A SEARCH FOR NUCLEON DECAY WITH MULTIPLE MUON DECAYS

HPW Collaboration

T.J. PHILLIPS [a,1], J. MATTHEWS [b,2], E. APRILE [a,3], D. CLINE [b,4], J. GAIDOS [c], K.L. GIBONI [a,5], G. KALKANIS [b,6], R. LOVELESS [b], R. MARCH [b], R. McHENRY [c,7], A. MORE [b,8], R. MORSE [b], J. NEGRET [c,9], T.R. PALFREY [c], C. RUBBIA [a,10], G. SEMBROSKI [c], C. WILSON [c], D.R. WINN [a,11] and W. WORSTELL [a,12]

[a] *Physics Department, Harvard University, Cambridge, MA 02138, USA*
[b] *Physics Department, University of Wisconsin, Madison, WI 53706, USA*
[c] *Physics Department, Purdue University, West Lafayette, IN 47907, USA*

Received 7 March 1989

A search was made for nucleon decays which result in multiple delayed muon decays using the HPW water Čerenkov detector. No contained events were found, which is consistent with the expected neutrino background of 0.7 ± 0.2 events. Lower lifetime limits are calculated for eleven proton decay modes and five bound neutron decay modes, ranging from 2×10^{30} yr to 1×10^{31} yr.

In recent years, many grand unified theories (GUTs) have been proposed to unify the strong, the weak, and the electromagnetic forces. Most of these theories predict that baryon number is not conserved and that protons and bound neutrons can decay. The simplest of these theories, minimal SU_5, predicts that the proton decays to $e^+ + \pi^0$ with a partial lifetime of $\tau/BR=4.5\times10^{29\pm1.7}$ yr [1–3]. Previous searches have set a lower limit on this decay mode of 2.5×10^{32} yr [4], which is inconsistent with the SU_5 prediction.

Other GUTs are less precise in predicting nucleon decay lifetimes and branching ratios. However, many of the theories, especially supersymmetric theories, predict that other decay modes will dominate. Many of these decay modes produce multiple muons [5], both directly and from the decay chains of mesons, as listed in table 1. The decays of these muons can provide a clean signature for nucleon decay events, but this requires a high muon decay detection efficiency. These nucleon decay modes will also result in missing energy, and, especially for Čerenkov detectors, require a detector capable for resolving low visible energies, as low as 50 MeV.

We have operated a 680 metric ton water Čerenkov detector, which has sufficient sensitivity to search for low energy, multi-muon decay events, at a depth of 1500 meters-of-water equivalent. The HPW (Harvard–Purdue–Wisconsin) detector consisted of a cylindrical tank of water 5.6 m in radius and 7 m deep. The tank was instrumented with 704 five-inch photomultiplier tubes on a volume array with a lat-

[1] Also at Fermilab, MS 318, Batavia, IL 60510, USA.
[2] Present address: Physics Department, University of Michigan, Ann Arbor, MI 48109, USA.
[3] Present address: Physics Department, Columbia University, New York, NY 10027, USA.
[4] Present address: Physics Department, UCLA, Los Angeles, CA 90024, USA.
[5] Present address: Schlumberger-Doll Research, Ridgefield, CT 06877-4108, USA.
[6] Present address: Physics Department, University of Athens, Athens, Greece.
[7] Present address: The Mitre Corporation, 1820 Dolly Madison Boulevard, McLean, VA 22102, USA.
[8] Present address: 85 South Ridgeview Drive, Bountiful, UT 84010, USA.
[9] Present address: Fermilab, MS 122, Batavia, IL 60510, USA.
[10] Present address: CERN, CH-1211 Geneva 23, Switzerland.
[11] Present address: Physics Department, Fairfield University, North Benson Road, Fairfield, CT 06430, USA.
[12] Present address: Physics Department, Boston University, Boston, MA, USA.

tice spacing of approximately one meter (88 tubes in each of eight layers). The inside walls of the tank were lined with mirrors to increase the light collection efficiency, which gave the detector good calorimetry. The detector was surrounded by an array of 422 proportional wire chambers 6.1 m long and 15 cm wide which acted as an active shield by recording the positions of charged particles which passed into and out of the tank with a resolution of 40 cm along the wire. The wire chambers provide 80% coverage on the top and the sides of the detector and 50% coverage on the bottom. The wire chambers were not used directly in this analysis, but were used as secondary evidence to help confirm interpretations of events. A schematic of the detector is shown in fig. 1.

