Search for Proton Decay into $e^+\pi^0$

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Observations were made 1570 meters of water equivalent underground with an 8000-metric-ton water Cherenkov detector. During a live time of 80 d no events consistent with the decay $p \to e^+\pi^0$ were found in a fiducial mass of 3300 metric tons. It is concluded that the limit on the lifetime for bound plus free protons divided by the $e^+\pi^0$ branching ratio is $\tau/B > 6.5 \times 10^{31}$ yr; for free protons the limit is $\tau/B > 1.9 \times 10^{31}$ yr (90% confidence). Observed cosmic-ray muons and neutrinos are compatible with expectations.

We have built and operated a large water Cherenkov detector deep underground in order to search for nucleon decay. We have chosen as the initial goal of our experiment to look for proton decay to the final state $e^+ + \pi^0$. This two-body mode gives a clear back-to-back decay signature which is especially well defined and distinct from background in a water Cherenkov detector.

The simplest grand unified gauge theory, minimal SU(5), predicts a partial lifetime $\tau/B = 4.5 \times 10^{29 \pm 1.7}$ yr for the $p \to e^+\pi^0$ decay mode.[1] Therefore in our detector, after 80 d of exposure (2.4×10^{32} proton yr), using $\tau/B = 2.2 \times 10^{31}$ yr, we expect to observe at least seven such events.

Previous searches for nucleon decay in iron at the Kolar gold fields[2] and the Mont Blanc tunnel[3] have reported a few candidate events tentatively ascribed to various modes of proton decay.

The Irvine-Michigan-Brookhaven (IMB) detector[4] is located at a depth of 1570 meters of water equivalent in the Morton-Thiokol salt mine east of Cleveland, Ohio. It consists of a large rectangular volume of purified water ($17 \times 18 \times 23$ m^3) viewed from its six faces by 2048 photomultiplier tubes (PMT), each of 12.5 cm diam, located on a rectangular grid of ~ 1 m spacing. The total sensitive volume of the detector is 8000 metric tons (tonnes) and the fiducial volume, inset by 2 m from the planes of the PMT's, is 3300 tonnes.

A relativistic charged particle traversing the detector produces a cone of Cherenkov light with a half-opening angle of 41° relative to its direction of motion. The particle continues to emit Cherenkov light until its velocity falls below

0.75c. The time of photon arrival and pulse height are recorded independently by each PMT, providing information which allows the reconstruction of position, direction, and energy of particles moving in the detector.

Two distinguishing characteristics of this detector are its large sensitive mass and its ability to determine unambiguously the sense of track direction. The uniform sensitivity of the active medium makes the energy resolution of the detector nearly independent of the fluctuations of electromagnetic shower development and Fermi motion of the decaying proton.

The resolution and absolute energy calibration of the detector in time, position, direction, and energy are evaluated by the use of programmable light sources in the detector volume and with cosmic-ray muons which penetrate or stop in the detector. The light sources have variable position, intensity, and firing time. They are also used to determine the attenuation length (> 30 m) for light in the wavelength region of interest (300–450 nm). Our system of PMT's and electronics is sensitive to light at the single photoelectron level.

The trigger threshold corresponds to the light output from a 50-MeV electron in the detector.[5] PMT's firing up to 7.5 μsec after the initial trigger are also recorded, providing identification of the electron from muon decay with 60% efficiency.

On the basis of the measured efficiency of PMT's and the geometry of our detector, computer event simulation predicts a signal from 170

± 18 (statistical) ± 18 (systematic) tubes if a proton decays to $e^+\pi^0$ inside the fiducial volume. Event simulation programs were calibrated with use of data from single cosmic-ray muons.

The time resolution of PMT's at the single photoelectron level (11 ns full width at half maximum) is the primary factor in determining the accuracy of the vertex position for $p \to e^+\pi^0$. For this mode the resolution is typically ± 60 cm, as confirmed by use of point sources of light at various positions in the detector.

For two-track events with an opening angle > 100° and where each track gives rise to signals from at least forty PMT's, the cones from both tracks are distinguishable and the opening angle has a typical uncertainty of ± 15°. For $p \to e^+\pi^0$ the two photons from π^0 decay are generally not separately distinguishable; nevertheless the π^0 shower gives a well identified cone similar to that from the e^+.

Performance checks on the detector operation were made by measuring the angular distribution, stopping muon rate, and muon lifetime.[4] These measurements are consistent with accepted values.

