NUCLEON STABILITY, MAGNETIC MONOPOLES AND ATMOSPHERIC
NEUTRINOS IN THE MONT-BLANC EXPERIMENT

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ABSTRACT

Ten totally confined events have been found in the Mont-Blanc Nucleon Stability Experiment. While nine can be interpreted as interactions of atmospheric neutrinos, one could be a proton decay. Limits are given for nucleon stability, $n-\bar{n}$ oscillations, magnetic monopoles and monopole catalysis of nucleon decay.

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1. INTRODUCTION

The Mont-Blanc Nucleon Stability Experiment has been operated for about a year at depth of ~ 5000 m water equivalent of standard rock. The first results and a description of the set-up and of the trigger have been reported previously [1]. The detector is a cube of 3.5 m side, made by 134 iron plates 1 cm thick, interleaved with planes of plastic streamer tubes [2]. Coordinates on each plane are read bidimensionally by means of X- and Y-strips parallel and orthogonal to the tubes, respectively. A fast OR signal available for each plane of the detector is used for the trigger logic electronics. Since August 1982 the 134 OR signals were also sent to a TDC system with 100 ns time resolution to determine the time at which each plane is fired. This also allows one to measure the delay of a positron from the decay of a positive muon stopping in the detector. The probability to detect unambiguously such a decay has been calculated with a Monte-Carlo procedure and found to be of $\sim 35\%$.

The detector has been operated for 7600 h of live time corresponding to 130 t $\times$ year and to 7.8×10^{31} nucleons $\times$ year. We have detected 7732 single muons crossing the detector, and 117 bundles of parallel muons. We discuss in the present paper our results on atmospheric neutrinos, nucleon stability, magnetic monopoles and monopole catalysis of nucleon decay.

2. CONTAINED EVENTS AND THEIR INTERPRETATION

In order to eliminate any spurious event due to charged particles entering the detector and interacting in it, we have restricted our study of nucleon stability and of atmospheric neutrino interactions to events where all the charged secondaries stop in the detector. For this analysis we have required that the vertex of an event must be at least five tubes inside the detector, and that all the tracks must stop. A track is defined to stop if the potential path at the end would cross at least two further active tubes. The 150 t total mass is thus reduced to 130 t.

Ten fully contained events have been found and are listed in table 1. The last six, not reported previously [1], are shown in fig. 1.

Eight of our events can be interpreted as interactions by atmospheric neutrinos: Four ν_μ and one ν_e quasi-elastic scatterings, one quasi-elastic or inelastic interaction by a muon neutrino, a two-prong neutrino interaction (with a visible muon decay) and an inelastic interaction of an electron or muon neutrino.

Events number 3, 4 and 10 are not incompatible with proton decay mode $p \rightarrow \pi^+ \nu$ taking into account Fermi motion. However due to the background of atmospheric neutrino interactions giving a single muon, they cannot be considered as candidates for proton decay

The three-prong event number 1 has already been discussed in [1] and found difficult to be interpreted as a neutrino interaction. On the basis of the present statistics of neutrino interactions and of a re-analysis of the interactions of accelerator neutrinos in a test module of our detector [3] we expect at the 90% confidence level less than 0.09 neutrino events with this topology. The event fits proton decay in the $K^0 \mu$, $K^* \nu$ and 3μ channels.

Interpretation of event number 6 is difficult. The characteristics of this event are given in table 2 and fig. 2. Track AB originates from vertex A because of the increase of scattering towards vertex B, and is likely to be a π^+ or μ^+ (95% c.l) because of the 0.2 μ s delayed signal at B.

Track FG we consider is of neutral origin, either from the vertex A or vertex E. The probability that FG is part of a charged track from the vertex E and has 4 missing hits is $< 2 \times 10^{-3}$. This probability was obtained using vertical muons.

The neutrino interpretations of this event are:

- (a) a muon AB plus a charged hadron ACE which interacts at E,
or
- (b) a muon AB plus a charged hadron ACED and a neutral hadron which interacts at F.

Note that the energies of tracks ACE and ED are small because they are in the direction of the plastic tubes.

In our test experiment, only 5 events had an additional single separated track. We conclude that the probability that this event is of neutrino origin is 2% at the 95% confidence level. As there are 10 contained events, the expected number is 0.2 events.

With respect to the nucleon decay hypothesis this event would be a decay into two charged particles, but because one of these interacts, no kinematical constraints can be applied to test this hypothesis of nucleon decay. It is worth pointing out that we have estimated, using our calibration data, that the probability for a pion from a $N \rightarrow \mu\pi$ decay to produce an interaction of the type observed at vertex F is $< 2 \times 10^{-3}$.

Also we cannot use this event as evidence for $n-\bar{n}$ transitions.