The detector was triggered by a coincidence of two or more phototubes in each of three or more groups. Each group contained three adjacent columns for a total of 24 phototubes. This trigger corresponds to a minimum energy of approximately $E_c \approx 10$ MeV, where the Čerenkov energy E_c is defined as the energy of a contained showering particle which would give the same light yield as observed.

The primary trigger caused timing and pulse height information from the phototubes to be recorded, as well as a current-division readout from the wire chambers. Phototube timing information was digitized with an accuracy of 3 ns for 512 ns after a primary trigger. Double hit resolution was 45 ns. The electronic data collection scheme is shown in fig. 2.

A secondary trigger was enabled for 15 μs after a primary trigger to record light from muon decay electrons. The secondary trigger consisted of a coincidence of two or more phototubes in each of at least two groups. Each secondary trigger caused an additional 256 ns of timing digitization; up to seven secondary triggers within the 15 μs window were permitted. All positive muons which stop in the tank will decay into electrons, while 18% of the negative muons will form muonic atoms and be absorbed before they can decay. Muon decay secondary triggers are selected from a background of triggers caused by phototube after-pulsing on the basis of the amount of light collected and the distribution of phototube hits in time. The efficiency for a muon which decays during the secondary trigger window to cause a trigger and pass the selection criterion is 83%. The timing and energy distributions of secondary triggers selected as muon decays are shown in figs. 3a and 3b, respectively. The low trigger threshold is apparent from fig. 3b.

The entire HPW data set consists of 17.2×10^6

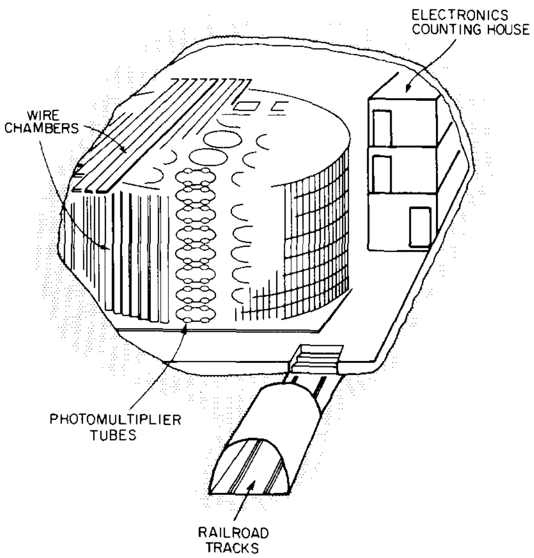

Fig. 1. Schematic representation of the HPW detector, showing the physical construction of the detector.

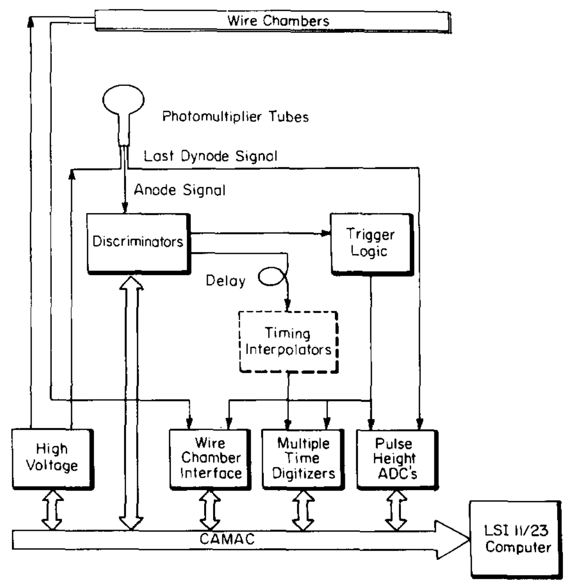

Fig. 2. Schematic representation of the data acquisition electronics. The timing interpolators were added half way through the data set and improved the time resolution from 8 ns to 3 ns.

