Search for Nucleon Decay into $\mu^+ K^0$ and νK^0

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Observations have been made 1570 m (water equivalent) underground with an 8000-metric-ton water Cherenkov detector. During a live time of 132 days, events consistent with the decay modes $p \rightarrow \mu^+ K^0$ and $n \rightarrow \nu K^0$ were searched for 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 $\mu^+ K^0$ branching ratio is $\tau/B > 2.6 \times 10^{31}$ yr. For bound neutrons decaying into νK^0 the limit is $\tau/B > 0.8 \times 10^{31}$ yr (90% confidence level).

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Proton decay is predicted in a variety of unified theories. Although $e^+\pi^0$ is the preferred decay mode for the minimal SU(5) models dominated by gauge bosons, $p \rightarrow \mu^+ K^0$ is predicted if the decay is dominated by Higgs scalars. It is also predicted in certain supersymmetric models. In other supersymmetric models $n \rightarrow \nu K^0$ is the dominant mode. The K^0 can decay via $\pi^0\pi^0$, giving easily detected Cherenkov light.

The Irvine-Michigan-Brookhaven proton decay detector[1] is located 600 m underground in the Morton-Thiokol salt mine in Painesville, Ohio. It is a large rectangular volume of water, $22.8 \times 17.8 \times 16.9$ m^3, viewed by 2048 photomultiplier tubes (PMT's) covering all six faces. The fuducial volume of 3300 metric tons or 2.0×10^{33} nucleons begins 2.0 m in from the tube planes, which, in turn, begin nominally 0.5 m in from the walls.

Charged-particle tracks in the water give off Cherenkov light above the threshold $\beta = 0.75$. A track that goes towards a wall and exits will leave a filled circle of lit PMT's, while a stopping track will light up a ring. By utilization of the relative timing of the lit PMT's and their geometric pattern, the vertex position of single tracks can be reconstructed to an accuracy of about 1 m. For multitrack nucleon-decay events with opening angles greater than 90° (so that the Cherenkov cones do not overlap), the vertex can be reconstructed to within 60 cm.

The trigger efficiency is $\sim 100\%$ for the proton-decay modes discussed in this paper. Three words of data are recorded for each PMT. T_1 is the time the tube fired relative to the trigger with 1 ns least count. (The PMT time resolution is 5.5 ns half width at half maximum at low light levels.) T_2 is the time that a PMT fired up to 7.5 μsec after the main trigger. This scale is used to detect decay electrons from particles which stopped in the detector, such as muons. Q is the integrated pulse height from the PMT, which is proportional to the energy E_c, the visible Cherenkov light yield of a massless, nonshowering particle of that total energy, E_T. For an electron, photon, or π^0, $E_c = E_T$. For a muon, $E_c = E_T - 250$ MeV, because of the muon rest mass and the energy deposited below Cherenkov threshold.

We record 2.7 triggers per second due to cosmic-ray muons passing through the water. The number of accidental triggers is negligible. All events in the energy range of interest to proton decay (0.05–2 GeV) are written on tape for off-line analysis.

The raw T_1, T_2, and Q values are transformed to times and energy with a calibration procedure. This is based on a pulsed nitrogen laser sending 337-nm light into an optical fiber which ends in a diffusing ball in the center of the pool. This forms an isotropic light source whose intensity can be varied over five orders of magnitude by placing neutral density filters in front of the beam under computer control. The time response (and corrections to it as a function of pulse height) can be obtained by varying the time of firing of the laser with respect to the trigger and by changing the light level.

The absolute energy scale is set by use of a sample of straight-through muons with 18.5-m path length. Since the mean muon energy is ~ 300 GeV, a correction must be made for knockon electrons, pair production, etc., which increase the Cherenkov light output relative to that of a single minimum-ionizing track (3.7 GeV). Averaging over the muon energy spectrum, we estimate that the peak is increased by 22%, with a tail at the high-energy end. The energy distribution observed agrees well with the simulation, even in the tail.

