NUCLEON DECAY RESULTS FROM THE IMB DETECTOR*

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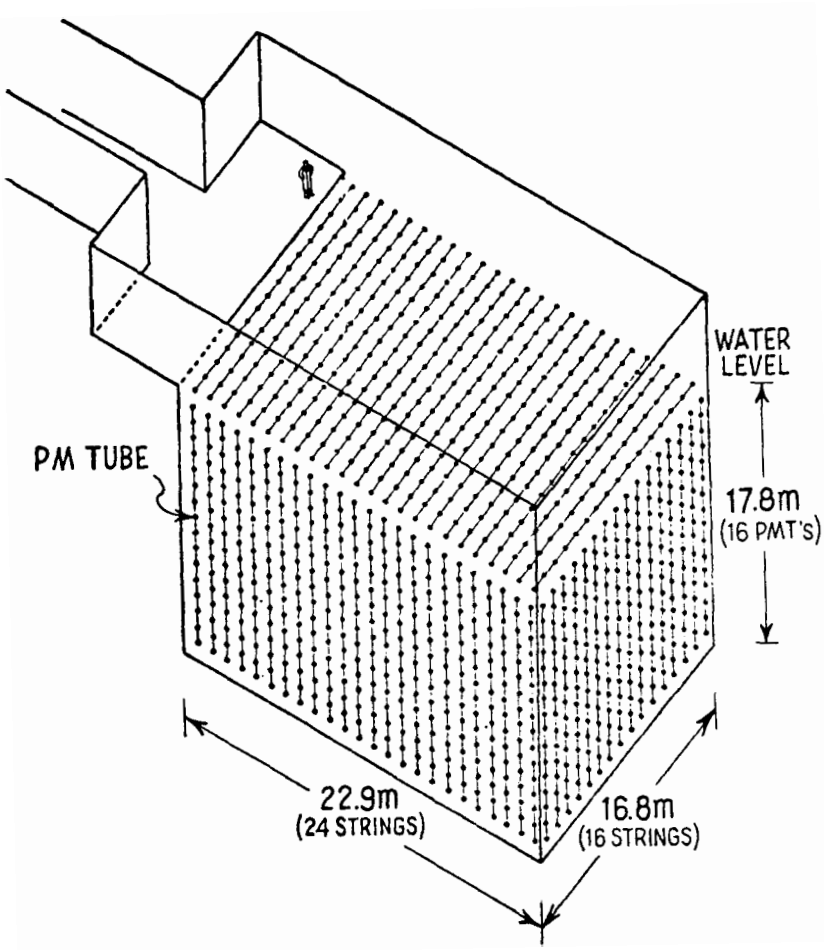
ABSTRACT

Results are presented from 204 days of live-time in the Irvine-Michigan-Brookhaven (IMB) proton decay detector. Partial lifetime limits at the 90% C.L. are given for 32 nucleon decay modes.

THE IMB DETECTOR

The Irvine-Michigan-Brookhaven (IMB) detector consists of a large rectangular volume of purified water ($17 \times 18 \times 23$ m^3) located in the Morton-Thiokol salt mine in Fairport Harbor, Ohio. The detector is situated at a depth of 2000', which corresponds to 1570 meters of water equivalent overburden and a cosmic ray muon flux of 2.7 per second through the detector. 2048 EMI 5" diameter hemispherical photomultiplier tubes (PM's), operated at the single photoelectron level, face inward toward the volume of water and record Cherenkov light produced by the passage of relativistic charged particles. The PM's are positioned on all six surfaces of a rectangular grid of ~1 m spacing, as shown in Figure 1, with 50 cm of water between the PM grid and the cavity walls. A fiducial volume which begins two meters in from the PM planes is used as the sensitive region for observing nucleon decay.

The arrival time (T_1) and the pulse height (Q) for each hit tube are recorded. The time resolution of the PM's is 5.5 ns (HWHM), which, together with the topological information provided by the PM hit pattern, allows for the reconstruction of the position and direction of relativistic charged particles in the detector. In addition to T_1, a second timing scale (T_2) records subsequent PM firings out to 7.5 μs, allowing for the detection of muon decays with a 65% efficiency. The number of false muon decay signals is less than 1%. Energies are obtained by summing the calibrated Q of all firing PMT's. The energy calibration is performed using cosmic ray muons and has a systematic uncertainty of ±15%. The measured energy of a particle will depend not only on its total energy but also its mass, due to Cherenkov threshold effects. The measured energy therfore labelled as a Cherenkov equivalent energy, E_C: the energy equivalent of a massless charged particle with total energy E_C. Electrons, gammas and π^0's will have $E_{tot} = E_C$, whereas a muon with 500 MeV of total energy will have E_C = 260 MeV.



