

## Search for Nucleon Decay via $n \rightarrow \bar{\nu}\pi^0$ and $p \rightarrow \bar{\nu}\pi^+$ in Super-Kamiokande

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We present the results of searches for nucleon decay via  $n \rightarrow \bar{\nu}\pi^0$  and  $p \rightarrow \bar{\nu}\pi^+$  using data from a combined 172.8 kt · yr exposure of Super-Kamiokande-I, II, and III. We set lower limits on the partial lifetime for each of these modes:  $\tau_{n \rightarrow \bar{\nu}\pi^0} > 1.1 \times 10^{33}$  years and  $\tau_{p \rightarrow \bar{\nu}\pi^+} > 3.9 \times 10^{32}$  years at a 90% confidence level.

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Although there is strong theoretical support that nature can be described by a grand unified theory (GUT) [1,2], there is currently no direct experimental evidence. One of the most powerful ways to test grand unification is to look for proton (or bound neutron) decay. Most GUTs have an unstable proton; in the absence of an observation, setting experimental limits on the proton lifetime can provide useful constraints on the nature of GUTs. Observation, on the other hand, would be tantalizing evidence of new physics beyond the Standard Model.

One of the more simple but interesting candidates for grand unification is SO(10), where the Standard Model's SU(3), SU(2), and U(1) are contained within the larger gauge group. The class of models based on SO(10) unification generally make predictions for neutrino masses and mixing that are broadly in accord with all known neutrino mixing data [3,4]. The minimal supersymmetric SO(10) model with a **126** Higgs field described in Ref. [3] is the particular motivation for the analysis presented here. In addition to predicting neutrino mass and mixing in agreement with observations, it leaves  $R$  parity unbroken, which guarantees the existence of stable dark matter. For some region of its allowed parameter space, this model predicts that the dominant nucleon decay modes will be  $p \rightarrow \bar{\nu}\pi^+$  and  $n \rightarrow \bar{\nu}\pi^0$ .

In this Letter, the fully contained (FC) atmospheric neutrino data (i.e., having activity only within the inner detector region and no activity in the outer detector) collected during the first three running periods of Super-Kamiokande (Super-K, SK) are analyzed in a search for both  $p \rightarrow \bar{\nu}\pi^+$  and  $n \rightarrow \bar{\nu}\pi^0$ : SK-I (May 1996–July 2001, 1489.2 live days), SK-II (January 2003–October 2005, 798.6 live days), and SK-III (September 2006–August 2008, 518.1 live days). The combined data set corresponds to an exposure of 172.8 kt · yr.

The 50-kiloton (22.59-kt fiducial) Super-K water Cherenkov detector is located beneath 1 km of rock overburden (2700-meters water equivalent) in the Kamioka mine in Japan. Details of the detector design, calibration, and simulations in SK-I may be found in Ref. [5], and a discussion of the reduced photosensor coverage in SK-II may be found in Ref. [6]. In SK-III, the photosensor coverage is recovered to the original 40% level of SK-I.

The efficiency of detecting nucleon decay occurring in the water is estimated by Monte Carlo (MC) simulation. As discussed in detail in Ref. [6], all nucleons in the H<sub>2</sub>O molecule are assumed to decay with equal probability, and Fermi motion, nuclear binding energy, and meson-nuclear interactions in oxygen are taken into account.

The  $n \rightarrow \bar{\nu}\pi^0$  ( $p \rightarrow \bar{\nu}\pi^+$ ) decay mode results in a  $\pi^0$  ( $\pi^+$ ) with mean momentum 460 MeV/ $c$  (458.8 MeV/ $c$ ), smeared by the Fermi motion of nucleons bound in oxygen, but uniquely determined for decays of the two free protons in the water's hydrogen nuclei. The pion's momentum is also affected by nuclear interactions as it travels through the

nucleus; it may undergo scattering, charge exchange, or absorption. Pion-nucleon interactions are carefully simulated to reflect our understanding of the processes, which may affect the ability to detect pions in water.

Since the final state neutrino is undetected, these two modes of nucleon decay are particularly challenging. It is not possible to develop a set of selection cuts that will eliminate most of the background of atmospheric neutrino interactions with a single pion and no other detected particles in the final state. Instead, we select events that appear to have only a single  $\pi^0$  or  $\pi^+$  and perform a spectrum fit to their reconstructed momentum distributions, respectively. In this method, the nearly monoenergetic pions from nucleon decay would appear as a bump on top of the broad distribution of pions from atmospheric neutrino interactions. Atmospheric neutrino background events are simulated using the NEUT neutrino interaction MC simulation [7] with an atmospheric neutrino flux calculated by Honda *et al.* [8], then passed through a GEANT-3-based [9] custom detector simulation that is described in detail in Ref. [10].

