RESULTS FROM KGF PROTON DECAY EXPERIMENT

M.R. Krishnaswamy, M.G.K. Menon, N.K. Mondal, V.S. Narasimham and B.V. Sreekantan
Tata Institute of Fundamental Research, Bombay 400005, India
Y. Hayashi, N. Ito, S. Kawakami
Osaka City University, Osaka, Japan
and
S. Miyake
Institute for Cosmic Ray Research, University of Tokyo, Japan

The Kolar Gold Field experiment has been in operation at a depth of 2.3 Km since Oct. 1980. The total weight of 140 tons of the detector is distributed in 34 horizontal layers of proportional counters and 12 mm thick iron plates and with this array it has been possible to measure ionisation, range as well as the time of flight (0.5 μSec. resolution) of particles.

Search for nucleon decay events has been simplified by the very low backgrounds encountered in this experiment. The great depth at which the detector is operated resulted in suppression of atmospheric muons to ~ 2/day and consequently the rate of neutral secondaries (n, K_L^0 etc.) unaccompanied by parent muons are estimated to be $\lesssim 0.01$/year for the energy range relevant for nucleon decay. The location of the site near the geomagnetic equator (~ 3°N) has resulted in the reduction of background from low energy neutrino interactions inside the detector as compared to those presently operating elsewhere in the world.

In this report, we shall discuss only the events confined to the volume of the detector. They would comprise the low energy ν-events as well as nucleon decay events. In a live-time of 3 years, we have recorded a total of 16 such events with energies in the range 0.25 - 2.0 GeV; about half of them are of multi-track nature. From the track configurations (i.e. momentum balance) and the total energy considerations, 4 events are identified as good candidates for nucleon decay, details of which are listed in Table 1.

Table 1

Event No.	Characteristic Features	Interpretation	ν-Background (for 3 yrs.)	τ/BR x 10^{31} (Yrs.)
587	Back-Back Ele. Mag. showers $E_{TOT} = .98 \pm .2$ GeV	$P \rightarrow e^+ + \pi^0$	0.3	2.5
867	Non-showering tracks with kink	a) $P \rightarrow \bar{\nu} + K^+ (K^+ \rightarrow \mu^+ \nu)$	0.05	3.2
		b) $P \rightarrow \bar{\nu} + \pi^+$	0.2	3.2
877	Downgoing μ upgoing π^+, π^- $E_{TOT} = .93 \pm .15$ GeV	$P \rightarrow \mu^+ + K_S^0 \quad (K_S^0 \rightarrow \pi^+ \pi^-)$	0.1	1.75
1766	Complex configuration; vis. energy .65 GeV	a) $N \rightarrow \bar{\nu} + \eta^0$	0.01	0.9
		b) $N \rightarrow e^+ + \rho^-$	0.05	3
		c) $P \rightarrow e^+ + K_S^0$		

Our data analysis relies strongly on the ionisation measurements, coupled with the ranges of tracks, compensating to a large extent the coarseness (10 x 10 cm^2) of individual cells. The absence of ionisation in neighbouring cells above the threshold of ~ 1/3 I_{min}, is given equal weight to that of the hit cells where the ionisation provides an estimate of the number of particles traversing them. Furthermore, the growth of ionisation, as the particle reaches the end part of its range is used to establish the direction of motion and to identify the particle nature such as e/γ or μ/π or K or P in favourable cases.

Event 587, the first candidate event recorded at KGF, is best explained in terms of $P \rightarrow e^+ + \pi^0$, even though the background due to electron neutrino interaction is $\lesssim 0.3$ events. On the basis of reanalysis of the events 867 and 877, using ionisation data, the most probable interpretation is proton decay through $P \rightarrow \bar{\nu} + K^+$ ($K^+ \rightarrow \mu^+ \nu$) and $P \rightarrow \mu^+ + K_S^0$ ($K_S^0 \rightarrow \pi^+ \pi^-$) respectively. The fourth event, 1766, is of complex configuration with a penetrating track embedded in a shower, which is nearly isotropic and has a total kinetic energy of 650 MeV. Plausible decay schemes for this event are indicated in Table 1. However, it is highly unlikely to be due to ν -interaction through any of the known dominant inelastic channels.

In summary, the KGF results strongly suggest a nucleon decay signal with $\tau/BR \sim 2 \times 10^{31}$ yrs. even though the small statistics does not allow clear preference of one decay mode over another. A new detector of 300 tons is now being assembled at a depth of 2 Km at KGF and this will provide adequate data to substantiate the present results.

RESULTS FROM NUSEX

G. Battistoni[1)], E. Bellotti[2)], G. Bologna[3)], P. Campana[1)], C. Castagnoli[3)], V. Chiarella[1)], D. Cundy[4)], B. D'Ettorre[3)], E. Fiorini[2)], P. Galeotti[3)], E. Iarocci[1)], C. Liguori[2)], G. Mannocchi[3)], G. Murtas[1)], P. Negri[2)], G. Nicoletti[1)], P. Picchi[3)], M. Price[4)], A. Pullia[2)], S. Ragazzi[2)], M. Rollier[2)], O. Saavedra[3)], L. Satta[1)], L. Trasatti[1)] and L. Zanotti[2)].

1) Laboratori Nazionali dell'INFN, Frascati, Italy

2) Dipartimento di Fisica dell'Università and INFN, Milano, Italy

3) Istituto di Cosmogeofisica del CNR, Torino, Italy

4) CERN, European Organization for Nuclear Research, Geneva, Switzerland

Presented by Ettore Fiorini

NUSEX is a nucleon decay experiment carried out in the Mont Blanc Tunnel at a depth of ∿ 5000 hectograms of standard rock, with a calorimeter made by 136 horizontal square plates of Iron with 350 cm side and 1 cm thickness. These plates are interspaced with planes of plastic limited streamer tubes of 1 x 1 cm^2 cross section read bidimensionally with X and Y strips (81472 in total). A model of the set-up has been exposed at CERN to beams of muons, pions and electrons and of neutrinos simulating the atmospheric ones. Minimum trigger requirements are that 4 contiguous planes, or a pair plus a triplet of three pairs are fired at least. Mu-e decay is detected with 35% efficiency.