IRVINE - MICHIGAN - BROOKHAVEN DETECTOR

Figure 1.

DATA ANALYSIS

We will report here on 204 days of live-time. Within this time, $\sim 5\times10^7$ triggers were recorded, most of them due to cosmic ray muons. A few percent of the triggers are due to stopping muons or multiple muons. The stopping muons are used to study the muon decay detection efficiency. The number of accidental triggers due to noise is negligible. The expected rate of neutrino induced background events is ~1 event/day which corresponds to a nucleon lifetime of $\sim 5\times10^{30}$ yr, observed with 100% efficiency in the fiducial volume.

There are actually three independent analysis chains, two carried out at Michigan and the other at Irvine, with the common goal of identifying and reconstructing all events in the energy range ($150 < E_c < 2000$ MeV) and which orginated in the fiducial volume. These events will consist of neutrino interactions, possible nucleon decays and perhaps other new physics. Computer simulations show that the efficiency for saving neutrino interactions in this energy range is >90% at higher energies and >70% at the lowest energies. The overlap of the two independent analyses is consistent with these efficiencies. Nucleon decay events such as $p \rightarrow e^+ \pi^0$ in the fiducial volume are saved with >90% efficiency.

In 204 days of livetime, we have identified 169 events originating in the fiducial volume and in the energy range $150 < E_c$ 2000 MeV. Some of the events have clear and reconstructable tracks, while others have no obvious distinguishable track. Other events may have one or more distinguishable tracks plus a significant number of PM hits which cannot be obviously associated with a track. The various nucleon decay modes we have studied will produced PM hit patterns which vary in topology and the number of distinguishable track. For example, the decay $p \rightarrow e^+ \pi^0$ will give 2 clear

and distinguishable tracks, whereas the decay:

$$n \rightarrow \nu K^0_S \rightarrow \pi^0 \pi^0$$

will result in an PM hit pattern much like that produced by an isotropic, instantaneous point source of light.

The events are characterized by three variables: E_c, the number of muon decays, and the anisotropy A. The variable A is defined as the magnitude of the sum of the unit vectors from the reconstructed vertex to each hit PM, and lies in the range from 0 to 1. Events which have isotropic PM hit patterns will have small values of A, which is characteristic of most nucleon decays. An event which consists of a single, contained, non-showering track (i.e. a muon) will have $A \simeq 0.75$, which is the cosine of the Cherenkov angle. Figure 1a shows the distribution of E_c vs. A for the 169 events found in 204 days of livetime.

The neutrino induced background was simulated using data summary tapes from the Gargamelle freon bubble chamber. The reconstructed particle types and momenta were used as input to the IMB computer simulation program, and the generated events were subsequently weighted to follow the atmospheric neutrino flux and put through the analysis chain. This technique automatically accounts for complicated nuclear effects which determine the topological and particle multiplicity distributions we should observe from neutrino interactions. Of course, this method has its drawbacks (e.g. freon is not water), but is more straightforward than a realistic first-principles simulation. It is vital that distributions of the various final states be simulated carefully, since it is the rare event on the edges of these distributions which can mimic nucleon decay. Figure 2c show the E_c vs. A plot for a simulation of neutrino interactions in 204 days. I will not give detailed background estimates here; they will be presented in a forthcoming PRL paper.

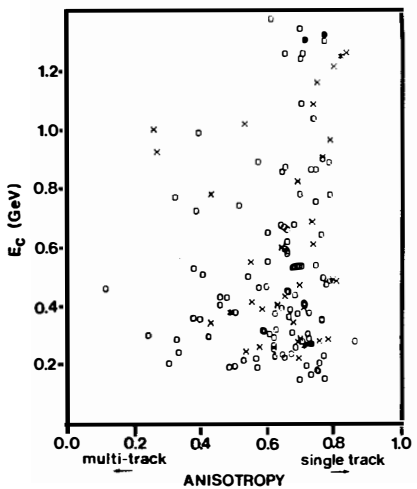


Fig. 2(a) E_c vs. A for the 169 contained events from 204 live days of data. Events with one identified $\mu \to e$ decay are indicated by "x", those with ≥2 by "*".