The event selection cuts applied to the FC atmospheric neutrino data are (i) the number of Cherenkov rings is two for  $n \rightarrow \bar{\nu}\pi^0$  (one for  $p \rightarrow \bar{\nu}\pi^+$ ), (ii) all rings are showering (electronlike) for  $n \rightarrow \bar{\nu}\pi^0$  [nonshowering (muonlike) for  $p \rightarrow \bar{\nu}\pi^+$ ], (iii) the number of electrons from muon decay is zero for  $n \rightarrow \bar{\nu}\pi^0$  (zero or one for  $p \rightarrow \bar{\nu}\pi^+$ ), and (iv) the reconstructed momentum is less than 1000 MeV/ $c$ . For the  $n \rightarrow \bar{\nu}\pi^0$  sample only, there is one additional requirement (v): that the reconstructed invariant mass of the  $\pi^0$  is between 85 and 185 MeV/ $c^2$ . A discussion of the momentum reconstruction and performance can be found in Refs. [6,11], and the method of decay electron finding is discussed in Ref. [10]. The selected fraction of single pions in the atmospheric neutrino MC simulation with these cuts is shown as a function of reconstructed momentum for SK-I in the top panel of Fig. 1 for  $\pi^0$  and the bottom for  $\pi^+$ . The efficiency curves for the SK-II and SK-III periods, not shown here but treated individually in the fit, are very similar to the SK-I curves shown in the figure. For the  $\pi^0$  mode, the majority of atmospheric neutrino-induced background events that pass the selection cuts arise from neutral current (NC) single pion production (76%). The other backgrounds are due to charged current (CC) single pion production with the outgoing charged lepton below Cherenkov threshold (7%), NC multiple pion production (7%), and small fractions of other processes (less than a few percent each). As this background is overwhelmingly made up of pions and their selection efficiency as a function of momentum is not flat, the uncertainty in selection efficiency is treated as a systematic error binned in momentum. Efficiency is defined as the fraction of all FC events in the fiducial volume (FCFV) with at least one  $\pi^0$  and no decay electrons, which pass the selection cuts for  $n \rightarrow \bar{\nu}\pi^0$ . For the  $\pi^+$  sample, a large fraction of the background events is

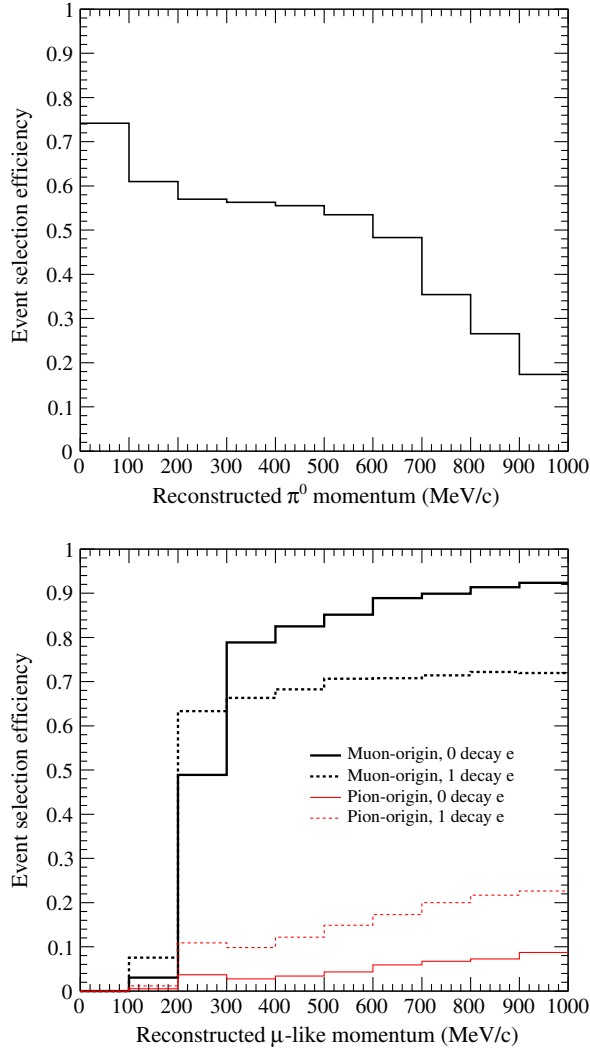


FIG. 1 (color online). Event selection efficiencies for atmospheric neutrino MC as a function of reconstructed momentum for  $n \rightarrow \bar{\nu}\pi^0$  selection cuts (top) and  $p \rightarrow \bar{\nu}\pi^+$  selection cuts (bottom). For the  $\pi^+$  sample, all momenta are calculated assuming a muon hypothesis. The atmospheric neutrino events that make up the background for the  $p \rightarrow \bar{\nu}\pi^+$  mode are treated separately in the spectrum fit according to their origin.