On July 13, 1984 the detector had been run for 16,000 hours of effective running time with the detection of 18,000 single muons, 197 bundles of two parallel muons, 28 bundles of three or more muons and 22 events with all tracks fully contained. The features of these events are as follows:

Event	Number of tracks	Energy (GeV)	Zenit angle (degree)	Interpretation
1	3	1.0 ± 0.2	-	ν_μ - inelastic, p-decay?
2	3	1.5 ± 0.4	170	ν_μ - ν_e inelastic
3	1	0.4 ± 0.1	35-145	ν_μ - elastic
4	1	0.33 ± 0.015	45-135	ν_μ - elastic
5	1	1.4 ± 0.25	65	ν_μ - elastic
6	2	1.2	72	ν_μ - inelastic?
7	2	0.73 ± 0.03	36	ν_μ - inelastic
8	2	$3.7\ ^{+1.8}_{-0.7}$	145	ν_e - elastic
9	1	1.11 ± 0.06	55	ν_e - elastic
10	1	0.33 ± 0.015	54	ν_μ - elastic
11	1	1.09 ± 0.03	156	ν_μ - elastic
12	2	$1.0\ ^{+0.25}_{-0.20}$	176	ν_e - elastic
13	1	0.36 ± 0.04	20-160	ν_μ - elastic
14	1	$2.1\ ^{+0.9}_{-0.6}$	74	ν_e - elastic
15	2	$1.2\ ^{+0.3}_{-0.25}$	67	ν_e - elastic
16	1	0.55 ± 0.03	43	ν_μ - elastic
17	1	0.30 ± 0.06	135	ν_e - elastic
18	2	0.49 ± 0.03	20	ν_μ - inelastic
19	1	0.66 ± 0.03	31	ν_μ - elastic
20	2-3	0.6 ± 0.09	59-28	ν_μ - elastic
21	1	0.33 ± 0.08	53	ν_e - elastic
22	1-3	$1.5\ ^{+0.35}_{-0.30}$	43-137	ν_e - elastic, p-decay?

In order to reduce the background from atmospheric neutrino interactions we have decided to introduce for the present analysis the following selection criteria for nucleon decay candidates: the zenit angle for one or two prong events has to be less than 60° for all tracks; tracks in three prong events have to be defined by at least two planes. After these criteria are applied, two events remain which are compatible with nucleon decay and hardly compatible with a neutrino interaction:

Event number 1 is compatible with a proton decay particularly in the mode $p \to \mu^+K$ with 1.0 ± 0.2 GeV total energy and 0.4 GeV/c momentum umbalance. The pion and kaon momenta are 0.38 ± 0.15 and 0.3 ± 0.2 GeV/c, respectively. The pi-pi invariant mass is of 0.55 ± 0.08 GeV/c^2. The background of neutrino interactions for this decay has been evaluated from our neutrino test carried out at CERN, where only two possible candidates where found on a total of 400 events, and with our present statistics is equal to 0.07 ± 0.05 events. The upper limit at the 90% Confidence Level is of 0.17 events.

Event number 22 is compatible with a proton decay into a positron and a pi-zero. Total energy and momentum umbalance are 1.1 ± 0.2 and 0.25 ± 0.15 GeV/c, respectively. The event is made by two showers with an angle of 158°, but one of the two showers could be made by two distinct showers indicative of a pi-zero decay, forming an angle of 53°. In this hypothesis the pion and positron tracks would indicate energies of 0.7 ± 0.1 and 0.4 ± 0.1 GeV, respectively. The study of the neutrino background (still in progress) is very difficult because neutrinos in the CERN run are mainly of the muonic type. We have therefore analyzed 220 electron tracks recorded in our detector in the CERN electron run with an angle of 45° with respect to the plates (similar to the one in our event). From this analysis we have found the proportion of single electrons in the atmospheric neutrino events simulating two distinct showers with a detectable angle among them. The background in our p-decay candidate has been conservatively evaluated to be 0.18 ± 0.06 events and less than 0.28 at the 90% Confidence Level.

The limits on the lifetimes at 90% Confidence Level taking into account detection and selection efficiency (as discussed before) are as follows, in unities of 10^{31} years:

Channel	Candidates	Limit	Channel	Candidates	Limit
π^0e^+	1	1	$\bar{\nu}K^+$	0	0.7
$\pi^0\mu^+$	0	1	$\bar{\nu}K^0$	0	1.1
$\bar{\nu}\pi^+$	6	0.2	μ^+K^0	1	0.7
$\bar{\nu}\pi^0$	0	0.8			

If our two candidates would be genuine proton decays, the corresponding half life would be of about 3 x 10^{31} for each of them.

THE SEARCH FOR PROTON DECAY[†]

John M. LoSecco
California Institute of Technology, Pasadena, California 91125 U.S.A.

R. W. Bionta,[2] G. Blewitt,[4] C. B. Bratton,[5] B. G. Cortez,[4] S. Errede,[2] G. W. Foster,[2]
W. Gajewski,[1] K. S. Ganezer,[1] M. Goldhaber,[3] T. J. Haines,[1] T. W. Jones,[7]
D. Kielczewska,[1] W. R. Kropp,[1] J. G. Learned,[6] E. Lehmann,[4] H. S. Park,[2]
F. Reines,[1] J. Schultz,[1] S. Seidel,[2] E. Shumard,[2] D. Sinclair,[2] H. W. Sobel,[1]
J. L. Stone,[2] L. R. Sulak,[2] R. Svoboda,[6] J. C. van der Velde,[2] and C. Wuest[1]

We have employed the 3300 ton fiducial mass IMB detector to search for evidence of proton or bound neutron decay. We report results based on an exposure of 204 days. In this period we have observed 169 contained events most of which are clearly neutrino interactions.

Our search for proton decay employs an imaging water Cherenkov counter. Events are recognized by the light emitted by the relativistic decay products. The light is recorded on 2048 5" photomultiplier tubes on the surface of the device. Timing and pulse height information is recorded from each tube. The pattern of tubes that record light, along with the time and pulse height, is used to reconstruct the events. Energies and track directions can be measured.

In our search for proton decay we employ 3 observables. E_c, the visible energy, is the energy of an event assuming all the light came from an electromagnetic shower. A, the anisotropy, is the magnitude of the mean vector sum of the unit vectors from the event vertex to the hit photomultiplier tubes. For a single track, $A \approx .75$. Finally we may require the presence or absence of a muon decay signal. This indicates the presence of a muon or π^+ in the final state.

Space does not permit a detailed presentation of the search for each mode. In general we rely on a Monte Carlo simulation of the specific proton decay mode. If the final state mesons have several decay modes, each of these is separately simulated. The Monte Carlo events are analyzed and cuts based on the simulation are used to isolate a signal from the real data sample. Finally, the same cuts are applied to simulated atmospheric neutrino interactions and backgrounds estimated. We are wary of systematic errors associated with the background estimate.

Our best limit for the decay $P \rightarrow e^+\pi^\circ$ is $\tau > 2 \times 10^{32}$ years. This is based on a special search in 250 days and is larger than the number in the table. The $e^+\pi^\circ$ has a very distinctive signature.

In spite of the number of candidates recorded, in actual fact there are at most 9 candidates. This is because many of the cuts for different modes overlap, so a given event may be a candidate for more than one mode. We have not subtracted the estimated background in obtaining our limits. We can not rule out nucleon decay as the source of some of the events.