Reduction of the 2.3×10^5 triggers/day (primarily due to penetrating muons) is accomplished with three independent and complementary analyses. In the first stages of analysis cosmic-ray muons are rejected by various energy and topological cuts. The first cut, which requires that from 40 to 300 PMT's be lit (i.e., 250–1700 MeV), reduces the event rate by a factor of 3.3. The times and spatial locations of the lit tubes are then used to find the vertex, under the assumption that the light originates from a point source. This is a good approximation for short tracks. A fiducial cut 2 m in from the planes of the tubes rejects entering tracks by more than a factor of 300.[6] Different pattern-recognition methods, including interactive scanning by physicists, are applied to the 230 events/day which survive these initial cuts. Events are fitted with one- and two-track hypotheses and track directions are determined by use of the known properties of Cherenkov light. The goal of the filtering procedures is to save all events which originate inside the fiducial volume. The process of pattern recognition is aided by color displays of the lit PMT signals generated as a function of time.

The survival efficiency of $p \to e^+\pi^0$ events through three procedures is estimated to be 0.9 ± 0.1, based on computer simulations whose validity has been verified by use of cosmic-ray muons

and artificial light sources. Cross correlation between the three analyses on data events which have properties similar to those expected for $p \to e^+\pi^0$ further confirm the estimated detection efficiency.

With 2.4×10^{32} proton yr of exposure we find 69 interactions in the fiducial volume which light at least 45 PMT's (see Fig. 1). Within the statistical accuracy of the sample the above events are uniform in vertex position and isotropic in track direction. There is no evidence for contamination of the sample by entering tracks or from events generated by the background associated predominantly with downward going muons. The fraction of fully contained events exhibiting muon decay is 0.4 ± 0.1 (after correction for our detection efficiency of 0.6 ± 0.1).[7] The distribution of visible energy, E_{min}, for the events is displayed in Fig. 2. The curve in this figure was calculated by passing simulated neutrino events through our filtering cuts. The neutrino events were generated by data from a wide-band neutrino exposure in the Gargamelle bubble chamber.[8] The spectrum was adjusted to agree with that expected for atmospheric neutrinos, and corrections were made for the lack of electron neutrinos in the Gargamelle data. We calculate the absolute rate of neutrino interactions which pass our energy cuts to be 0.9 ± 0.4 per day, based on estimated fluxes[9] and cross sections[10] appropriate to the
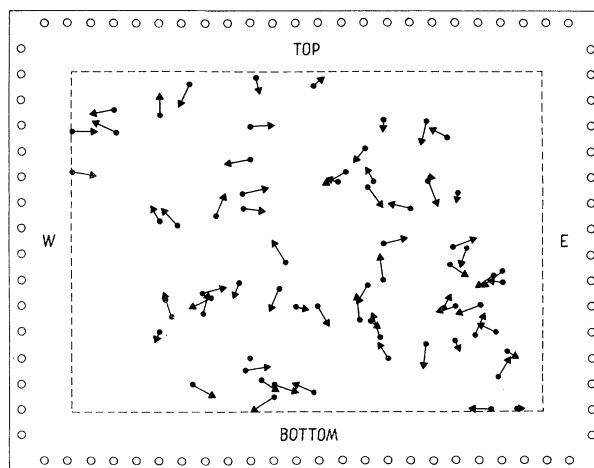

FIG. 1. Side view of the detector indicating vertex positions for one- and two-track events. Arrows indicate the projection of the direction unit vector for the best-fit tracks in this view. PMT positions are indicated near the outside (solid line) of the water volume. The dashed line represents the boundary of the software-controlled fiducial volume.
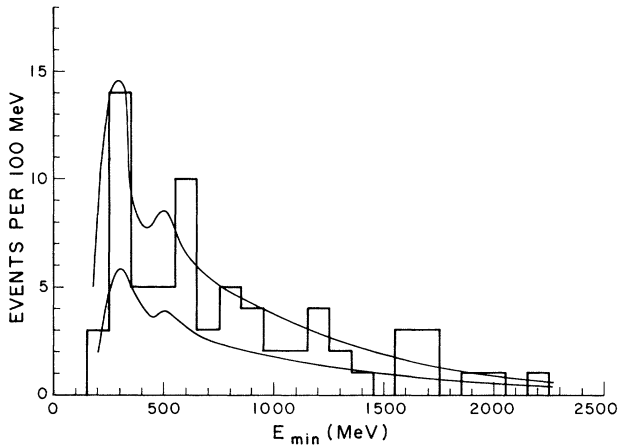
FIG. 2. Energy (E_{min}) distribution of the 69 contained events. The expected distribution from atmospheric neutrinos lies between the upper and lower curves. The uncertainty arises primarily from the atomspheric flux estimate. The secondary peak near 500 MeV is due to events with observed muon decays whose visible energy has accordingly been increased by 230 MeV.