of nonpionic origin, as shown in the first row of Table I. Since the shape and level of the selection efficiency differ for backgrounds of pionic and muonic origin, these two cases are treated as separate systematic errors in the spectrum fit. The pion detection efficiency is lower than that of the muons; this is due to the fact that pions, unlike muons, may undergo hadronic interactions in the water. Efficiency curves in this case are calculated using the MC truth neutrino interaction mode in the denominator to determine what fraction of events pass the  $p \rightarrow \bar{\nu}\pi^+$  selection cuts for (1) FCFV events that originate from CC quasielastic (CCQE) interactions (muonic origin) and (2) FCFV events that originate from interactions that truly have a  $\pi^+$  (pionic origin).

TABLE I. Sources of atmospheric neutrino-and antineutrino-induced background for the  $p \rightarrow \bar{\nu}\pi^+$  decay mode.

Interaction mode	Fraction of background
CCQE ( $\nu n \rightarrow \mu p$ )	0.75
Single $\pi$ ( $\nu N \rightarrow \ell N' \pi^{(+/-/0)}$ )	0.20
Multi $\pi$ ( $\nu N \rightarrow \ell N' (n\pi)$ )	0.03
Other	0.02

The SK particle identification (PID) algorithm only classifies Cherenkov rings as showering ( $e^\pm, \gamma$ ) or non-showering ( $\mu^\pm, \pi^\pm$ ), as described in Ref. [10]. Another PID algorithm that uses additional information about the Cherenkov ring opening angle to attempt further classification between  $\mu$  and  $\pi^\pm$  rings also exists [6], but was shown to add no improvement to this analysis; thus, no attempt is made to separate muon-induced rings from pion-induced rings.

The fit to the reconstructed momentum spectrum is a  $\chi^2$  minimization based on a Poisson probability with systematic errors taken into account by quadratic penalties (pull terms). This technique is the same as that described by Fogli *et al.*, in Ref. [12]. The  $\chi^2$  is defined as

$$\chi^2 = 2 \sum_{i=1}^{\text{nbins}} \left( N_i^{\text{exp}} \left( 1 + \sum_{j=1}^{N_{\text{syserr}}} f_j^j \epsilon_j \right) - N_i^{\text{obs}} \right) + N_i^{\text{obs}} \ln \frac{N_i^{\text{obs}}}{N_i^{\text{exp}} \left( 1 + \sum_{j=1}^{N_{\text{syserr}}} f_j^j \epsilon_j \right)} + \sum_{j=1}^{N_{\text{syserr}}} \left( \frac{\epsilon_j}{\sigma_j} \right)^2, \quad (1)$$

where  $i$  indexes the data bins,  $N_i^{\text{exp}}$  is the MC expectation, and  $N_i^{\text{obs}}$  is the number of observed events in the  $i$ th bin. The Monte Carlo simulation expectation is given by  $N_i^{\text{exp}} = \alpha N_i^{\text{bkg}} + \beta N_i^{\text{sig}}$ , where  $\alpha$  and  $\beta$  are the normalization parameters for background (atmospheric neutrinos) and signal (nucleon decay), respectively. In the two-dimensional fit space, the allowed ranges of the parameters are defined such that a value of 1.0 for  $\alpha$  (atmospheric neutrino background normalization) and a value of 0.0 for  $\beta$  (nucleon decay signal event normalization) would indicate that the SK data are perfectly described by the atmospheric neutrino simulation alone, with no contribution from nucleon decay. The effect of the  $j$ th systematic error is included via a ‘‘pull term,’’ which includes the error parameter  $\epsilon_j$  and  $f_j^j$ , which is the fractional change in the MC expectation for bin  $i$  that would occur for a one-sigma change in systematic error  $\sigma_j$ . In total, 30 bins are used to compute the value of  $\chi^2$  for the  $n \rightarrow \bar{\nu}\pi^0$  analysis (10 for SK-I, 10 for SK-II, and 10 for SK-III), and 60 bins are used for the  $p \rightarrow \bar{\nu}\pi^+$  analysis. The number of bins in the  $\pi^+$  analysis is double that of the  $\pi^0$  analysis due to the presence of two independent subsamples (events with zero and