The efficiency ($\sim 15\%$) for photons striking a PMT to produce a detected photoelectron is determined by comparison of the generated straight-through muons with the data. There is good agreement between the data and the calculation for the probability of a PMT to fire as a function of the distance the photon traveled from the track to the tube. We estimate a systematic error of 15% in our absolute energy determination at 1 GeV.

There are three independent analysis chains to find events originating in the fiducial volume. These could be atmospheric neutrino interactions, possible proton-decay candidates, or other new physics. The details of one of these analysis chains are presented here; the results are consistent with those of the other chains. The details of the other analysis chains can be found in Wuest *et al.*[2]

There are 2.3×10^5 triggers per day, predominantly straight-through cosmic-ray muons. The first step in the analysis requires 20–300 lit PMT's, reducing the data by a factor of 3. This range includes most nucleon-decay modes. For example, the final states μ^+K^0 ($K_s^0\rightarrow \pi^0\pi^0$), νK^0 ($K_s^0\rightarrow \pi^0\pi^0$), and μ^+K^0 ($K_s^0\rightarrow \pi^+\pi^-$) are expected to light up 100 to 180, 90 to 160, and 20 to 70 PMT's, respectively.

A good approximation for the short tracks produced by neutrino interactions and proton decay is to assume that the lit tubes were illuminated by a single point source of light. The second step locates that point, with use of the timing information from the tubes. By requiring that this point lies within the fiducial volume, we eliminate the entering tracks by a factor of 100 while saving 80% of neutrino interactions (predominantly single visible tracks) originating in the fiducial volume. Over 90% of simulated nucleon-decay events are saved. The main advantage of this point fit is its high speed coupled with good efficiency.

The remaining triggers are primarily short stopping muons and longer tracks that clip the corners of the detector. At this stage we require that the light illuminating a PMT emanate at the Cherenkov angle of 41° from the hypothesized track. The first guess for the vertex is the point on the surface of the detector where the earliest tubes fired. We calculate the likelihood for this vertex using the PMT firing time and geometry. If the likelihoood is good enough, the event is considered an entering track and rejected. For those events that are kept, the vertex is allowed to vary throughout the detector to maximize the likelihood. About three events per day remain with a best fit in or near the fiducial volume, with 40 or more lit PMT's. Physicists scanning with a color graphics system reduce this to ~ 1 event per day. They eliminate events kept by the fitting program which are primarily top-entering and downward-going tracks with small numbers of PMT's. A small number of neutrino interactions near the top at the edge of the fiducial volume going downward could be thrown out by such scanning. This is included in the overall efficiency (75%), averaged over ν types and energies, of keeping the predominently low-energy, single-track ν events. The number of candidates with a vertex in the fiducial volume, 109 in 132 days, is consistent with the prediction for neutrinos based on either of two neutrino flux calculations[3] and the above detection efficiency. We use the accelerator neutrino events found by the Gargamelle collaboration in a Freon-filled bubble chamber[4] to give the relative weighting and track topologies of quasielastic single-pion and multipion production in neutrino interactions in nuclei. In this way large-angle pions that could mimic proton decay are properly put in. The Gargamelle events are selected to follow the expected atmospheric neutrino energy spectrum, and electron-neutrino events are generated by changing the observed μ to an electron of the same momentum. Neutral currents are also included. The characteristics of the 109 events are consistent with those expected from ν interactions. The energy distribution[4] agrees well, and the event vertices[1] are distributed uniformly in the detector and are reasonably isotropic in direction.

We have two different methods to search for $p\rightarrow \mu^+K^0$. The first is based on the decay $K_s\rightarrow \pi^0\pi^0$, which gives four γ's and produces a nearly isotropic source of Cherenkov light. The rings from the four tracks overlap, so that it is difficult to separate the showers. Instead, we construct a measure of the isotropy of the event. We calculate the magnitude of the vector sum of the unit vectors from the vertex to each lit PMT, divided by the total number of lit PMT's. If this quantity A

(the anisotropy) is near 0, the event is isotropic; for an event with a single short track, we find that $A \sim 0.1$, the cosine of the Cherenkov angle. Only PMT's within ± 15 ns of their expected firing times are used to calculated A so as to minimize the smearing due to scattering of the light in the tank.