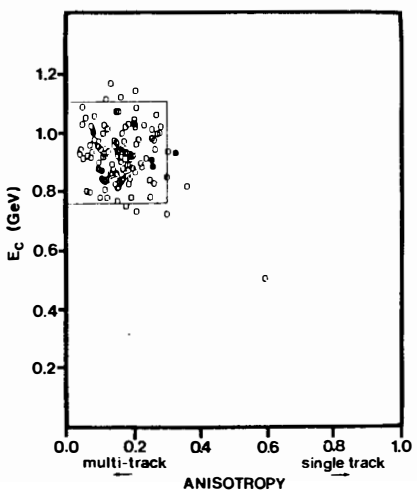


Fig. 2(b) E_c vs. A for a representative nucleon decay mode, $P \to e^+ \eta^o$; $\eta^o \to \gamma\gamma$ The square box cuts indicate the region in which candidates are accepted for this mode.

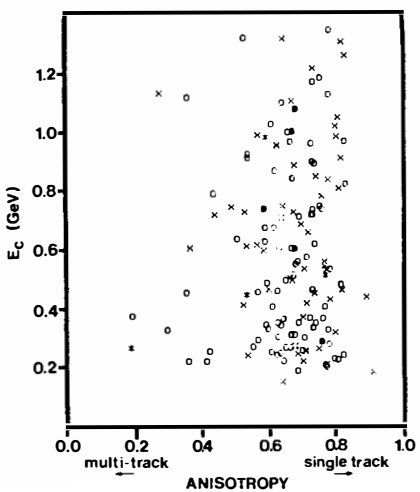


Fig. 2(c) E_c vs. A for a simulation of 204 days of atmospheric neutrino interactions.

RESULTS

By using the neutrino background simulation and the simulation of individual decay modes, we identify the cuts in E_C, A, and number of muon decays which gives the best signal-to-background for each mode. We have chosen to make simple, rectangular cuts in E_C vs. A. Figure 2b shows the simulation of one nucleon decay mode and the cuts chosen. For modes such as $p \rightarrow e^+ \pi^0$, which will give very distinctive PM hit patterns, we also make a cut based on inspection of the events on our color graphics system. This cut is denoted by "b-b" (back-to-back) in Table 1. All simulations of nucleon decays include nuclear interactions of mesons, both within ^{16}O and in water (pion and kaon scattering, absorption and charge exchange, and K_L interactions) and Fermi motion. Simulations of neutrino interactions have nuclear interactions in ^{16}O inherently included by the simulation method, while meson interactions in water are simulated explicitly as above.

Table 1 summarizes the cuts and results for the 32 nucleon decay modes. The nucleon lifetime limits are 90% C.L. limits obtained without performing any background subtraction. For the nucleon decays which do not include a neutrino, there are eight events which fall within the union of all the cuts. These eight events are listed in Table 2.

CONCLUDING REMARKS

To summarize the IMB search for nucleon decay events in 204 days of live-time:

- We have obtained limits on 32 different nucleon decay modes. Although I have not presented detailed background estimates for specific decay modes, it is apparent from Figures 2a and 2c that there is no glaring nucleon decay signal in the data. For many of the simple SU(5) modes ($e^+\pi^0$, $\mu^+\pi^0$,...) we have observed no compatible events.
- The overall rate and characteristics of the events which originate in the fiducial volume are consistent with neutrino interactions.

• Yes, Virginia, we do have events which are consistent with nucleon decays. These events are, however, also consistent with expectations from neutrino interactions.

• We have recently recieved the go-ahead on plans to upgrade the detector, which will eventually increase our light collection by a factor of four. This will provide us with much cleaner looking events, and we will be able to improve our seperation of nucleon decays from neutrino background.

ACKNOWLEDGEMENTS

I would like to thank the Moriond gang for inviting me so I could learn how to ski.

