# Search for proton decay into $e^+ + \pi^0$ in the IMB-3 detector

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(Received 4 May 1990)

We report the results of a search for proton decay into $e^+ + \pi^0$ in the 6800-ton IMB-3 water Čerenkov detector. During 376 days of live time no events consistent with this decay were found in the 3300 ton fiducial volume. From this observation we derive a limit on the partial lifetime to be $\tau/B > 2.4\times 10^{32}$ yr (90% C.L.), which, combined with our previous result of $3.1\times 10^{32}$ yr, provides a limit of $5.5\times 10^{32}$ yr. The general features of the observed contained events are compatible with those expected from atmospheric neutrino interactions.

Experimental searches for processes exhibiting baryon nonconservation have not yielded evidence for such decays. The lower limit from world data collected until 1988 on the partial lifetime for the most distinct proton decay channel ($p \to e^+ + \pi^0$) is $\tau/B > 5.9\times 10^{32}$ yr.[1] The world data support our first result[2] ruling out minimal SU(5), the simplest grand unified theory (GUT). However, the supersymmetric GUT derived from string theory, flipped SU(5)×U(1) (Ref. 3), provides definite predictions for baryon instability which are not far beyond the range of sensitivity of recent experiments. In contrast with other supersymmetric GUT's, this model incorporates a very economical Higgs sector which does not contribute significantly to baryon instability. As a result, baryon instability is dominated by gauge-boson exchange. This model predicts the nucleon lifetime to be $\tau = 2\times 10^{34\pm 2}$ yr. The lower part of this range is testable with current experiments. The main decay channels are $p \to e^+ + \pi^0$ and $n \to \nu + \pi^0$. The decays $p \to \nu + \pi^+$ and $n \to e^+ + \pi^-$ are half as probable.[4]

In this paper we discuss the latest results obtained from the IMB-3 detector for the nearly background-free proton decay mode $p \to e^+ + \pi^0$. The analysis of the other channels of baryon decay predicted in the flipped SU(5)×U(1) model are in progress.

IMB-3 refers to the third phase of the water Čerenkov detector in the Fairport Mine (Ohio), after major modifications were made to improve its performance. The original 5-in.-diam photomultipliers (PMT's) were replaced by 8-in. PMT's attached to wave-shifting plates.[5] These changes increased the sensitivity of the detector from 4 MeV per collected photoelectron (pe) to 0.8 MeV per pe and improved the PMT time resolution from 11 to 8 ns full width at half maximum (FWHM). As a result, the vertices of isotropic events like $p \to e^+ + \pi^0$ can be reconstructed with a resolution of 35 cm instead of 60 cm. In addition, because of increased sensitivity, the trigger threshold was lowered to about 18 MeV instead of 50 MeV.[6] Increased noise of the detector limited the efficiency of observation of the muon decay signal on the coarse time scale of 0.3–7.5 $\mu$s. This has been mitigated by the fact that the mean signal increased from 8 to 40 tubes per recorded decay electron. Thus, although the higher level of noise required a more stringent threshold condition for muon decay detection, the efficiency of observation of decay electrons from entering and stopping muons remained at the level of 65–70 %. Such capability for muon decay detection provides sufficiently high efficiency for rejection of false candidates for $p \to e^+ + \pi^0$.

The increased light collection of IMB-3 affords better pattern recognition of Čerenkov rings produced by tracks in the detector. For example, $\pi^0$'s in the energy range below 500 MeV, decaying into two $\gamma$'s with a separation angle greater than 30°, produce patterns visually distinguishable as two tracks. This provides a powerful criterion for selection of candidates for baryon decay with a $\pi^0$ in the final state.

The detector is calibrated by means of a light source (diffusing ball illuminated by a computer-controlled nitrogen laser). This provides timing constants and conversion factors for pulse height to photoelectron number for each photomultiplier tube. The relation of recorded Čerenkov light to track length is obtained from muon tracks passing vertically through the center of the detector. This, along with the calculated track length of the electromagnetic showers in water, provides our absolute energy calibration. A Monte Carlo program which accurately reproduces the amount of light recorded from muon track segments is then used to predict the detector response to tracks of different particles with different energies and geometries. The same program also accurately reproduces the signal due to muon decay electrons, even though they are at much lower energy. The described method introduces only 5% overall systematic uncertainty in the absolute energy scale, compared with the statistical uncertainty which is approximately $4.7\%/\sqrt{E_c(\text{GeV})}$.

During 376 live days from May 1986 through December 1988, 495 events were collected with vertices inside a 3300-ton fiducial volume.

In Fig. 1 the distribution of the total visible energy, $E_c > 75$ MeV, of the events is compared with a similar sample of Monte Carlo events of atmospheric neutrino interactions in the detector. There are no significant differences between these two spectra, indicating that the bulk of the data agrees with the expected neutrino background.