The second requirement is that $500 < E_c < 850$ MeV. (We do not require the presence of a muon decay.) Figure 1 is a scatter plot of E_c vs A for the 109 events. The dashed region is the area in which 90% of the events for the decay mode $\mu^+ K^0$ ($K_s^0 \rightarrow \pi^0\pi^0$) are expected, including measurement errors in these variables. Three events fall inside the region. The first event (299) can be ruled out because there is 600 MeV in one track, which is not kinematically possible for this decay mode. The second event (510) is a two-track event with opening angle $\sim 100°$. The light can nearly be contained in one hemisphere. We can eliminate this event because $\sim 100\%$ of simulated $\mu^+ K^0$ events cover a larger fraction of the backward hemisphere. The third event (143) cannot be simply ruled out. Although it could be considered a possible candidate, we cannot exclude the possibility that it is neutrino induced. Setting a conservative limit by not subtracting the expected neutrino background and using one candidate yields

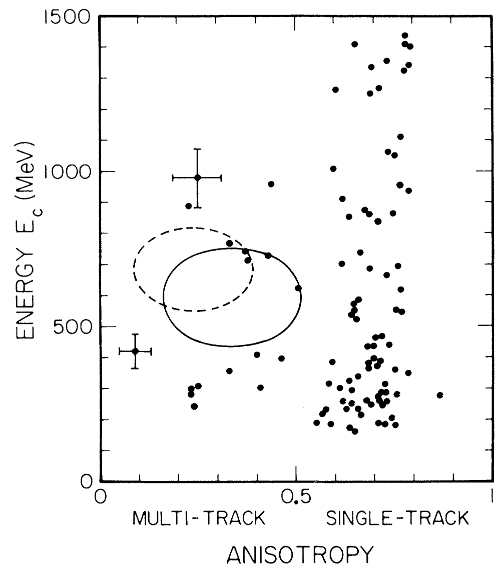

FIG. 1. Scatter plot of Cherenkov energy vs anisotropy for the 109 contained events. The region inside the dashed curve contains 90% of simulated $p \rightarrow \mu^+ K^0$, $K^0 \rightarrow \pi^0\pi^0$ events including the reconstruction errors in these variables, and the region inside the solid curve is for $n \rightarrow \nu K^0$, $K^0 \rightarrow \pi^0\pi^0$. Typical error bars are shown for two events with the vertex in the fiducial volume.

$$\tau/B(p \rightarrow \mu^+ K^0) > (1/3.9) \times (132/365) \times 2 \times 10^{33} \times (10/18) \times 0.16 \times 0.9 \times 0.95,$$

where 0.16 is the branching ratio for $K^0 \rightarrow K_s^0$, $K_s^0 \rightarrow \pi^0\pi^0$ (ignoring all K_L^0 interactions) and 0.9 ± 0.1 is the detection efficiency. The last factor for nuclear absorption is 0.95 since we assume that K^0's (and not $\bar{K}^0$'s) are produced. The K^0's escape from the oxygen nucleus with a 3% probability of charge exchange and 2% probability of scattering outside the energy-versus-anisotropy region in Fig. 1.