REFERENCES

1. B. Cortez, "A Search for Nucleon Decay Into Lepton and K^0", Harvard University, PhD. Thesis, 1983

TABLE 1

Summary of Nucleon Lifetime Limits From 204 Days of Livetime

1	2	3	4	5	6	7	8
Mode	Requirements				Eff. with Nuclear Corr.	No. of Cand Obs.	Limit on τ / B ($\times 10^{31}$ yr)
	E_c (Mev)	A	#μ	b-b			
1 $p \to e^+\pi^\circ$	750-1100	< 0.3	0	0	0.61	0	17.
2 $p \to \mu^+\pi^\circ$	550-850	< 0.5	1	1	0.39	0	11.
3 $p \to e^+\eta^\circ$	750-1100	< 0.3	0		0.42	0	12.
4 $p \to \mu^+\eta^\circ$	550-850	< 0.4	1		0.31	0	9.
5 $p \to e^+\rho^\circ$	300-600	< 0.5	1		0.12	1	1.9
6 $p \to \mu^+\rho^\circ$	175-400	< 0.5	1,2		0.16	2	1.9
7 $p \to e^+\omega^\circ$	300-600	< 0.5	1		0.12	1	2.0
8 $p \to \mu^+\omega^\circ$	200-450	< 0.5	1,2		0.33	2	4.
9 $p \to e^+\gamma$	750-1100	< 0.4	0	2	0.74	0	20
10 $p \to \mu^+\gamma$	550-800	< 0.5	1	1	0.47	0	13.
11 $p \to e^+K^\circ$	†				0.31	1	5.7
12 $p \to \mu^+K^\circ$	†				0.35	2	4.4
13 $p \to \nu K^+$	150-375	0.3-.65	1		0.11	3	1.0
14 $p \to \nu K^*$	250-500	0.3-0.6	1		0.09	4	0.7
15 $p \to e^+e^+e^-$	750-1100	<0.3	0		0.93	0	25.
16 $p \to \mu^+\mu^+\mu^-$	200-425	< 0.5	2,3		0.57	1	9.
17 $n \to \nu \pi^\circ$	325-625	0.6-0.8	0		0.52	27	0.7
18 $n \to \nu \eta^\circ$	475-800	< 0.5	0		0.56	4	3.5
19 $n \to \nu \gamma$	325-600	0.6-0.8	0		0.76	26	1.1
20 $n \to \nu \omega^\circ$	200-425	0.3-.65	1		0.16	6	0.8
21 $n \to e^+\pi^-$	500-950	< 0.5	0		0.35	4	2.2
22 $n \to \mu^+\pi^-$	200-700	< 0.5	1		0.42	1	5.
23 $n \to e^+\rho^-$	500-850	< 0.5	0		0.40	4	2.5
24 $n \to \mu^+\rho^-$	250-625	< 0.5	1		0.22	1	2.9
25 $n \to e^-\pi^+$	500-950	< 0.5	0,1		0.34	6	1.6
26 $n \to \mu^-\pi^+$	200-550	< 0.5	1,2		0.32	2	3.0
27 $n \to e^-\rho^+$	500-850	< 0.4	1		0.12	0	2.6
28 $n \to \mu^-\rho^+$	225-600	< 0.5	1,2		0.25	2	2.3
29 $n \to \nu K^\circ$	450-750	0.2-0.5	0		0.11	3	0.8
30 $n \to \nu K^*$	200-700	.15-0.5	1		0.06	1	0.7
31 $n \to e^+e^-\nu$	500-850	< 0.5	0		0.41	4	2.6
32 $n \to \mu^+\mu^-\nu$	150-375	.2-.65	1,2		0.45	4	2.8

Notes:

1. For 3-body decay modes flat phase space was assumed.
4. No. of muon decay signals required.
5. No. of events rejected by a two-track with opening angle >140° requirement. Efficiencies include an estimated 90% scanning efficiency for this requirement.
6. This efficiency includes the detection efficiency after all requirements, including nuclear effects, and meson branching ratios.
7. Some events are candidates for more than one mode. (see Table 2 for the 8 events which are candidates for non-neutrino modes.)
8. Lifetime limits quoted are at 90% CL for 204 days of livetime and do not include background subtraction.

† Cuts for e^+K° and μ^+K° are different for K°_L, $K^\circ_S \to \pi^\circ\pi^\circ$, and $K^\circ_S \to \pi^+\pi^-$. See ref. 1.

Table 2. Nucleon Decay Candidates*

EVENT NO.	ENERGY E_c (MeV)	ANISOTROPY A	NO OF MUON DECAYS	POSSIBLE INTERPRETATION
143-21939	780	0.43	1	$e^-\pi^+$
225-7794	920	0.27	1	$e^-\pi^+$
299-72044	770	0.32	0	$e^+\pi^-, e^+\rho^-$ $e^-\pi^+$
510-54208	720	0.39	0	$e^+\pi^-, e^+\rho^-$ $e^-\pi^+$
588-8320	370	0.49	2	$\mu^+\rho^0, \mu^-\rho^+, \mu^+\omega^0$ $\mu^+\mu^+\mu^-, \mu^-\pi^+$ μ^+K^0
656-11673	530	0.38	0	$e^+\pi^-, e^+\rho^-$ $e^-\pi^+$
663-1770	500	0.41	0	$e^+\pi^-, e^+\rho^-$ $e^-\pi^+$
747-44203	340	0.43	1	$e^+\rho^0, \mu^+\rho^0$ $e^+\omega^0, \mu^+\omega^0$ $\mu^+\pi^-, \mu^+\rho^-$ $\mu^-\pi^+, \mu^-\rho^+$ e^+K^0, μ^+K^0

*Modes with a neutrino are not included, e.g., νK^+, $\nu\pi^0$, $e^+e^-\nu$.