In order to extract candidates for $p \to e^+ + \pi^0$ decay from the total sample of contained events, we consider the distribution of an "anisotropy" parameter[7] $A$ vs $E_c$ for a sample of Monte Carlo–generated events. Of these events, 61% fall within the limits of $750 < E_c < 1150$ MeV and $A < 0.25$. This is shown in Fig. 2. In the data sample there are only two events which satisfy such cuts and which are not accompanied by a muon decay signal. One of these can be eliminated immediately because it has more than three clearly well-separated tracks. The other event has two tracks in one hemisphere with a separation angle of 33°±5° and with a total energy of 563±35 MeV. These two tracks fit the hypothesis of being due to $\pi^0$ decay. In the other hemisphere there is a Čerenkov pattern at an angle to the $\pi^0$ of 146°±8° with an energy of 472±35 MeV. This second pattern appears to be due to two overlapping tracks. However, because the event has an identifiable $\pi^0$ with measured energy close to that expected from proton decay, we investigate this event in greater detail.

Interpreting this second pattern as a single positron track leads to an invariant mass of 986±50 MeV and an unbalanced momentum of 315±70 MeV/$c$ for the event. A similar analysis performed on a Monte Carlo–generated sample of $e^+ + \pi^0$ proton decays selected according to the same criteria leads to invariant mass and unbalanced momentum distributions shown in Fig. 3. The values obtained for this candidate are also drawn in these pictures. Under the above assumptions, the event appears to be a marginal candidate for the decay $p \to e^+ + \pi^0$. However, closer examination of the pattern assumed to be due to the "positron" track (especially the pattern of PMT's with the highest pulse height) shows that, with high probability, the pattern is caused by an overlay of two tracks. One of them appears due to a particle moving with $\beta \approx 1$ and producing a normal-size ring, the other from a slower particle producing a smaller ring, as expected from a recoiling proton from a neutrino interaction. Such details would not have been resolved in the IMB-1 detector, but with the increased sensitivity of IMB-3 the event can be ruled out as a candidate for nucleon decay.

In order to check how often such fluctuations in the Čerenkov pattern would occur for electron tracks (for instance, due to fluctuations in electromagnetic shower development), a sample of events was generated by means of a Monte Carlo program with the configuration of the event under consideration. In about 5% of these events, pattern density fluctuations of a comparable or larger size were observed, none of them, however, with a similar tracklike shape. Thus our interpretation of this event is that it has an additional fourth track, probably a recoiling proton or a scattered charged pion, and is due to a

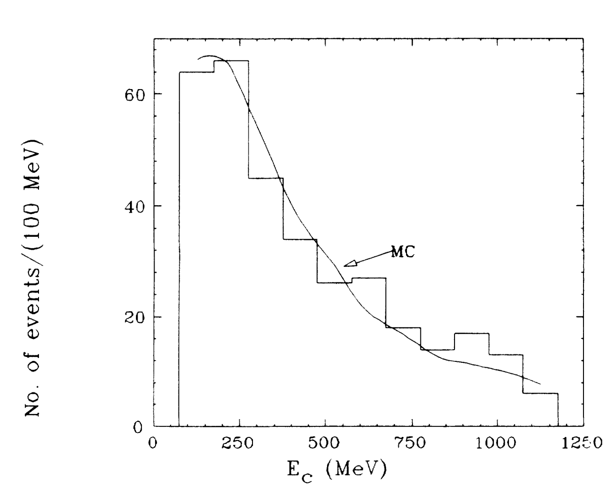


FIG. 1. Visible-energy spectrum for contained events.

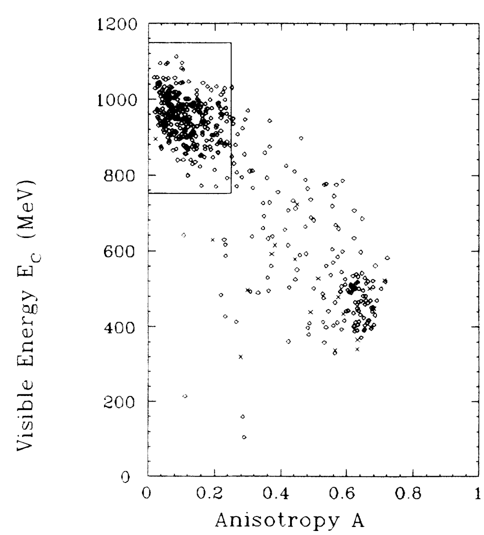


FIG. 2. Visible energy vs anisotropy for Monte Carlo–generated proton decay events.