TABLE I(a) -- IMB Proton Decay Partial Lifetime Limits

1	2	3	4	5	6	7	8	9	10
	Requirements				Effic. with Nuclear Corr.	Effic. without Nuclear Corr.	No. of Cand. Obs.	No. of Bkgnd. Est. -50% +100%	Limit on τ/B ($\times 10^{31}$ yr) at 90% C.L.
Mode	E_c (MeV)	A	#μ	Back to Back					
$p \rightarrow e^+\pi^\circ$	750-1100	<0.3	0	0	0.54	0.75	0	0.1	15
$p \rightarrow \mu^+\pi^\circ$	550-900	<0.4	1	1	0.34	0.47	1	0.2	5.4
$p \rightarrow e^+\eta^\circ$	750-1100	<0.3	0		0.40	0.53	0	0.2	
	400-650	<0.5	1		0.06	0.15	0	2	12
$p \rightarrow \mu^+\eta^\circ$	550-900	<0.5	1		0.22	0.44	2	2	
	200-400	<0.5	1,2		0.12	0.22	2	2	3.0
$p \rightarrow e^+\rho^\circ$	200-600	0.1-0.5	1		0.16	0.30	1	4	2.5
$p \rightarrow \mu^+\rho^\circ$	150-400	0.1-0.5	1,2		0.11	0.16	2	2	1.3
$p \rightarrow e^+\omega^\circ$	300-600	0.1-0.5	1		0.18	0.39	1	3	
	750-1100	<0.3	0		0.05	0.06	0	0.2	3.8
$p \rightarrow \mu^+\omega^\circ$	200-450	0.1-0.5	1,2		0.18	0.32	2	2	
	650-900	<0.5	1		0.02	0.04	2	0.8	2.1
$p \rightarrow e^+\gamma$	750-1100	<0.4	0	2	0.74	0.74	0	0.1	20
$p \rightarrow \mu^+\gamma$	550-900	<0.5	1	2	0.52	0.52	0	0.4	14
$p \rightarrow e^+K^\circ$	300-500	<0.5	1		0.12	0.12	1	2	
	750-1100	<0.3	0		0.14	0.14	0	0.2	4.8
$p \rightarrow \mu^+K^\circ$	150-400	0.1-0.5	1,2		0.19	0.20	2	2	
	550-900	<0.5	1		0.10	0.11	2	2	2.6
$p \rightarrow \nu K^+$	150-375	0.3-0.6	1		0.08	0.08	3	4	0.8
$p \rightarrow \nu K^{*+}$	250-500	0.3-0.6	1		0.09	0.19	4	4	0.7
$p \rightarrow \nu\rho^+$	300-600	0.2-0.5	1		0.08	0.19	1	3	1.3
$p \rightarrow e^+e^-e^+$	750-1100	<0.3	0		0.93	0.93	0	0.2	25
$p \rightarrow \mu^+\mu^-\mu^+$	200-425	<0.5	2,3		0.57	0.57	1	0.2	9

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[1] The University of California at Irvine, Irvine, California 92717
[2] The University of Michigan, Ann Arbor, Michigan 48109
[3] Brookhaven National Laboratory, Upton, New York 11973
[4] California Institute of Technology, Pasadena, California 91125
[5] Cleveland State University, Cleveland, Ohio 44115
[6] The University of Hawaii, Honolulu, Hawaii 96822
[7] University College, London, U.K.

TABLE I(b) -- IMB Neutron Decay Partial Lifetime Limits

1	2	3	4	5	6	7	8	9	10
Mode	Requirements				Effic. with Nuclear Corr.	Effic. without Nuclear Corr.	No. of Cand. Obs.	No. of Bkgnd. Est. -50% +100%	Limit on τ/B ($\times 10^{31}$ yr) at 90% C.L.
	E_c (MeV)	A	#μ	Back to Back					
$n \rightarrow \nu\eta^\circ$	450-800	0.1-0.5	0		0.30	0.56	5	3	1.6
$n \rightarrow \nu\omega^\circ$	200-450	0.2-0.5	1		0.08	0.24	1	2	
	650-950	<0.3	0		0.04	0.06	0	0.3	1.7
$n \rightarrow e^+\pi^-$	450-950	<0.4	0		0.39	0.55	4	2	2.4
$n \rightarrow \mu^+\pi^-$	200-700	<0.5	1		0.42	0.43	1	4	5.5
$n \rightarrow e^+\rho^-$	400-800	<0.4	0		0.26	0.42	4	2	1.6
$n \rightarrow \mu^+\rho^-$	300-500	<0.5	1		0.11	0.29	1	2	1.5
$n \rightarrow e^-\pi^+$	400-700	<0.5	1		0.15	0.24	0	2	
	700-950	<0.5	0		0.09	0.07	2	2	3.0
$n \rightarrow \mu^-\pi^+$	200-500	<0.5	1,2		0.30	0.45	2	3	2.8
$n \rightarrow e^-\rho^+$	400-800	<0.4	0,1		0.19	0.57	4	3	1.2
$n \rightarrow \mu^-\rho^+$	300-550	<0.5	1,2		0.08	0.41	2	2	0.7
$n \rightarrow \nu K^\circ$	450-700	0.2-0.5	0		0.10	0.11	2	2	1.0
$n \rightarrow \nu K^{*\circ}$	200-700	0.15-0.50	1		0.06	0.11	1	4	0.7
$n \rightarrow \nu\pi^\circ$	350-600	>0.5	0		0.54	0.82	28	19	0.8
$n \rightarrow \nu\gamma$	350-600	>0.5	0		0.76	0.76	28	19	1.1
$n \rightarrow \nu\rho^\circ$	150-500	0.1-0.4	0,1		0.04	0.11	7	3	0.1
$n \rightarrow e^+e^-\nu$	500-850	<0.5	0		0.41	0.41	4	3	2.6
$n \rightarrow \mu^+\mu^-\nu$	150-375	0.2-0.65	1,2		0.30	0.30	4	7	1.9

Notes to columns:

1: For 3-body decay modes, flat phase space was assumed.

4: Number of muon decay signals required.

5: Number of events rejected by requiring two clear tracks with opening angle >140°. Efficiencies (columns 6 and 7) 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.For each mode, 400 events were simulated in the total volume of the detector to determine the detection efficiency.

7: Identical to column 6 except that the effects of meson interaction in the nucleus have been neglected.

8: Some events are candidates for more than one mode.

10: Limits are derived from columns 6 and 8. Note that no background subtraction has been made.

RESULTS FROM KAMIOKANDE

K.Arisaka,1) T.Kajita,1) T.Kifune,3) M.Koshiba,1), 2) K.Miyano,5) M.Nakahata,1) A.Sato,2) T.Suda,3) A.Suzuki,1) K.Takahashi,4) M.Takita,1) and Y.Totsuka.2)
1) Department of Physics, Univ. of Tokyo, Tokyo 113, Japan
2) Intern'l Center for Elem. Part. Physics, Univ. of Tokyo, Tokyo 113, Japan
3) Institute for Cosmic Ray Research, Univ. of Tokyo, Tokyo 188, Japan
4) National Laboratory for High Energy Physics, Ibaragi-ken 305, Japan
5) Department of Physics, Univ. of Niigata, Niigata-ken 950-21, Japan

Presented by M.Koshiba.

KAMIOKANDE has been in operation since July 6, 1983, at 2700 m.w.e. underground in KAMIOKA Mine, 26° N geomagnetic and 300km west of Tokyo. It is a cylindrical water Čerenkov detector, 15.6m ϕ x 16mh, viewed by 1000 x 20'ϕ PMT's; the photocathode covering 20% of the entire surface. The fiducial volume, excluding the peripheral volume within 2m of the PMT planes, is 880 m^3.