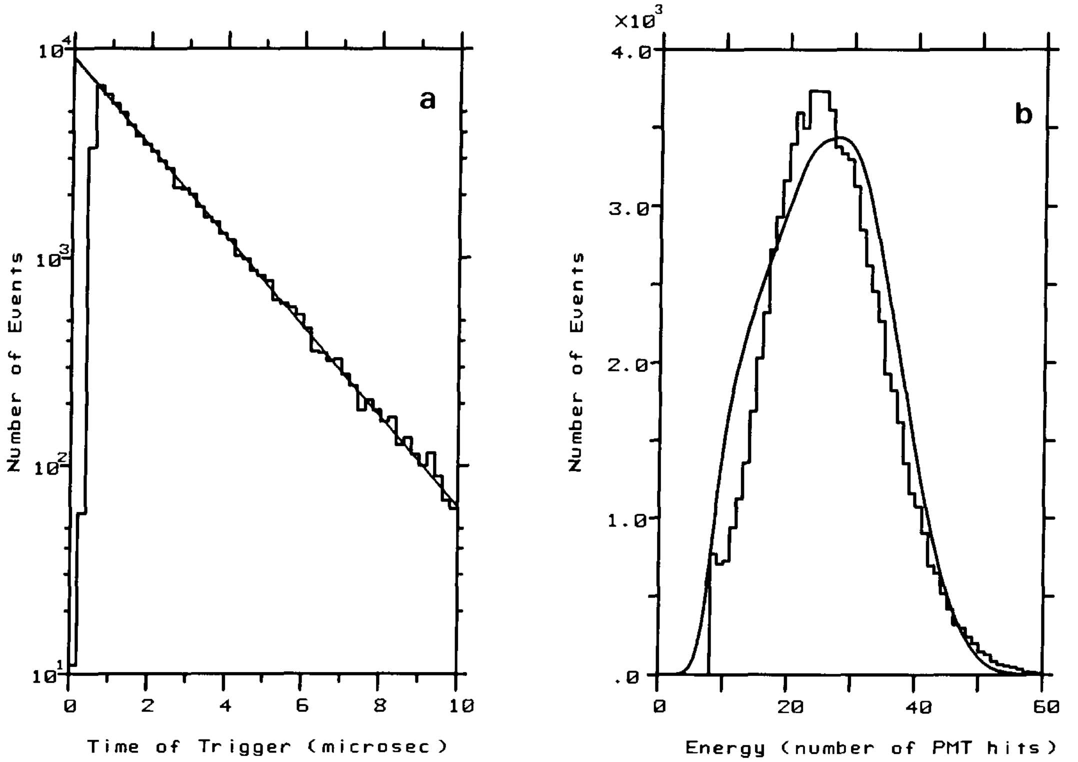

Fig. 3. Characteristics of secondary triggers with muon decays. (a) shows the time of the trigger, along with the predicted exponential lifetime based on the lifetimes of positive and negative muons in water and the measured charge ratio [6]. (b) shows the measured energy distribution of the muon decay triggers along with the Monte Carlo prediction in units of photomultiplier (PMT) hits.

events collected in 282 d of live time over the period from May 1983 to October 1984. This corresponds to a full-tank exposure of 1.8×10^{32} proton yr and 1.4×10^{32} neutron yr. Approximately 1.4% of these events had at least one secondary trigger which passed the muon decay selection criteria, consistent with the predicted rate of stopping cosmic-ray muons. 13 000 events had two or more secondary triggers which passed the muon decay selection criterion. Essentially all of these 13 000 events were caused by showers of particles created by muon inelastic photonuclear reactions in the rock surrounding the detector, but with energies deposited in the water too high to be compatible with nucleon decay.