The total number of neutrino interactions found in this experiment seems in good agreement with the theoretically expected rates [4-7] and with the results of other experiments [8-10] if the effects due to geomagnetic latitude are taken into account. Four of the clearly identified neutrino interactions are directed downwards, two upwards and two with uncertain directions. The two remaining events, if interpreted as neutrino interaction, are one downwards and one upwards.

3. NUCLEON STABILITY

From our results we give the limits on the lifetime for various decay modes in table 3. The limits take into account fiducial volume, trigger and angular efficiency, nuclear absorption and μ -e detection when applicable [3]. From previous discussions only one of the ten contained events is a candidate for nuclear decay. On the basis of the present statistics of atmospheric neutrino interactions we evaluate that the background to this event due to atmospheric neutrinos is less than 0.09 of an event, at the 90% confidence level. For a K^0_{μ} decay this event would correspond

to a lifetime of 1.5×10^{31} and 3.0×10^{31} years per proton or per nucleon, respectively. Our results allow also to investigate the existence of $\Delta B = 2$ processes and particularly of $n-\bar{n}$ oscillations inside the nuclei [11,12]. We have evaluated by means of a Monte-Carlo calculation where pion absorption has been taken into account, that 75% of these oscillations would give rise to the emission of at least one neutral pion. In order to be conservative, we have taken as a possible candidate for this process event number 4, even if its most natural interpretation would be as neutrino interaction.

We conclude that the lifetime for $n-\bar{n}$ oscillation has to be larger than 0.6×10^{31} years. According to recent calculations specially carried out for iron nuclei [13,14], this value would correspond to a limit between 3 and 4×10^7 s on the free oscillation time of the neutron. We would like to stress however, that it has been pointed out [15] that $n-\bar{n}$ oscillation could be forbidden in nuclei.

Our result also sets a limit of 1.0×10^{31} years for the decay $n \rightarrow \bar{p} + e^+ + \nu_e$ [16] and of 4×10^{29} years (per nucleus) for the decay $(A,Z) \rightarrow (A-2, Z-2) + 2 e^+$ [17].

4. MAGNETIC MONOPOLES

Since April 1983, a special trigger has been added to record slow monopoles [18,19] by OR-ing together the detector planes into 9 groups: the upper 2, where radioactivity is more intense, are made of 8 planes each, the next 7 by 16 planes each. The trigger configuration is reached when at least one detector of the second group is fired within 7 μ s from the first, and at least one detector of each other group is fired within 15 μ s from the preceding one. When this configuration is reached the times of 16 groups of planes (the 128 planes are OR-ed in groups of 8) are recorded with a time resolution of $\sim 1 \mu$ s. This would allow to record monopoles with ionization down to $\sim 10^{-2}$ of the minimum ionization and β down to 10^{-4} . The counting rate ($\sim 9 \times 10^{-6}$ Hz) can be attributed to radioactivity. Since no event shows the linearity in time typical of a monopole crossing entirely the detector, we can exclude at the 90% confidence level fluxes of more than $4 \times 10^{-9} \text{ m}^{-2} \text{ sr}^{-1} \text{ d}^{-1}$ for these monopoles.

It has been recently suggested [20,21] that nucleon decay can be catalyzed by GUT monopoles with an interaction length given in metres by $\lambda = \frac{43}{\rho} \frac{\beta}{\sigma_0}$, where ρ is the relative density of the detector, and β and σ_0 are the relative velocity and the reduced cross section of the monopole. Two or more nucleon decay induced by the same monopole would be recorded by our set-up, if they occur in a time interval lower than 5 μ s or larger than 20 ms. Since no such event has been recorded, the corresponding lower limit for the flux of monopoles can be obtained as a function of the interaction length (fig. 3). In addition our single nucleon decay candidate can be used to give further constraints on the monopole flux in the cases of when only one, or more than one event could be visualized (fig. 3).

5. CONCLUSIONS

Nine of our contained events can be attributed to interactions of atmospheric neutrinos, in good agreement with the expected rate at our geomagnetical latitude. Our single-nucleon decay candidate would correspond to a lifetime of 3.0×10^{31} years and would indicate the $K^0 \mu^+$ mode. The limits on the lifetimes for various decay modes is shown in table 3. We find no evidence for $n-\bar{n}$ oscillations with a lower limit of 0.6×10^{31} years on the lifetime and of $3\sim 4 \times 10^7$ s on the free neutron oscillation time at the 90% CL. We also find no evidence for magnetic monopoles crossing the detector with ionization of at least $10^{-2} I_{\min}$ and relative velocity of at least 10^{-4} , and for monopole catalysis of nucleon decay.