As of July 6, 1984, a total live time of 274 days, i.e. 661 ton.year, was achieved and the data analyzed. After the data reduction, a total of 1.24×10^5 events were scanned by two independent groups of physicist and 89 contained events were obtained. A five year equivalent of Cosmic Ray ν-interactions has been Monte Carlo generated and subjected to the same analysis as the real data in order to estimate the ν-background. Monte Carlo simulation produced also artificial nucleon decays in the detector and they were subjected to the same analysis program in order to estimate the detection efficiencies of various decay modes of nucleon decay.

The results in the form of 90% C.L. lower limit, background unsubtracted, of (life time/branching ratio) are given in Table 1 for the decay modes with $\Delta B = \Delta L$.

Decay Mode	Detection Efficiency	ν-B.G/(upper limit 90%C.L.)	Number of Candidates	Lower limit 90% C.L. τ/B in 10^{31} yrs.
$p \to e^+\pi^0$	0.53	0	0	5.1
$p \to e^+\eta^0$	0.53	0	0	5.1
$p \to e^+\omega^0$	0.35	0.3/(0.8)	1	2.0
$p \to e^+\rho^0$	0.10	0.5	0	1.0
$p \to e^+K^0$	0.31	0	0	3.0
$p \to e^+K^{*0}$	0.14	0.3/(0.8)	1	0.8
$p \to \mu^+\pi^0$	0.39	0.2	0	3.8
$p \to \mu^+\eta^0$	0.36	0/(0.3)	1	2.1
$p \to \mu^+\rho^0$	0.10	0.2/(0.6)	1	0.6
$p \to \mu^+K^0$	0.26	0.2/(0.6)	2	1.1
$n \to e^+\pi^-$	0.27	0.2	0	2.6
$n \to e^+\rho^-$	0.14	0.3/(0.8)	2	0.6
$n \to \mu^+\pi^-$	0.21	0	0	2.0
$n \to \mu^+\rho^-$	0.05	0.3/(0.8)	1	0.3
$p \to \bar{\nu}\pi^+$	0.22	13.5	8	0.4
$p \to \bar{\nu}\rho^+$	0.20	1.8/(2.7)	3	0.9
$p \to \bar{\nu}K^+$	0.41	2.1/(3.0)	3	1.5
$p \to \bar{\nu}K^{+*}$	0.51	3.8/(4.9)	6	1.7
$n \to \bar{\nu}\pi^0$	0.27	1.3	0	2.1
$n \to \bar{\nu}\eta^0$	0.35	0	0	3.4
$n \to \bar{\nu}\omega^0$	0.47	1.3	1	2.1
$n \to \bar{\nu}\rho^0$	0.05	1.5	1	0.4
$n \to \bar{\nu}K^0$	0.21	0.5	0	1.6
$n \to \bar{\nu}K^{0*}$	0.17	3.8/(4.9)	7	0.4
$p \to e^+\gamma$	0.90	0	0	8.7
$p \to e^+\gamma\gamma$	0.80	0	0	7.7
$p \to e^+e^+e^-$	0.80	0	0	7.7
$p \to e^+\mu^+\mu^-$	0.45	0	0	4.3
$p \to \mu^+\gamma$	0.65	0	0	6.2
$p \to \mu^+\gamma\gamma$	0.53	0/(0.3)	1	3.0
$p \to \mu^+e^+e^-$	0.53	0/(0.3)	1	3.0
$p \to \mu^+\mu^+\mu^-$	0.67	0	0	6.4
$n \to \bar{\nu}\mu^+\mu^-$	0.33	0.3	0	3.2
$n \to \bar{\nu}e^+e^-$	0.71	0.8/(1.4)	3	2.4
$n \to \bar{\nu}\gamma$	0.81	6.0	4	2.2
$n \to \bar{\nu}\gamma\gamma$	0.71	0.8/(1.4)	3	2.4

Table 1 90% C.L. lower limits of τ/B

The great majority of the fully contained events are consistent with the interpretation of being produced by the atomospheric neutrinos; the total number, the energy spectrum, the multiplicity distribution, etc..

We notice, however, that there are some cases which stand out above the 90% C.L. upper limit of the ν-background. We now look at these events individually. For each Čerenkov ring the number of photoelectrons was counted in the 45° cone and at this stage one should allow 15% error for the energy and/or the momentum assigned to each ring. S or M denotes whether it is showering type, e, γ, π^0 or meson type, $\mu^\pm$, $\pi^\pm$(non-showering).

1. Event #166-13338; Total photoelectron number 2890, μ-e signal Yes/No.
   Ring #1, 1202 photoelectrons, S/M, 462 MeV/c for (e, γ) 595 MeV/c (μ), 800 MeV/c (π).
   Ring #2, 184 photoelectrons, M, 367 MeV/c for (π), 249 MeV/c for (μ).
   Ring #3, 819 photoelectrons, S, 320 MeV/c for (e, γ).
   $\theta_{12} = 101^\circ$, $\theta_{23} = 133^\circ$, $\theta_{31} = 106^\circ$, and $\theta_{12} + \theta_{23} + \theta_{31} = 340^\circ$.
   $M_{1,2}(\pi^0,\pi) = 670$ MeV, $M_{3,1,2}(e,\pi^0,\pi) = 1100$ MeV and $|\Delta p| = 380$ MeV/c.
   Possible interpretation; $n \rightarrow e^+\rho^-(\pi^0\pi^-)$.

   $M_{1,3}(e\gamma\pi^0,\ e\gamma\pi^0) = 610$ MeV, $M_{2,1,3}(\mu,\ e\gamma\pi^0,\ e\gamma\pi^0) = 980$ MeV and $|\Delta p| = 380$ MeV/c.
   Possible interpretations; $p \rightarrow \mu^+\eta^0(\gamma\gamma)$, $\mu^+\gamma\gamma$, $\mu^+e^+e^-$, $\mu^+K^0(2\pi^0)$.
2. Event #231-16480; Total photoelectron number 1708, μ-e signal No.
   Ring #1, 548 photoelectrons, S likely, 216 MeV/c (e,γ).
   Ring #2, 366 photoelectrons, S/M, 118 MeV/c (e,γ), 402 MeV/c (π).
   Ring #3, 192 photoelectrons, S/M, 80 MeV/c (e,γ), 357 MeV/c (π).
   Ring #4, 201 photoelectrons, S likely, 83 MeV/c (e,γ).
   Ring #5, 266 photoelectrons, S likely, 109 MeV/c (e,γ).
   $M_{3,4}(\gamma,\gamma) = 130$ MeV, $M_{2,3,4,5}(\pi,\gamma,\gamma,\gamma) = 620$ MeV,
   $M_{1,2,3,4,5}(e,\pi,\gamma,\gamma,\gamma) = 880$ MeV $|\Delta p| = 250$ MeV/c.
   Possible interpretation; $p \rightarrow e^+\omega^0(\pi^+\pi^0\pi^-)$,

   $M_{1,5}(\gamma,\gamma) = 110$ MeV, $M_{2,1,5}(\pi,\gamma,\gamma) = 680$ MeV, $M_{1,2,3,4,5}(\gamma\pi e\gamma\gamma) = 880$ MeV, $|\Delta p| = 250$ MeV/c.
   Possible interpretation; $n \rightarrow e^+\rho^-(\pi^-\pi^0)$.