We calibrated the energy response of the detector by comparing the measured and the expected energy distributions of through-going muons and of muon decay electrons. The comparison for the latter can be seen in fig. 3b. The energy resolution at 100 MeV is ± 15 MeV and at 500 MeV is ± 65 MeV.

In order to distinguish contained events from events caused by entering charged particles, we fitted the vertices of events with a maximum likelihood reconstruction program. The program predicts all possible phototube hit times for light emitted from a single vertex in the tank, including hits for light reflected from the mirrors. The program then compares these predicted hit times to the data for an event, and varies the vertex position to get the best match [7]. Vertex resolution varies depending on the type of event and its location within the detector, but in general it is better than 1 m.

The fiducial volume was increased halfway through the data set when additional hardware was installed which improved the phototube timing resolution. Before the upgrade, the fiducial volume consisted of the region with radius less than 3.1 m and more than 2.7 m from the top, which corresponds to a fiducial volume of 130 t. After the hardware upgrade, the fiducial volume was increased to a radius of 3.5 m and

Table 1
Selected nucleon decay modes, showing the maximum number of muon decays possible, the Čerenkov-equivalent energy range (E_c) of the primary trigger, the full tank net detection efficiencies with 8 ns and with 3 ns timing resolution, and the lifetime upper limit (90% CL) for each mode. Note that the net efficiencies are dominated by the 130 or 180 t/680 t fiducial cut.

Decay mode		μ decays Max. #	E_c range (MeV)	Net efficiencies (%)		Limit τ/BR(10^{30}yr)
				ϵ_{8ns}	ϵ_{3ns}	
$p \to \nu K^+$	$\to \nu\pi^+\pi^+\pi^-$	2	50–190	6.0	7.1	5.0
$p \to \mu^+ K^0_S$	$\to \mu^+\pi^+\pi^-$	2	270–500	4.9	6.8	4.4
$p \to \mu^+ \eta^0$	$\to \mu^+\pi^+\pi^-\pi^0$	2	340–560	5.3	7.1	4.7
	$\to \mu^+\pi^+\pi^-\gamma$	2	280–540	5.6	7.3	4.9
$p \to \mu^+ \rho^0$	$\to \mu^+\pi^+\pi^-$	2	270–470	4.9	6.6	4.3
$p \to \mu^+ \omega^0$	$\to \mu^+\pi^+\pi^-\pi^0$	2	360–560	5.2	6.7	4.9
	$\to \mu^+\pi^+\pi^-$	2	230–420	4.5	6.5	4.1
$p \to e^+\mu^+\mu^-$		2	540–800	5.6	7.9	5.0
$p \to e^-\mu^+\mu^+$		2	540–800	6.6	9.4	6.0
$p \to e^-\pi^+\pi^+$		2	320–540	2.3	2.9	2.0
$p \to \mu^-\mu^+\mu^+$		3	320–540	11.8	16.2	10.5
$p \to \mu^-\pi^+\pi^-$		2	230–420	3.7	5.0	3.3
$p \to \mu^-\pi^+\pi^+$		3	230–420	8.7	11.8	7.8
$n \to \mu^-\pi^+$		2	470–690	3.0	4.0	2.7
$n \to e^- K^+$	$\to e^-\pi^+\pi^+\pi^-$	2	270–600	6.0	7.8	4.1
$n \to \mu^- K^+$	$\to \mu^-\mu^+\nu$	2	140–540	5.5	7.3	4.8
	$\to \mu^-\pi^+\pi^0$	2	540–800	4.7	6.1	4.1
	$\to \mu^-\pi^+\pi^+\pi^-$	3	200–440	10.4	14.8	9.4
	$\to \mu^-\mu^+\pi^0\nu$	2	400–750	6.5	8.5	5.6
	$\to \mu^-\pi^+\pi^0\pi^0$	2	620–860	5.1	6.9	4.5
$n \to \mu^-\rho^+$	$\to \mu^-\pi^+\pi^0$	2	520–700	2.8	4.0	2.6
$n \to \mu^-\mu^+\nu$		2	80–690	5.8	7.8	5.1

2.25 m from the top, which corresponds to 180 t. These fiducial cuts eliminate 99% of the low energy ($E_c \leqslant 1.1$ GeV) events with at least one muon decay which are caused by entering charged particles. The remaining 1% of the events were rejected as entering particles by examining the phototube hit time distributions. These events had at least one tube which prepulsed deep inside the tank and pulled the fit into the fiducial volume. Pre-pulsing is a relatively rare phenomenon caused by photons directly striking the dynode of the phototube rather than the photocathode.

