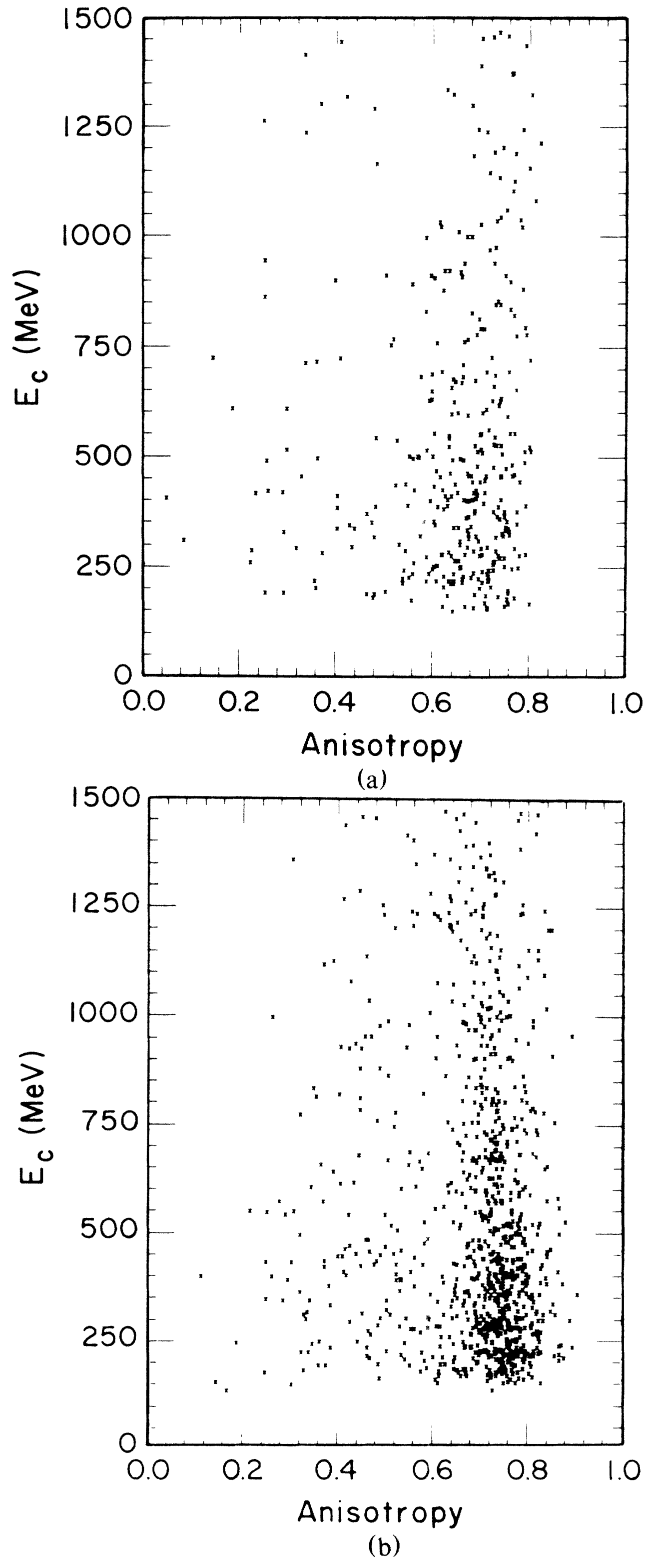

FIG. 2. E_C vs A for (a) the 417-day data and (b) 3.4-yr representative portion of the 12-yr ν simulation. Each cross represents an event.

the parton model of deep-inelastic scattering. Because of the rapid decrease with energy of the atmospheric ν spectrum, we have found three- or more-pion production to contribution about 2% of the total atmospheric rate and to be a negligible contribution to nucleon-decay backgrounds. The leptonic vertex has been calculated by use of the parton x and y distributions; the final hadronic configuration is taken randomly from the available phase space. This model of multiple-pion production has been adjusted to agree with the available data.[8]

In order to evaluate the expected signal from atmospheric ν's, it is necessary to simulate the ν-induced events in our detector with Monte Carlo techniques. The event simulation begins by choosing the ν flavor, energy, and zenith angle from the expected atmospheric flux as well as the initial-nucleon type and Fermi momentum when appropriate. The final-state particles, cross sections, and kinematics are chosen based on the model of ν interactions. If the interaction was on an oxygen nucleus, the pions are propagated through the parent nucleus using a nuclear cascade model developed by us.[9] In the nucleus the pions may scatter, charge exchange, or be absorbed. The final particles are then propagated through the water where pions again undergo interactions on nuclei. The Cherenkov light output is calculated and the response of the detector to the light is simulated. In this way, we have a complete simulation of the response of our detector to a large exposure of atmospheric ν interactions.

To include the effects of our detection thresholds, efficiency, and resolutions, the simulated events are passed through our standard analysis procedures. The results of this analysis confirm our previous estimates of the event-finding efficiency of between 70% and 90% depending on the particular event topology.

The final sample of simulated atmospheric ν events corresponds to about 12 years of live time. From the simulation, we expect to record 402 ± 20 events in 417 days of live time. This agrees well with our observed value of 401 events in 417 days.

As in Ref. 3, we characterize the events using the two parameters E_C, the Cherenkov equivalent energy, and A, the anisotropy. Essentially, E_C is a measure of the visible energy and A is a measure of the visible momentum imbalance in an event. For a single radiating track in the detector one expects $A \simeq 0.7$, while for two symmetric, back-to-back tracks $A \simeq 0$.