   $M_{1,5}(\gamma,\gamma) = 110$ MeV, $M_{1,2,3,5}(\gamma\pi\gamma\gamma) = 780$ MeV, $M_{1,2,3,4,5}(\gamma,\pi,\gamma,e,\gamma) = 880$ MeV,
   $|\Delta p| = 250$ MeV/c. Possible interpretation; $p \rightarrow e^+K^{0*}(\pi^+\pi^0\pi^-)$.

   $M_{1,2,3,4,5}(\gamma\pi\gamma\gamma\gamma) = 880$ MeV, assume 1 $\bar{\nu}$ with $p(\bar{\nu}) = 50$ MeV/c then $M_{total} = 940$ MeV,
   $|\Delta p|$ (Fermi momentum) = 200 MeV/c.
   Possible interpretations; $\bar{\nu}\rho^+(\pi^0\pi^+)$, $\bar{\nu}K^{0*}(\pi^+\pi^0\pi^-)$, $\bar{\nu}K^{+*}(\pi^0\pi^0\pi^+)$.
3. Event #391-43295; Total photoelectron number 1755, μ-e signal Yes.
   Ring #1 1406 photoelectrons, S, 535 MeV/c(e,γ,π^0).
   Ring #2, 43 photoelectrons, M, 219 MeV/c(π), 175 MeV/c(μ).
   $\theta_{12} = 166^\circ$, $M_{12}(\pi^0,\pi) = 720$ MeV, $|\Delta p| = 320$ MeV/c, Assume 1 μ^+ with $p(\mu^+) = 130$ MeV/c then $M_{total} = 940$ MeV, $|\Delta p|$(Fermi momentum) = 200 MeV/c.
   Possible interpretation; $n \rightarrow \mu^+\rho^-(\pi^-\pi^0)$.

   Assign π^0, μ to rings 1,2 and assume 1 π^+ with $p(\pi^+) = 170$ MeV/c then $M_{total} = 940$ MeV, $|\Delta p|$(Fermi momentum) = 200 MeV/c. Possible interpretation; $n \rightarrow \mu^+\rho^-(\pi^-\pi^0)$.

   Assign π^0,π to rings 1,2 and assume 1 $\bar{\nu}$ with $p(\bar{\nu}) = 160$ MeV/c, then
   $M_{total} = 940$ MeV, $|\Delta p|$ (Fermi momentum) = 170 MeV/c.
   Possible interpretation; $p \rightarrow \bar{\nu}\rho^+$.
4. Event #579-55318; Total photoelectron number 804, μ-e signal Yes.
   Ring #1, 404 photoelectrons, M, 337 MeV/c(μ), 477 MeV/c(π).
   Ring #2, 203 photoelectrons, M, 253 MeV/c(μ), 374 MeV/c(π).
   $\theta_{12} = 146^\circ$, $M_{12}(\pi,\pi) = 850$ MeV and $|\Delta p| = 290$ MeV/c. Assume 1 μ^+ with
   $p(\mu^+) = 0$ MeV/c, then $M_{total} = 960$ MeV, $|\Delta p|$(Fermi momentum) = 290 MeV/c.
   Possible interpretation; $p \rightarrow \mu^+\rho^0(\pi^+\pi^-)$.

   Assume 1 $\bar{\nu}$ with $p(\bar{\nu}) = 70$ MeV/c then $M_{total} = 940$ MeV,
   $|\Delta p|$ (Fermi momentum) = 220 MeV/c.
   Possible interpretation; $p \rightarrow \bar{\nu}\rho^0(\pi^+\pi^-)$.

   Assign μ, π(π, μ) to rings 1,2 and assume 1 π with $p(\pi) = 130$ MeV/c(130 MeV/c), then $M_{total} = 940$ MeV, $|\Delta p|$ (Fermi momentum) = 100 MeV/c(190 MeV/c).
   Possible interpretation; $p \rightarrow \mu^+K^0(\pi^\pm,\pi^\mp)$.

We conclude that we are observing some signals above the heavy ν-background and that these signals are consistent with some of the nucleon decay modes. However, the issue is of the utmost importance and one has to, before reaching any, definite conclusion, accumulate more data of better resolution together with a better understanding of the ν interaction in water.

SEARCH FOR NUCLEON DECAY INTO FINAL STATES WITH $\mu^{\pm}(\pi^{+})$ (The HPW Collaboration)**

David B. Cline

University of Wisconsin-Madison
Physics Department
Madison, WI 53706 U.S.A.

In 320 live days of running (0.62 kiloton years) the HPW experiment has identified four $2\mu^{\pm}$ (or π^{+}) events that are contained in the detector. Two events display the characteristics expected for neutrino interactions. One event displays an isotropic light pattern and is unlikely to be due to a neutrino interaction. Another event has a very low visible energy again unlikely for a neutrino event. One possible candidate for a $3\mu^{\pm}(\pi^{+})$ decay was observed. These three events are compared with the expectation of the Pati-Salam model and other models of nucleon decay.

We report here the search for nucleon decay into channels with 2 or more μ^{+} or μ^{-} or π^{+} or a mixture of these particles. The HPW water cherenkov is especially well suited to this search having a volume array of photo multileptons, very low noise, an excellent light collection and a 4π proportional wire tube active shield surround the active detector.

The HPW detector is a cylindrical tank (radius 5.60m, height 7.15m) containing 700 metric tons of water. It is located in the Silver King mine in Park City, Utah at a depth of 170 kg/cm^{2}. At this depth the flux of cosmic ray muons through the tank is approximately 0.6 Hz. The experiment can be operated remotely from a trailer at the mine entrance.

The tanks holds 704 five-inch photomultipliers (EMI 9870B), on a cubic lattice of ~1.0 m spacing. Light collection is further enhanced by mirrors on the inner surface of the tank. (Fig. 1)

Since December 1983 a two-dimensional wire chamber array has been in place. The tope and sides of the tank are completely covered, and coverage of the bottom is about 70%.

Trigger logic is based on groups of 24 contiguous tubes. A primary trigger requires at least three groups to have signals in two or more tubes, in a 50 ns coincidence window. Secondary triggers for muon decays require two tubes in each of two groups. Up to 6 secondary triggers are permitted within 25 μsec of the primary trigger. Both pulse height and time are digitized on the primary trigger, while secondary triggers give time only. Initial time resolution was 8 ns, improved to 3 ns in January 1984.