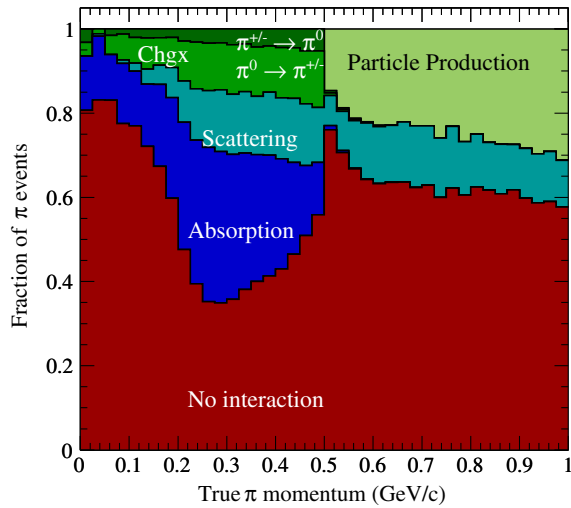


FIG. 2 (color online). Cumulative fractions of nuclear effects for  $\pi^0$  as a function of true  $\pi^0$  momentum for atmospheric neutrino interactions. The fractions of events that undergo charge exchange, multiple particle production, scattering, and absorption are shown by various shades as labeled. Pions that exit the nucleus without experiencing any nuclear effect are indicated by the portion labeled “No interaction.”

one decay electron, respectively) in the selected data for that decay mode.

Equation 1 is minimized with respect to the  $\epsilon_j$  according to  $\partial\chi^2/\partial\epsilon_j = 0$ , which yields a set of iteratively solved equations in the epsilons. The  $\chi^2$  is calculated by this procedure for 10 000 points in the fit parameter space ( $\alpha: [0.8, 1.2], \beta: [0.0, 0.2]$ ). Each SK run period uses an independent sample of 500 years of atmospheric neutrino MC simulation and an independent sample of 5000 events of the pertinent nucleon decay MC simulation to calculate

$N_i^{\text{exp}}$ . The global minimum  $\chi^2$  for each decay mode is defined as that decay mode’s best fit point.

Six sources of systematic uncertainty are considered in the  $n \rightarrow \bar{\nu}\pi^0$  analysis, and 15 sources are considered in the  $p \rightarrow \bar{\nu}\pi^+$  analysis. These can be divided into two classes: those that are common to all SK run periods and those that depend on the detector geometry of an individual run period. Uncertainties in the nuclear effect cross sections (charge exchange and particle production, absorption, and inelastic scattering) are dominant and are treated as common to all SK run periods. We neglect other common uncertainties such as atmospheric neutrino flux and neutrino interaction cross sections because they are overwhelmed by the nuclear effect uncertainties. Uncertainties in detection efficiency are treated independently for each subsample and run period. The detection efficiencies for  $n \rightarrow \bar{\nu}\pi^0$  nucleon decay signal, for  $\pi^0$  background, and for muon-induced background in the  $p \rightarrow \bar{\nu}\pi^+$  analysis, are taken to have an overall 5% uncertainty due to contributions from detector performance uncertainties, as described in Ref. [6]. The signal and background detection efficiency uncertainties in each decay mode are treated as fully correlated. For  $p \rightarrow \bar{\nu}\pi^+$  signal and  $\pi^+$ -induced backgrounds, the detection efficiency uncertainty is estimated to be larger (15%) due to the possibility that charged pions may interact hadronically as they travel through the water.

The systematic errors that contribute the most to the fits are those from nuclear effects. The cumulative fractions of each category of nuclear effect are shown in Fig. 2 as a function of true  $\pi^0$  momentum for atmospheric neutrino events (and the corresponding plot for  $\pi^+$  momentum is similar). We assume an uncertainty of 30% on the cross section for each nuclear effect, based on the measurements made in Ref. [13] and estimates made for SK in Ref. [6].

TABLE II. Systematic error terms in the  $n \rightarrow \bar{\nu}\pi^0$  and  $p \rightarrow \bar{\nu}\pi^+$  spectrum fits, with  $1\sigma$  uncertainties and resulting size of pull terms after fit.