Figure 1 shows the observed E_C distributions for the data and atmospheric ν simulation. These agree quite well over the entire range of energies; the χ^2 for the comparison between these two distributions is 43/44 degrees of freedom (DOF). Figure 2 shows scatter plots of E_C and A for both the data and simulation. We have checked that these distributions agree very

TABLE I. IMB limits on nucleon partial lifetime. Different estimates are given for different meson decay modes. Some events are candidates for more than one mode. Lifetime limits are 90% C.L. not including background subtraction. Reference 5 details the method used for combining modes with more than one requirement region.

Mode	Effic. With Nuclear Corr.	Candidates Observed	ν Simulation Background Estimate $\pm - 30\%$	Unsubtracted Limit on τ/β ($\times 10^{31}$ Yr.) 90% C.L.
$p \to e^+ \gamma$	0.66	0	0.28	36.
$p \to e^+ \pi^0$	0.46	0	0.28	25.
$p \to e^+ K^0$	0.12	5	4.2	
	0.14	0	0.28	7.7
$p \to e^+ \eta^0$	0.37	0	0.28	
	0.07	5	3.0	20.
$p \to e^+ \rho^0$	0.16	7	6.7	1.7
$p \to e^+ \omega^0$	0.19	6	5.0	
	0.05	0	0.28	3.7
$p \to \mu^+ \gamma$	0.52	3	1.9	9.7
$p \to \mu^+ \pi^0$	0.32	2	0.9	7.6
$p \to \mu^+ K^0$	0.19	4	4.5	
	0.14	3	1.9	4.0
$p \to \mu^+ \eta^0$	0.23	3	1.9	
	0.12	4	4.2	4.6
$p \to \mu^+ p^0$	0.10	4	4.5	1.6
$p \to \mu^+ \omega^0$	0.18	6	5.5	
	0.03	2	1.1	2.3
$p \to \nu K^+$	0.08	6	4.7	1.0
$p \to \nu \rho^+$	0.07	6	4.7	0.8
$p \to \nu K^{*+}$	0.09	7	6.2	1.0
$p \to e^+ e^+ e^-$	0.93	0	0.28	51.
$p \to \mu^+ \mu^+ \mu^-$	0.58	1	0.1	19.
$n \to e^+ \pi^-$	0.40	8	8.6	3.1
$n \to e^- \pi^+$	0.10	5	3.1	
	0.10	4	3.6	1.6
$n \to e^+ \rho^-$	0.20	9	3.9	1.4
$n \to e^- \rho^+$	0.22	13	5.6	1.2
$n \to \mu^+ \pi^-$	0.30	8	7.2	2.3
$n \to \mu^- \pi^+$	0.29	7	6.2	2.5
$n \to \mu^+ \rho^-$	0.07	6	4.6	0.7
$n \to \mu^- \rho^+$	0.10	7	4.9	0.9
$n \to \nu \gamma$	0.77	73	60.	0.9
$n \to \nu \pi^0$	0.51	73	60.	0.6
$n \to \nu K^0$	0.10	3	5.0	1.5
$n \to \nu \eta^0$	0.29	7	5.9	2.5
$n \to \nu \rho^0$	0.05	15	9.7	0.2
$n \to \nu \omega^0$	0.08	5	5.0	
	0.03	1	0.5	1.2
$n \to \nu K^{*0}$	0.06	8	7.1	0.5
$n \to e^+ e^- \nu$	0.41	5	5.0	4.5
$n \to \mu^+ \mu^- \nu$	0.31	14	7.3	1.6

well not only globally but also in small regions. The simulation predicts that 34% ± 1% of the events should have an identified muon decay while our data has 26% ± 3%. This discrepancy could be a statistical fluctuation or a systematic error due to (i) an incorrect assumption as to the ratio of muon ν's to electron ν's in the atmospheric fluxes, (ii) an incorrect estimate of the efficiency for our observing a muon decay, or (iii) some other as-yet-unaccounted-for physics. Any effect of this discrepancy has not been considered in calculating the nucleon-decay results.

Possible systematic errors in the background estimates include the uncertainties in the absolute atmospheric ν flux (± 20%), uncertainties in absolute ν cross sections (± 20%), and uncertainties in the details of the kinematical distributions of ν interactions. In conclusion, we estimate the systematic uncertainty in the background calculation to be ± 30%. We note that this background calculation in general agrees rather well with our previous estimate[3] which was based on a very different method, namely, extracting experimental information on final states from Gargamelle bubble-chamber data.

We proceed to search for a nucleon-decay signal by making requirements on E_C, A, and the number of observed muon decays for each event. The specific requirements for all 34 decay modes considered are given in Ref. 3. Table I gives the results of the search and a comparison with the background estimate. Also included is the 90% C.L. lower limit on the nucleon partial lifetime. Upon examination of Table I, it can be seen that the observed number of candidates for each mode is consistent with the background estimate. There is no significant excess of events in any decay mode; the apparent excess of neutron decays to states with ρ mesons is not statistically significant and is not observed for protons.

In summary, we have completed an investigation of the backgrounds to nucleon decay due to atmospheric ν interactions. We have found that, in order to provide reliable background estimates, it is necessary to include not only ν-induced single-pion production but also multiple-pion production. There is no significant difference between the ν interaction simulation and the data we have observed in the detector, except perhaps the fraction of events with an identified muon decay. Also, there is no significant excess of events observed in any decay mode that would indicate a nucleon-decay signal. The lower limits for the nucleon lifetime range from roughly order of 10^{31} years to order of 10^{32} years. We believe our background estimate is now limited by systematic uncertainties in the atmospheric ν flux and the available data for ν interactions. To reduce these systematic uncertainties will require specific experiments dedicated to a more detailed understanding of low-energy ν interactions and more precise atmospheric ν flux measurements.

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