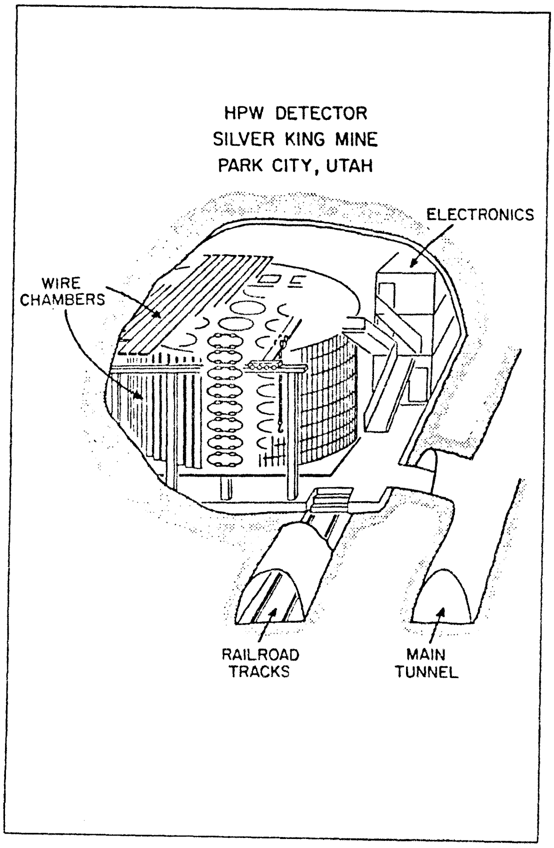

Fig. 1: Schematic of HPW detector.

For secondary triggers, energy is estimated from the count of phototubes that fire. This is calibrated against the spectrum for $\mu \to e\nu\nu$ decays, and with muons that tranverse the chamber during the primary trigger. Both methods indicate that one tube will fire for each 1.5 MeV of energy loss by a relativistic particle. Events with small signals in the primary trigger have nearly all phototubes firing at the single photoelectron level, so for purposes of energy cuts we employ the hit count to the primary trigger as well. The threshold is approximately 10 MeV of visible energy.

Backgrounds random in time are eliminated by a combined cut on the number of phototube hits and their r.m.s. time deviation from the centroid of

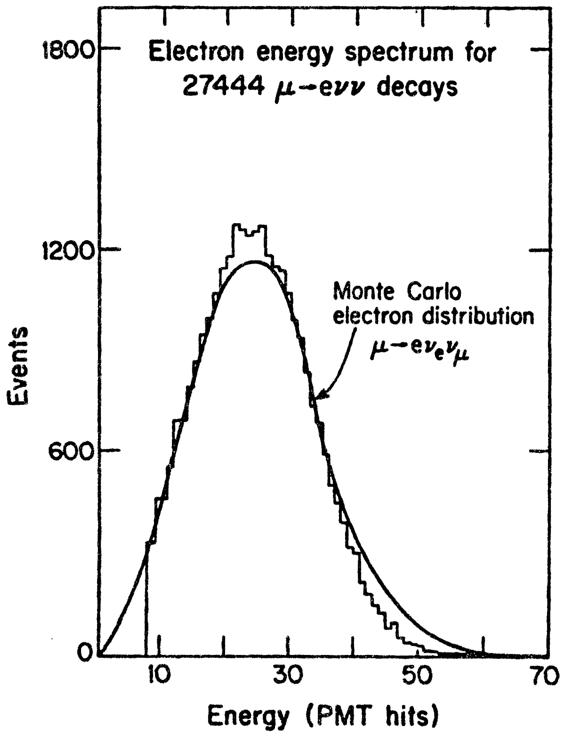

Fig. 2: Energy spectrum of electrons from μ decay compared with expectations.

muon decays. There remain 93,029 events with at least one valid muon decay, 1622 of which have two or more. Monte Carlo studies indicate that the detection efficiency for muon decays is 88%.

The muon decay spectrum is shown in Fig. 2. The predicted distribution comes from a Monte Carlo simulation with the energy resolution of the detector folded in.

The main source of two muon events is hadronic showers, which normally give a large signal in the primary trigger. A cut at 350 phototube hits eliminates 99% of this sample.

The sample is further reduced by a careful scan on the primary vertex, and we find 4 events with $2\mu(\pi^{+})$ decays that are contained inside the detector (See Fig. 3).

The visible energy of these 4 events is reported in Table 1, under the assumption of different physical origins (ν interactions or proton decay).

Table 1

VISIBLE ENERGY FOR DIFFERENT HYPOTHESIS

Event	Photo Electrons	ν_μ Interation (Hypothesis)	Nucleon Decay (Hypothesis)
$A_{2\mu}$	81	630 MeV (1μ+1π)	955 MeV (2μ+1π)
$B_{2\mu}$	132	740 MeV (1μ+1π)	1070-1245 MeV (2μ+1π) (3μ)
$C_{2\mu}$	17	480 MeV (1μ+1π)	855 MeV (3μ)
$D_{2\mu}$	162	790 MeV (1μ+1π)	1010-1335 MeV (2μ+1π) (3μ)
$A_{3\mu}$	92	770 MeV (1μ 2π)	945-980 MeV (2μ+1μ) (2μ+1π)

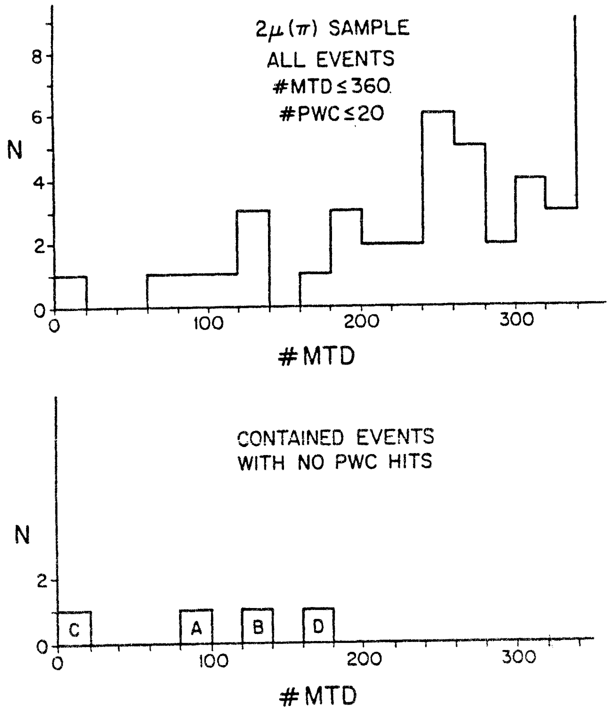

Fig. 3: Energy of all $2\mu(\pi)$ decay events (upper) for contained events (lower).

One event was observed that is consistent with $3\mu(\pi^{+})$ decay. This event appears to be contained but is the upper half of the detector. However there is no evidence for PWC hits in the vicinity of the event as would be expected for on entering $3\mu(\pi)$ cosmic ray event. Therefore we tentatively assume that this event is contained. The visible energy of the event is given in Fig. 4.

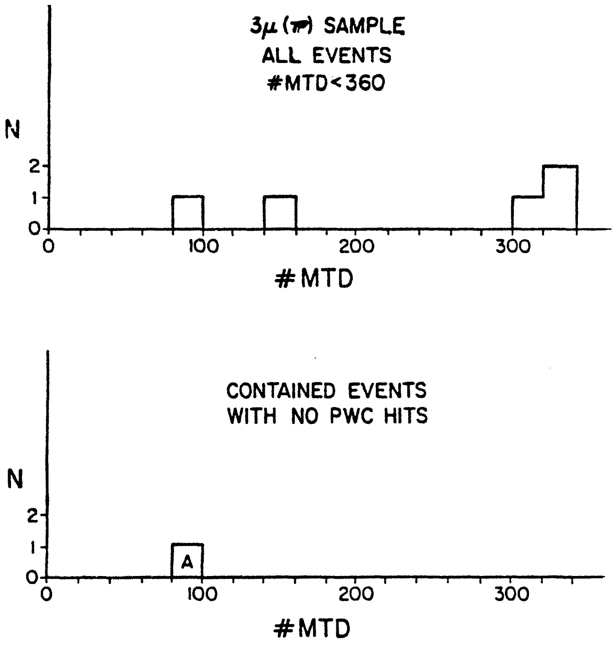

Fig. 4: Energy of all $3\mu(\pi)$ decay events (upper) for contained events (lower).