Decay mode	Systematic error	$1\sigma$ uncertainty (%)	Size of pull after fit (units of $\sigma$ )
$n \rightarrow \bar{\nu}\pi^0$	Charge exchange + particle production cross section	30	-1.26
	Pion absorption cross section	30	0.83
	Inelastic scattering cross section	30	-0.42
	SK-I single $\pi^0$ background detection efficiency	5	0.08
	SK-II single $\pi^0$ background detection efficiency	5	-0.19
	SK-III single $\pi^0$ background detection efficiency	5	-0.01
$p \rightarrow \bar{\nu}\pi^+$	Charge exchange + particle production cross section	30	-0.61
	Pion absorption cross section	30	0.30
	Inelastic scattering cross section	30	-0.12
	SK-I muonic background detection efficiency 0 decay-e (1 decay-e)	5(5)	0.01(0.16)
	SK-II muonic background detection efficiency 0 decay-e (1 decay-e)	5(5)	0.00(0.25)
	SK-III muonic background detection efficiency 0 decay-e (1 decay-e)	5(5)	-0.01(0.18)
	SK-I pionic background detection efficiency 0 decay-e (1 decay-e)	15(15)	0.01(-0.29)
	SK-II pionic background detection efficiency 0 decay-e (1 decay-e)	15(15)	0.00(-0.08)
	SK-III pionic background detection efficiency 0 decay-e (1 decay-e)	15(15)	0.00(0.01)

TABLE III. Best fit parameter values, signal-detection efficiency for each SK running period, 90% C.L. value of  $\beta$  parameter, and allowed number of nucleon decay events in the full 172.8 kt · yr exposure (SK-I: 91.7, SK-II: 49.2, SK-III: 31.9), and lower partial lifetime limit for each decay mode at 90% C.L.

Decay mode	Best fit values ( $\alpha$ , $\beta$ )	Unphysical best fit ( $\alpha$ , $\beta$ )	Signal efficiency (SK-I,-II,-III)%	$\beta_{90\text{CL}}$	Number signal events at 90% C.L. ( $N_{90\text{CL}}$ )	$\tau/\mathcal{B}$ ( $\times 10^{32}$ yrs)
$n \rightarrow \bar{\nu}\pi^0$	(0.940,0.000)	(0.976,-0.020)	(48.5, 44.0, 48.5)	0.020	19.1	11.0
$p \rightarrow \bar{\nu}\pi^+$	(0.976,0.000)	(0.996,-0.010)	0-decay-e: (20.4, 23.0, 22.0) 1-decay-e: (14.8, 12.4, 14.2)	0.010	52.8	3.9

As is seen in the figure, charge exchange and absorption effects occur with greater frequency in the momentum range of these decay modes ( $\sim 460$  MeV/ $c$ ). The discontinuity at 500 MeV/ $c$  is the result of the transition from the custom simulation used to track pions in the nucleus that are below 500 MeV/ $c$  and the G<sub>CALOR</sub> simulation of pion propagation for pions with momentum equal to or above 500 MeV/ $c$ . To study the impact of the relative contribution of the different nuclear effects, we varied the systematic uncertainty from 5% of the nominal value to 100% of the nominal value; this had a negligible impact on the final number of fitted events. Nevertheless, we are actively improving the model of pion interactions, and this improvement will be included in future SK analyses.

The systematic errors used in this analysis and their uncertainties and relative pulls after performing the fitting procedure are shown in Table II. As can be seen in the table, all of the systematic error pulls stay near or below  $1\sigma$  of their nominal values after the fit, indicating no strong tension between data and MC simulation.

In an unconstrained fit, the best fit value for the  $\beta$  parameter (nucleon decay normalization) falls in the unphysical region for both the  $n \rightarrow \bar{\nu}\pi^0$  and the  $p \rightarrow \bar{\nu}\pi^+$  analyses, preferring a negative amount of nucleon decay. To avoid this, we constrain the  $\beta$  values to be in the physical region and determine the 90% C.L. value of  $\beta$  according to the Feldman-Cousins prescription [14]. The partial lifetime lower limit for each decay mode is then calculated according to

$$\tau/\mathcal{B} = \frac{\Delta t \epsilon N_{\text{nucleons}}}{N_{90\text{CL}}}, \quad (2)$$

where  $\mathcal{B}$  is the decay mode branching ratio,  $\Delta t$  is the exposure in kt · yr,  $\epsilon$  is the overall signal detection efficiency of the nucleon decay mode,  $N_{\text{nucleons}}$  is the number of nucleons per kiloton of water ( $2.7 \times 10^{32}$  neutrons or  $3.3 \times 10^{32}$  protons), and  $N_{90\text{CL}}$  is the number of nucleon decay events allowed at 90% C.L. as determined from the  $\beta$  value.