In order to determine energy ranges and detection efficiencies for various nucleon decay modes we simulated 10^5 events of each decay mode branch capable of producing two or more muons. These events were used to determined the containment efficiency of the particles which lead directly to muon decays, and the survival probabilities of the positive pions as a function of energy [8]. These pions eventually decay into muons if they stop.

Of the events which contained at least two muon decays, we selected 10^3 events at random and used a Monte Carlo program to simulate the detector's response to these events. These Monte Carlo events were used to determine the expected E_c range for each decay mode, the primary trigger detection efficiency, and the fiducial containment efficiency. The values obtained for each of the decay mode branches are shown in table 1.

From the 13 000 events with two or more secondary triggers which passed the muon decay selection criterion, only 277 are in an energy range consistent with nucleon decay. Here we have used an energy cut of $E_c \leqslant 1.1$ GeV, which is more than adequate to include all nucleon decays with multiple muons.

We fitted the vertex positions for these low-energy multiple muon events with the maximum likelihood program described above. Two events reconstructed in the fiducial volume, but upon examination we determined that these events were clearly caused by entering particles. Čerenkov rings are visible for an entering track in each event, and isolated pre-pulsing tubes are clearly responsible for pulling the reconstructed vertices into the fiducial volume. Two events out of 277 is consistent with the 1% leakage expected for these fiducial cuts. All 277 events were examined to determine whether a contained event was pulled out of the fiducial volume by pre-pulsing; we found none.

We computed the lower limits (90% confidence level) on the nucleon lifetime on the basis of no candidate events for 16 nucleon decay channels. These limits are shown in table 1.

Neutrino interactions present the most serious background to nucleon decay events. Based on the NUSEX Collaboration neutrino beam data [9], we estimate that neutrinos from atmospheric cosmic-ray interactions will produce 14.1 events/kt yr (in water) having two muon decays. The error is estimated to be $\pm 30\%$. With our detection efficiencies we would see 6.3 events/kt yr (without an energy cut). Given our fiducial exposure, we estimate a background of 0.7 ± 0.2 events from neutrino interactions.

We wish to thank J. Blandino, M. Jaworski, J. McElhaney, J. Oliver, T. Smart, and J. West for help in designing the apparatus. We thank the shops at Harvard, Purdue, and Wisconsin and the mine crew in Park City, Utah, for help in constructing and operating the experiment. We also thank the Physics Department at the University of Utah for their hospitality. Work was supported in part by the United States Department of Energy.

References

[1] D.H. Perkins, Ann. Rev. Nucl. Part. Sci. 34 (1984) 1.
[2] P. Langacker, Phys. Rep. 72 (1981) 185.
[3] J.C. van der Velde, presented Aspen Winter Conf. (1985).
[4] IMB Collab. H.S. Park et al., Phys. Rev. Lett. 54 (1985) 22. IMB Collab. T.J. Haines et al., Phys. Rev. Lett. 57 (1986) 16.
[5] S. Dimopoulos, S. Raby and F. Wilczek, Phys. Lett. B 112 (1982) 133.
[6] K. Ashley et al., Phys. Rev. Lett. 31 (1973) 1091; Phys. Rev. D 12 (1975) 20.
[7] T.J. Phillips, A search for nucleon decay with multiple muon decays, thesis, UMI 86-20519-mc, Harvard University (1986).
[8] J.M. Matthews, A search for nucleon decays into muonic final states, thesis, University of Wisconsin-Madison (1984).
[9] G. Battistoni et al., Nucl. Instrum. Methods 219 (1984) 300.