The remaining background comes from charged-current neutrino interactions within the fiducial volume (Table 2). We observe 12 candidates for neutrino events with a simple $\mu \to e$ decay in a very restricted fiducial volume consistent with expectations. We estimate its rate by a Monte Carlo simultion that uses neutrino events measured at Argonne National Laboratory, weighted to the expected spectrum from atmospheric cosmic rays. The interaction rate is assumed to be 100 charged-current ν^μ interactions per kiloton-year. Approximately 20% have one or more pi-mu decays, and 70% survive our energy cuts. After correcting for detection efficiency, there remain 4.7 events per kiloton-year, or 2.35 events in our data sample.

A more reliable geometric criterion is provided by the "light anisotropy" of the primary trigger, defined as the sum of unit vectors from the decay vertex to all phototube hits, divided by the number of hits. To avoid confusion due to reflections, only hits in the first 30 ns of the primary event are used. This parameter samples all tracks that exceed the Cherenkov threshold; a significant fraction of neutrino interactions have only one such track. Thus events with very low values are unlikely to be neutrino interactions. Two events $B_{2\mu}$, $D_{2\mu}$ consistent with the neutrino interactions.

TABLE 2

BACKGROUNDS FOR $\underline{2\mu(\pi)}$
FINAL STATES (MTD< 150)

$\nu_\mu + N \to \mu^- + \pi^+ \ldots$ (no π^0)
$\nu_\mu + N \to \nu_\mu + \pi^+ + \pi^+ + ..$ (no π^0)
$\bar{\nu}_\mu + N \to \mu^+ + \pi^+ \ldots$ (no π^0)
$\nu_\mu + N \to \mu^- + \pi^0 + ..$
$\pi^0 + p \to \pi^+ + n$

$\underline{3\mu\ (\pi))}$ FINAL STATES

$\nu_\mu + N \to \mu^- + \pi^+ + \pi^0$
$\pi^0 + p \to \pi^+ + \ldots$
$\to \nu_\mu + \pi^+ + \pi^+ + \pi^+ + \ldots$
$\bar{\nu}_\mu + N \to \mu^+ + \pi^+ + \pi^0$
$\pi^0 + p \to \pi^+ + n$

Two events ($A_{2\mu}$, $C_{2\mu}$) appear less likely to be due to neutrino interaction.

These two events, if intepreted as nucleon decay could come from processes such as

$$N \to \mu + k^0_s$$
$$\mu + \rho$$
$$\mu + \omega$$

or Pati Salam type decays

$$P \to \nu \bar{\mu} \pi^+ \pi^+$$

etc. The expected visible energy for such processes is shown in Figs. 5 and 6.

The $3\mu(\pi^+)$ candidate is unlikely to be due to a neutrino interaction. It could be due to a nucleon decay in the Pati Salam model, but might still be due to an incident shower with small probability. Table 3 gives a summary of the various interpretations of the five events observed.

Assuming that the two events we observe are not proton decays, we obtain a 90% confidence limit of

$$\frac{\tau_p}{BR(2\mu)} > 2.0 \times 10^{31} \text{ years}$$

for modes in which one of the muons is a product of pion decay. For modes of the form $\mu\mu X$, a more sensitive limit of 2.9×10^{31} years can be set. If they are due to proton decay the lifetime divided by branching ratio is of order (3-5) × 10^{31} years.

We gratefully acknowledge the difficult and strenuous labors of miners L. North and M. Ryan, and engineer T. Smart, who made it possible to conduct this experiment in a most inhospitable environment. We also wish to acknowledge the efforts of those who designed and built much of the apparatus: J. Blandino, M. Jaworski, J. Oliver, and J. West.

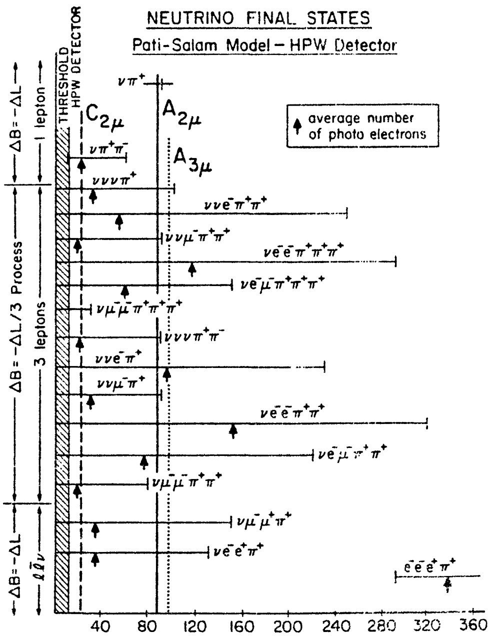

Fig. 5: Comparison of energies of events with expectations of the Pati-Salam theory.

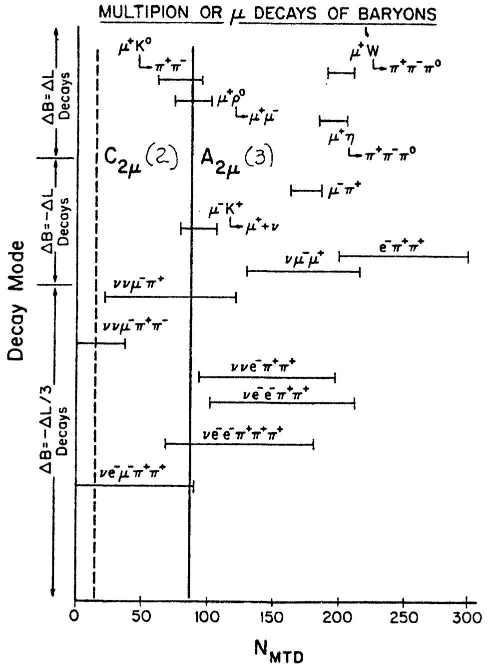

Fig. 6: Comparison of the energies of events with other possible decays of the nucleon.