The physical and unphysical best fit parameter values, signal detection efficiencies for each running period of SK, and number of nucleon decay events allowed in the data sample at 90% C.L. are shown in Table III. Using the constrained physical best fit parameters and pull terms, the

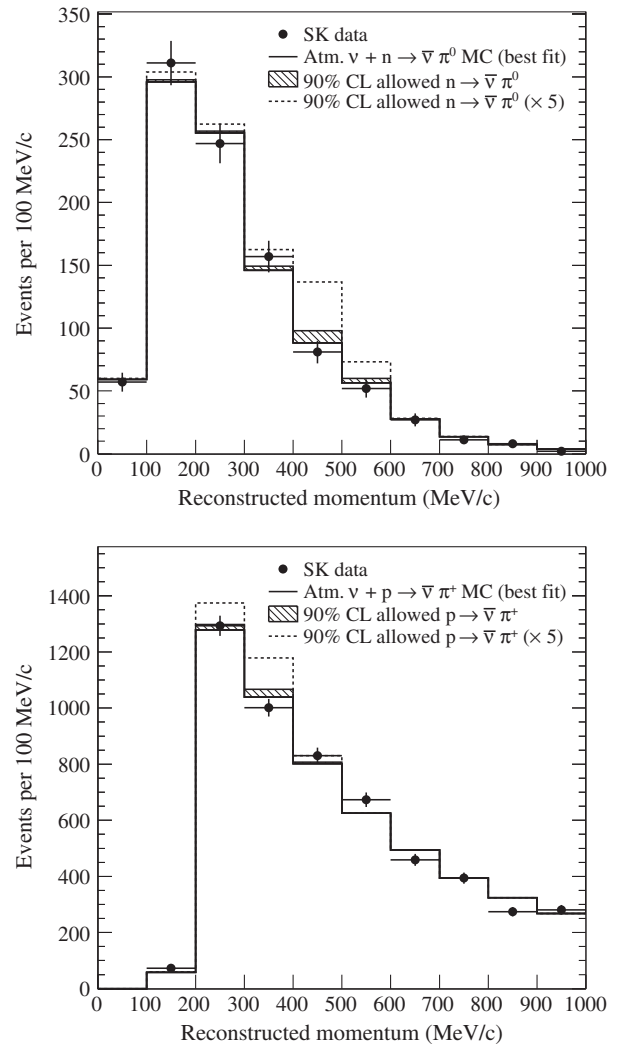


FIG. 3. Reconstructed momentum for 172.8 kt · yr of SK-I + II + III data (black dots), best fit result of atmospheric neutrino plus nucleon decay MC simulation (solid line), and the 90% C.L. allowed amount of nucleon decay (hatched histogram) for  $n \rightarrow \bar{\nu}\pi^0$  (top) and  $p \rightarrow \bar{\nu}\pi^+$  (bottom). The dashed line shows how a positive signal of nucleon decay would look, corresponding to five times the limit we set on the decay partial lifetimes. The  $p \rightarrow \bar{\nu}\pi^+$  nucleon decay contribution in the bottom figure is reconstructed at lower momentum than the expected value (458.8 MeV/ $c$ ) because a muon hypothesis is assumed in the reconstruction.

resulting fitted momentum spectra are shown combined for all running periods as the solid black lines in Fig. 3, with the nonobservation 90% C.L. allowed amount of signal nucleon decay shown by the hatched histogram and overlaid SK data by black dots. The 90% C.L. partial lifetime lower limits we set for these two decay modes are then  $\tau_{n \rightarrow \bar{\nu}\pi^0} > 1.1 \times 10^{33}$  and  $\tau_{p \rightarrow \bar{\nu}\pi^+} > 3.9 \times 10^{32}$  years. In comparison, the predicted range of partial lifetimes allowed for the SO(10) model presented in Ref. [3] is  $\tau_{n \rightarrow \bar{\nu}\pi^0} = 2\tau_{p \rightarrow \bar{\nu}\pi^+} \leq 5.7 - 13 \times 10^{32}$  years; the model's allowed ranges are nearly ruled out by the limits presented here. These limits represent an order of magnitude improvement over previously published limits for these two decay modes [15–17] and can be used to more tightly constrain other GUT models that allow these modes.

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