We estimate that 10% of the K_L^0's will interact producing Λ's, Σ's, or K_s^0's that decay and give a signal within the same region of the E_c-A plot. Including the K_L^0's effectively increases the branching ratio from 0.16 to 0.21, resulting in

$$\tau/B(p \rightarrow \mu^+ K^0, K_s^0 \rightarrow \pi^0\pi^0 + K_L^0) > 1.8 \times 10^{31} \text{ yr at 90\% C.L.}$$

The second method to search for $p \rightarrow \mu^+ K^0$ makes use of the decay $K_s \rightarrow \pi^+\pi^-$ and the eventual decay $\pi^+ \rightarrow \mu^+$. This mode gives two muon decays, a distinctive signal. Since the mean number of PMT's hit is 45 for $p \rightarrow \mu^+ K^0$, $K^0 \rightarrow \pi^+\pi^-$, we require at least twenty to fire. The detecton efficiency for seeing the charged-pion mode is found to be 0.83 ± 0.1. The probability for the π^+ to decay into a μ^+ rather than to be absorbed is calculated to be 80%.

A muon-decay electron is identified by a coincidence of five or more PMT's in a 60-ns window up to 7.5 μsec after the main event (7.8 PMT's fire on average). We have measured the efficiency for μ-decay detection to be $61 \pm 5\%$ for a sample of entering stopping tracks, which is corrected to $66 \pm 5\%$ for μ^+ decay alone, after accounting for μ^+ absorption in water. This gives an overall detection efficiency of $0.80 \times 0.83 \times (0.66)^2 \times 0.94 = 0.27$, where the 0.94 corrects for the probability of the two muon decays overlapping in our time resolution.

We observe two events with two μ decays. The first event has only one clean track with 500-MeV total energy. One of the muon decays probably comes from a π^+ produced below Cherenkov threshold by a ν interaction. Since a simulation of 250 $p \rightarrow \mu^+ K^0, K^0 \rightarrow \pi^+\pi^-$ events yields no event with one track of so high an energy, this event is not a viable candidate. The second event has one clean track which illuminates 22 tubes and is therefore just inside our tube cut. Based on the one possible candidate, the 90% C.L. limit for this decay mode is

$$\tau/B(p\to\mu^+K^0) > (1/3.9)\times(132/365)\times 2\times 10^{33}\times(10/18)\times 0.27\times 0.35\times 0.95$$

with use of the branching ratio of 0.35 for $K_s^0\to\pi^+\pi^-$. 30% of K_L^0 interactions eventually produce a π^+ or μ^+ increasing the effective branching ratio to 50%. This yields

$$\tau/B(p\to\mu^+K^0, K_s^0\to\pi^+\pi^- + K_L^0\text{ interactions}) > 1.3\times 10^{31}\text{ yr.}$$

Combining the limits for $p\to\mu^+K^0$ into the two independent modes (by calculating the combined detection efficiency) we arrive at a 90% C.L. limit of

$$\tau/B(p\to\mu K^0) > 2.6\times 10^{31}\text{ yr.}$$

The Mont Blanc collaboration reports a single possible μ^+K^0 event.[5] With a factor of ~ 10 more sensitivity we have $\leqslant 2$ candidates.

We can apply the first method used above to obtain a limit on $n\to\nu K^0, K^0\to\pi^0\pi^0$. The energy-versus-anisotropy region for 90% of the events in this mode is shown by the solid curve Fig. 1. The event that was a possible $p\to\mu^+K^0$ candidate (143) is no longer one for $n\to\nu K^0$ because it has a muon decay. The second event that appeared in the dashed region (299) fails as a νK^0 candidate for the same reason it failed as a μK^0 event. The third event (510), while not isotropic enough for μ^+K^0, is sufficiently isotropic for νK^0. There are two additional events to consider. Although they cannot easily be rejected as candidates, we cannot exclude the possibility that they are neutrino induced. In the same conservative spirit employed above, using three candidates we obtain at 90% C.L.

$$\tau/B > (1/6.7)\times(132/365)\times 8/18\times 2\times 10^{33}\times 0.15\times 0.9\times 0.95,$$

where the branching ratio, detection efficiency, and nuclear absorption factors are the last three numbers. When we include K_L^0 interactions as done for μ^+K^0 ($K^0\to\pi^0\pi^0$), the effective branching ratio increases to 0.21 yielding

$$\tau/B(n\to\nu K^0) > 0.8\times 10^{31}\text{yr.}$$

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