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TABLE 1

Event No.	Date	Vertex Position in centimetres			No. of tracks	Total energy GeV	Angle to verticle in degrees	Interpretation
		X	Y	Z				
1	23.7.82	82	93	181	3	1.00 ± 0.2	170	See text
2	01.8.82	268	90	321	3	1.50 ± 0.4		ν_μ or ν_e inelastic
3	04.8.82	287	74	154	1	0.40 ± 0.1	35	ν_μ elastic
4	06.8.82	199	307	119	1	0.33 ± 0.015	45 135	ν_μ elastic
5	09.1.83	215	36	200	1	1.40 ± 0.25	65	ν_μ elastic
6	02.2.83	48	157	94	2	0.87 ± 0.08	36	see text
7	25.2.83	44	73	200	2	0.73 ± 0.03		ν_μ inelastic
8	06.4.83	120	67	327	2	$3.70 + 1.8$ $- 0.7$	145	ν_e elastic
9	28.6.83	45	160	138	1	1.11 ± 0.06	55	ν_μ elastic
10	24.7.83	67	137	80	1	0.33 ± 0.015	54	ν_μ elastic

TABLE 2

Track	Range gms iron	Kinetic Energy MeV
AB	240 ± 20	$390 \pm 30 \mu$
ACE	100 ± 50	$195 \pm 70 \pi$
ED	3 ± 1	$2 \pm 1 \pi$
FG	40 ± 3	$200 \pm 30 p$
$\hat{BAC} = 107 \pm 5^\circ$		$\hat{BAF} = 75 \pm 2^\circ$

TABLE 3

Mode	Candidates	Lifetime/Branching ratio in years (90% c.)
$N \rightarrow e^+ \pi^-$	0	$> 1.5 \times 10^{31}$
$N \rightarrow \mu^+ \pi^-$	0	$> 1.0 \times 10^{31}$
$p \rightarrow \nu \pi^+$	≤ 3	$> 0.2 \times 10^{31}$
$n \rightarrow \nu \pi^0$	0	$> 0.7 \times 10^{31}$
$p \rightarrow \mu^+ K^0$	1	$> 0.6 \times 10^{31}$
$p \rightarrow \nu K^+$	0	$> 0.2 \times 10^{31}$
$n \rightarrow \nu K^0$	0	$> 0.5 \times 10^{31}$

REFERENCES

- [1] G. Battistoni et al., Phys. Lett. 118B (1982) 461.
- [2] G. Battistoni et al., Nucl. Instr. and Meth. 202 (1982) 459.
- [3] G. Battistoni et al., An Experimental Study of the Neutrino Background in Underground Experiments on Nucleon Decay, preprint submitted to Nucl. Instr. & Methods.
- [4] J.L. Osborne, S.S. Said and A.W. Wonfendale, Proc. Phys. Soc. (London) B6 (1965) 93.
- [5] M.F. Crouch et al., Phys. Rev. D18 (1978) 2239.
- [6] T.K. Gaisser et al., The flux of atmospheric cosmic ray neutrinos, preprint.
- [7] A. Dar, Atmospheric neutrinos in proton decay experiments, Invited talk at the 4th Int. Workshop on GUT's, Philadelphia April 25-28, 1983.
- [8] M.R. Krishnaswamy et al., Neutrino Background in the Kolar Gold Field Nucleon Decay Experiment, in PRAMANA.
- [9] R.M. Bionta et al., A search for Proton Decay (Irvine-Michigan-Brookhaven Collaboration), Phys. Rev. Letters.
- [10] M.R. Krishnaswamy et al., Phys. Lett. 115B (1982) 349.
- [11] M. Baldo Ceolin, Invited paper to the 1982 International Conference on Neutrino Physics and Astrophysics, Balaton fured, June 1982.
- [12] G. Fidecaro, Invited paper to the Fourth Workshop on Grand Unification, Philadelphia, 21-23 April 1983.
- [13] G.B. Dover, A. Gal and J.M. Richard, Phys. Rev. D27 1090 (1983.)
- [14] W. Alberico et al., CERN/TH 3537, February 1983, preprint.
- [15] P.K. Kabir, P.R.L. 51B (1983) 231.
- [16] V. Gupta, S. Pakvasa and V. Sigh, Phys. Lett. 118B (1982) 352.
- [17] J.D. Vergados, Phys. Lett. 118B (1982) 107.
- [18] G. Giacomelli, Invited paper to ICOMAN 1983, Frascati, 17-22 January 1983.
- [19] R.A. Carrigan Jr and W.P. Trower, Magnetic Monopoles: A status Report, preprint.
- [20] V. Rubakov, JEPT Lett. 33 (1981) 644 and Nucl. Phys. B203 (1982) 311.
- [21] C.G. Callan, Phys. Rev. D25 (1982) 2141 and Nucl. Phys. B203 (1982).

FIGURE CAPTIONS

Fig. 1 The two orthogonal projections of the additional six events.

Fig. 2 Details of event 6.

Fig. 3 Limits on monopole fluxes as a function of the catalytic
interaction length.

a)

x

y

Event 5

Event 6

Event 7

Fig. 1a

b)

x

y

Event 8

Event 9

Event 10

Fig. 2

Fig. 3