Table 3

Event Interpretation: $2\mu(\pi)$ Decay

$A_{2\mu}$ $E_{VIS} = 600\ \mathrm{MeV}/_{c}2$	
$I = 0.2$	Unlikely to be neutrino interaction
Possible $p \rightarrow \mu + \rho^o$ $p \rightarrow \mu + k^o$ $N \rightarrow \mu\mu\nu\pi$ P.S.	(<1.6% have $I < 0.3$ $E_{VIS} < 600$ MeV BG = 0.18 Events 90%CL
$B_{2\mu}$ $E_{VIS} = 720\ \mathrm{MeV}/_{c}2$	
$I = 0.5$	Most likely ν_μ Interaction
$C_{2\mu}$ $E_{VIS} = 400$ MeV/c	
$I = 0.4$	Unlikely to be ν_μ Interaction due to low E_{VIS}
Possible $p \rightarrow \mu^+\rho^o$ ρ^o absorbed $\rightarrow$ low energy $\pi\nu$	(less than 5% of ν_μ interaction give this low E_{VIS})
$N \rightarrow \mu\mu$ Pati Salam Model	0.54 90% CL
$D_{2\mu}$ $E_{VIS} = 800$ MeV/c $I = 0.35$	Likely to be ν_μ interaction $E_{VIS} + I$
$A_{3\mu}$ $E_{VIS} < 840\ \mathrm{MeV}/_{c}2$	
$I = 0.4$	
$p \rightarrow \mu^+\mu^-\nu\pi^+$.. Pati Salam Model	Unlikely to be ν_μ Interaction due to low rate of $\nu_\mu + N \rightarrow \mu^-\pi^+\pi^+$...
$p \rightarrow \mu^+\rho^o$ $\rightarrow \pi^+$	Small prob. of penetrating shower if PWC not effective
$p \rightarrow \mu^+\omega^o$ $\rightarrow \pi^+\pi^-\pi^o$ $\pi^o p \rightarrow \pi^+ n$	

**The HPW Collaboration is:
E. April-Giboni,[2] D. Cline,[1] J. Gaidos,[3] K. Giboni,[2] D. Joutras,[1] G. Kalkanis,[1] R. Loveless,[1] R. March,[1] J. Matthews,[1] R. McHenry,[3] A. More,[1] R. Morse,[1] J. Negret,[3] T. Palfrey,[3] T. Phillips,[2] C. Rubbia,[2] G. Sembroski,[3] C. Wilson,[3] D. Winn,[2] and W. Worstell[2]

[1] Physics Department, University of Wisconsin-Madison, WI 53706

[2] Physics Department, Harvard University, Cambridge, MA 02138

[3] Physics Department, Purdue University, West Lafayette, IN 47907

ROUND TABLE ON NUCLEON DECAY

(Conclusions summarized by the Chairman)

At the end of the Proton Decay session there was a round table with the participation of the representatives of all running experiments: V.S. Narasimham (KGF), E. Fiorini (NUSEX), J. Lo Secco (IMB), M. Koshiba (Kamiokande), D. Cline (HPW) and S. Jullian (Frejus). All these experiment are running and various candidates for nucleon decay are presented: 4 by the KGF experiment, 2 by NUSEX (after the application of selection criteria), 4 by Kamiokande and 8 by IMB. The number of contained events are 16, 22, 89 and 169, respectively. The HPW also presents 2 proton decay candidates, but it is not possible for the moment to relate them to the number of contained events in a way similar to that of the other experiments, due to the special selection of the events (two muon decay). The Frejus experiment, still at the beginning and with a sensitive mass reduced with respect to the total one, presents three contained events and no nucleon decay candidate.

In a first part of the discussion, on request of F. Reines, future plans for all collaborations were presented. The Kamiokande collaboration is going to install, during a ten week shutdown, an anticoincidence shield around the detector. In the near future the installation of timing electronics, in collaboration with American physicists, is planned, while for the distant future a proposal is going to be presented, also in collaboration with American groups, for the construction and installation in the Kamioka mine of a 32 kiloton total, 20 kiloton fiducial Cerenkov detector, where 40% of the walls of the fiducial volume will be covered with photomultipliers, V.S. Narasimham informs that a new laboratory has been already escavated near the present KGF experiment. A new detector of 6 x 6 x 6 m^3 made with the same tubes as used in the present experiment, but without layers of Iron (the thickness will only be due to the counter walls), is being installed and should be ready at the end of the year. A second detector of the same size, but made with proportional tubes of 4 x 4 cm^2 cross section, is planned and should be ready at the end of the next year. J. Lo Secco reported about the upgrading of the IMB detector by adding 2048 new phototubes of 8 inches, rather than 5 inches as the present one. The addition of waveshifter plates in front of the phototube will also increase light collection. D. Cline commented about future plans in the United States and at CERN to construct a large (one to two kiloton) detector with liquid argon, or possible other liquids, with TPC detection of the tracks. A detector like that could perhaps be installed in the Gran Sasso laboratory being constructed in Italy. E. Fiorini summarize other plans by groups not represented at the Conference: the Soudan II experiment, by an American-British collaboration, has been approved. The detector will be made by Iron with an honeycomb structure and by drift chambers. The total mass will be around a kiloton. The set-up should operate in 1986 in a laboratory near and slightly deeper than the present Soudan I, at about 2000 hectrograms of water equivalent. The construction of the Gran Sasso laboratory in central Italy is proceeding satisfactorily. A first gallery of about 116 m length and about 30 m^2 cross section has been totally escavated and funds have been already appropriated for the construction of a second laboratory in the form of a huge disc with vertical axis with about 30 m diameter and 25 meter height. While experiments on monopoles, on the penetrating component of cosmic rays and on solar neutrinos have been suggested, no proposal exists yet for experiments on nucleon decay.

Concerning interpretation of the data M. Koshiba has pointed out the difficulties connected with nuclear absorption on secondaries of nucleon decay and of atmospheric neutrino interactions. For Cerenkov detectors, predictions are extrapolated from bubble chamber data, where nuclei could behave in a very different way than Oxigen, while for Iron detectors, where nuclear effect are expected to be larger, the only existing test (by NUSEX at CERN) is limited in statistics and should be repeated at other angles of exposure. This remark was followed by a more general discussion on the need for a serious evaluation of the neutrino background, both with a better extrapolation of the existing bubble chamber data (as being done by T. Jones with the Gargamelle film) and with possible exposures of part of the detectors to artificial neutrino beams at various angles.

The last part of the discussion, was stimulated by J.C. Pati who was requesting the experimenters if the present candidates could be indicative of "exotic" nucleon decays like those into a lepton plus a lepton-antilepton pair and possibly hadrons. In particular he requested if the μ^+K^0 decay of the NUSEX collaboration could be alternatively interpreted as due to proton decay into a neutrino, a pair of positive and negative muons and a positive pions. A similar interpretation was also requested for the Kamiokande candidates. The conclusion was that, while the NUSEX event can easily be accounted for with this interpretation, this seems much harder for the Kamiokande results, which do not support Pati's suggestion.

The general conclusion of the round table was that, even if nucleon decay is far from being discovered, there is no doubt that a few events have been found which fit well proton decay and are hard to be accounted for by interaction of atmospheric neutrinos. Future efforts should therefore be addressed not only to the construction of more massive detectors, but especially to the development of techniques where the events can be studied in more precise details (for instance with better light collection in Cerenkov detectors, with better granularity in calorimeters, and with new "bubble chamber" techniques like liquid TPC). It seems however essential to develop much further, possibly with new experiments, our present knowledge of atmospheric neutrino interactions which represent the main bottleneck towards the possible discovery of nucleon decay.