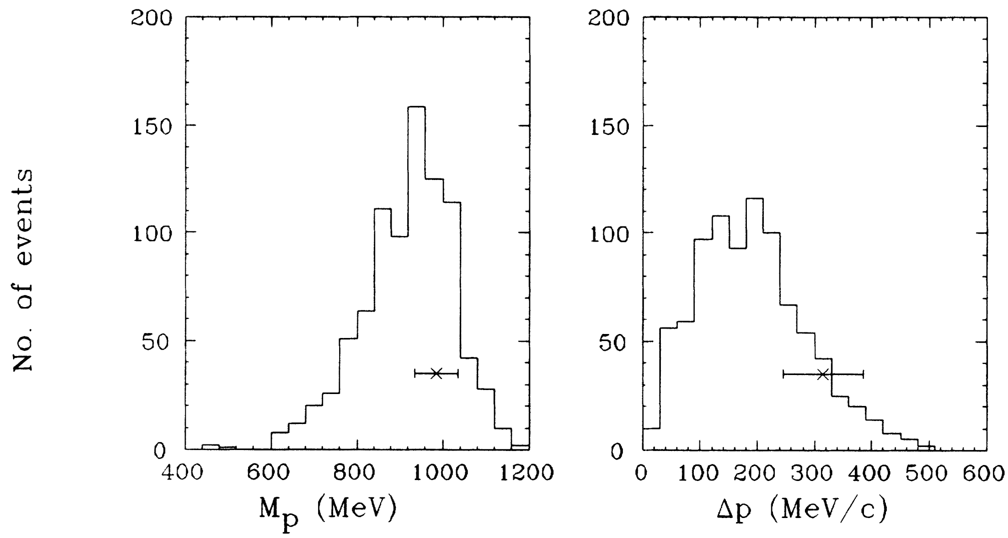


FIG. 3. Invariant mass ($M_p$) and unbalanced momentum ($\Delta p$) distributions for Monte Carlo–generated $p \rightarrow e^+ + \pi^0$. The values obtained from the analysis of the discussed event are also shown.

neutrino interaction.

The expected background to the search for $p \rightarrow e^+ + \pi^0$ decay under the new, more stringent conditions facilitated by the properties of the IMB-3 detector has been estimated in the following way. A sample of atmospheric neutrino interactions from about 50 yr of detector live time has been generated by means of Monte Carlo programs. We have used the neutrino flux predicted for our site by Gaisser *et al.* and by Lee.[8] For neutrino interactions in water, we have used two independent models described in Ref. 9. Outgoing pion interactions in parent oxygen nuclei and in water were taken into account using an impulse approximation (following an improved scheme from Ref. 10). The results of this simulation are in agreement with the observed event sample, after the simulated events are passed through the analysis chain.

The simulated neutrino events which passed energy and anisotropy cuts applied for $p \rightarrow e^+ + \pi^0$ analysis were scanned and manually reconstructed using a fitting-display program. Only events with three tracks, two clustered together, as from a $\pi^0$ decay, and the third in the opposite hemisphere were selected. Out of these events only four had invariant mass within the range $750 < M < 1100$ MeV and unbalanced momentum $p < 350$ MeV/$c$. All had unbalanced momentum greater than 200 MeV/$c$. We therefore estimate the expected background for $p \rightarrow e^+ + \pi^0$ decay to be less than 0.1 events/yr for the IMB-3 detector. Limits on the $p \rightarrow e^+ + \pi^0$ lifetime from this detector can, in principle, continue to grow linearly with observation time.

In summary, we have found no candidates for the decay of $p \rightarrow e^+ + \pi^0$ during 376 days of detector live time in IMB-3. The expected background during this time is $\sim 0.1$ events. When we include a data filtering efficiency of 0.8 and a kinematical cut efficiency of 0.6, we determine the partial lifetime limit for $p \rightarrow e^+ + \pi^0$ to be $2.4 \times 10^{32}$ yr. Combinging this result with the result of the negative search from 417 days in the IMB-1 detector, we determine a limit of $5.5 \times 10^{32}$ yr (90% C.L.).

This work was supported in part by the U.S. Department of Energy. We would like to thank the Morton-Thiokol company which operates the Fairport Mine for their hospitality.

[1]F. Raupach, in *Proceedings of XXIV International Conference on High Energy Physics,* Munich, West Germany, 1988, edited by R. Kotthaus and J. Kuhn (Springer, Berlin, 1988).

[2]R. M. Bionta *et al.*, Phys. Rev. Lett. **51**, 27 (1983).

[3]J. Ellis *et al.*, CERN Report No. TH 4990/88, 1988 (unpublished); J. Ellis *et al.*, Nucl. Phys. **B311**, 1 (1988).

[4]We note, however, that in the improved version of the three-generation model, it is also possible that the decays involving the next family $p \rightarrow \mu^+ + \pi^0$ or $p \rightarrow \nu + \pi^+$ and $n \rightarrow \mu^+ + \pi^-$ or $n \rightarrow \nu + \pi^0$ can dominate [D. V. Nanopoulos, in *Last Workshop on Grand Unification,* proceedings, Chapel Hill, North Carolina, 1989, edited by P. H. Frampton (World Scientific, Singapore, 1989)].

[5]R. Claus *et al.*, Nucl. Instrum. Methods A **261**, 540 (1987).

[6]Since January 1990, the detector has been collecting data with a trigger level of about 10 MeV.

[7]Essentially, $E_c$ is a measure of the energy deposite by a particle emitting Čerenkov light and the "anisotropy" $A$ is a crude measure of the visible momentum imbalance in an event. For a single track one expects $A \sim 0.75$, while for most of nucleon decays $A \sim 0$.

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