energy range we observe. Our estimated efficiency for the detection of atmospheric neutrinos is 0.7 ± 0.2. The predicted rate could be in error by as much as a factor of 2 because of uncertainties arising from the calculation of the neutrino flux. The results are thus seen to be consistent with expectations.

The 69 contained events can be summarized as follows: (1) 66 single-track or multitrack events which do not possess a track lighting more than forty tubes in the backward hemisphere, and hence are outside the angle and energy requirements for $p \to e^+ \pi^0$; (2) two wide-angle two-track events both of which have a muon decay signal and hence do not qualify as $p \to e^+ \pi^0$ decays; and[11] (3) one two-track event in which 340 PMT's were

lit, about a factor of 2 greater than expected for $p \to e^+ \pi^0$ in our detector, and in addition, in which the opening angle $115° \pm 15°$ was outside the predicted range ($> 140°$) for free or bound proton decay to $e^+ \pi^0$. The characteristics of these two-track events are summarized in Table I.

Results on other nucleon decay modes and a more complete analysis of neutrino interactions will be discussed in future publications.

For free protons, we obtain a lifetime limit independent of nuclear effects. Since $\frac{1}{5}$ of the protons in our detector are not bound in nuclei, we can conclude that the partial lifetime for free protons is $\tau/B > 1.9 \times 10^{31}$ yr.

For free plus bound protons we assume a 40% loss of events in the oxygen nucleus and ignore possible lifetime changes from nuclear effects.[12] Using 2.3 events to obtain a 90% confidence limit we calculate τ/B as follows:

$$\tau/B > Nf\epsilon_n\epsilon T/2.3 = 6.5 \times 10^{31} \text{ yr},$$

where $N = 2.0 \times 10^{33}$ nucleons; $f = \frac{10}{18}$, proton fraction in water; $\epsilon_n = 0.68$, average nuclear π^0 survival efficiency (oxygen plus free protons); $\epsilon = 0.9 \pm 0.1$, detection efficiency; and $T = \frac{80}{365}$ yr.

These results are to be compared with the theoretical prediction for $p \to e^+ \pi^0$ of $4.5 \times 10^{29 \pm 1.7}$ yr.

Note added.—With a running time of 130 days and no events seen we have now achieved a limit $\tau/B > 10^{32}$ yr for free plus bound protons.

TABLE I. Wide-angle two-track events.

Event number	Number of PMT's lit	Minimum energy[a] E_{min} (MeV)	Track opening angle (deg)	Observed muon decays
151—35 037	188	1230 ± 125	135 ± 7	1
225—7794	166	1180 ± 120	125 ± 25	1
338—19 376	340	1700 ± 170	115 ± 15	0

[a] Does not include possible systematic errors of $\pm 15\%$. E_{min} is the minimum energy of the event as inferred from the Cherenkov light yield after making a 230-MeV correction for rest mass and Cherenkov yield of observed muons.

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[5]More precisely, the trigger requires that either > 12 PMT's fire within 50 nsec or that > 3 PMT's fire in any 2 of 32 groupings of 8×8 PMT's in 150 nsec.

[6]The actual fiducial-volume cut is topology dependent and can be as close as 1.0 m from the tube planes in rare cases. Our nominal "fiducial mass" is obtained by determing the fraction of simulated events generated throughout the entire detector which pass all of our filtering cuts.

[7]In the energy range with which we are concerned the ν_μ/ν_e ratio is expected to be $\sim 2/1$. As a result of the different sensitivities of our detector to electrons and muons, with the requirement of > 45 PMT's we expect that the observed ratio will be ~ 0.5.

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[11]These two events have fifteen and twelve PMT's, respectively, associated with a muon-decay electron in a time window of 100 nsec. Both of these numbers are far above the threshold of six PMT's set by accidental coincidences in our second timing scale.

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