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S. N. Ahmed
Queen's University

A. E. Anthony
The University of Texas at Austin

E. W. Beier
University of Pennsylvania

A. Bellerive
Carleton University

S. D. Biller
University of Oxford

See next page for additional authors

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Authors

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S. N. Ahmed,[10] A. E. Anthony,[12] E.W. Beier,[9] A. Bellerive,[3] S. D. Biller,[8] J. Boger,[2] M. G. Boulay,[7] M. G. Bowler,[8] T. J. Bowles,[7] S. J. Brice,[7] T.V. Bullard,[14] Y. D. Chan,[6] M. Chen,[10] X. Chen,[6] B.T. Cleveland,[8] G. A. Cox,[14] X. Dai,[3,8] F. Dalnoki-Veress,[3] P. J. Doe,[14] R. S. Dosanjh,[3] G. Doucas,[8] M. R. Dragowsky,[7] C. A. Duba,[14] F. A. Duncan,[10] M. Dunford,[9] J. A. Dunmore,[8] E. D. Earle,[10] S. R. Elliott,[7] H. C. Evans,[10] G. T. Ewan,[10] J. Farine,[5,3] H. Fergani,[8] F. Fleurot,[5] J. A. Formaggio,[14] M. M. Fowler,[7] K. Frame,[8,3] W. Frati,[9] B. G. Fulsom,[10] N. Gagnon,[14,7,6,8] K. Graham,[10] D. R. Grant,[3] R. L. Hahn,[2] J. C. Hall,[12] A. L. Hallin,[10] E. D. Hallman,[5] A. S. Hamer,[7,*] W. B. Handler,[10] C. K. Hargrove,[3] P. J. Harvey,[10] R. Hazama,[14] K. M. Heeger,[6] W. J. Heintzelman,[9] J. Heise,[7] R. L. Helmer,[13,1] R. J. Hemingway,[3] A. Hime,[7] M. A. Howe,[14] P. Jagam,[4] N. A. Jelley,[8] J. R. Klein,[12,9] M. S. Kos,[10] A.V. Krumins,[10] T. Kutter,[1] C. C. M. Kyba,[9] H. Labranche,[4] R. Lange,[2] J. Law,[4] I. T. Lawson,[4] K. T. Lesko,[6] J. R. Leslie,[10] I. Levine,[3,†] S. Luoma,[5] R. MacLellan,[10] S. Majerus,[8] H. B. Mak,[10] J. Maneira,[10] A. D. Marino,[6] N. McCauley,[9] A. B. McDonald,[10] S. McGee,[14] G. McGregor,[8] C. Mifflin,[3] K. K. S. Miknaitis,[14] G. G. Miller,[7] B. A. Moffat,[10] C.W. Nally,[1] M. S. Neubauer,[9] B. G. Nickel,[4] A. J. Noble,[10,3,13] E. B. Norman,[6] N. S. Oblath,[14] C. E. Okada,[6] R.W. Ollerhead,[4] J. L. Orrell,[14] S. M. Oser,[1,9] C. Ouellet,[10] S. J. M. Peeters,[8] A.W. P. Poon,[6] B. C. Robertson,[10] R. G. H. Robertson,[14] E. Rollin,[3] S. S. E. Rosendahl,[6] V. L. Rusu,[9] M. H. Schwendener,[5] O. Simard,[3] J. J. Simpson,[4] C. J. Sims,[8] D. Sinclair,[3,13] P. Skensved,[10] M.W. E. Smith,[14] N. Starinsky,[3] R. G. Stokstad,[6] L. C. Stonehill,[14] R. Tafirout,[5] Y. Takeuchi,[10] G. Tešić,[3] M. Thomson,[10] M. Thorman,[8] R. Van Berg,[9] R. G. Van de Water,[7] C. J. Virtue,[5] B. L. Wall,[14] D. Waller,[3] C. E. Waltham,[1] H. Wan Chan Tseung,[8] D. L. Wark,[11] N. West,[8] J. B. Wilhelmy,[7] J. F. Wilkerson,[14] J. R. Wilson,[8] P. Wittich,[9] J. M. Wouters,[7] M. Yeh,[2] and K. Zuber[8]

(SNO Collaboration)

[1]*Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1*
[2]*Chemistry Department, Brookhaven National Laboratory, Upton, New York 11973-5000, USA*
[3]*Ottawa-Carleton Institute for Physics, Department of Physics, Carleton University, Ottawa, Ontario, Canada K1S 5B6*
[4]*Physics Department, University of Guelph, Guelph, Ontario, Canada N1G 2W1*
[5]*Department of Physics and Astronomy, Laurentian University, Sudbury, Ontario, Canada P3E 2C6*
[6]*Institute for Nuclear and Particle Astrophysics and Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[7]*Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[8]*Department of Physics, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, United Kingdom*
[9]*Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104-6396, USA*
[10]*Department of Physics, Queen's University, Kingston, Ontario, Canada K7L 3N6*
[11]*Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, United Kingdom*
[12]*Department of Physics, University of Texas at Austin, Austin, Texas 78712-0264, USA*
[13]*TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia, Canada V6T 2A3*
[14]*Center for Experimental Nuclear Physics and Astrophysics, and Department of Physics, University of Washington, Seattle, Washington 98195, USA*

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Data from the Sudbury Neutrino Observatory have been used to constrain the lifetime for nucleon decay to "invisible" modes, such as $n \rightarrow 3\nu$. The analysis was based on a search for γ rays from the deexcitation of the residual nucleus that would result from the disappearance of either a proton or neutron from ^{16}O. A limit of $\tau_{\text{inv}} > 2 \times 10^{29}$ yr is obtained at 90% confidence for either neutron- or proton-decay modes. This is about an order of magnitude more stringent than previous constraints on invisible proton-decay modes and 400 times more stringent than similar neutron modes.

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Experimental signatures of the grand unification of the electroweak and strong interactions have been sought with increasing sensitivity for the past 25 years. Much effort has gone into identifying specific decay modes of free protons and bound nucleons as signatures of grand unification, but no signal has been observed to date. Decay modes more unusual than those typically explored cannot, however, be ruled out (see, for example, [1]). A recent paper has even suggested a model in which $n \rightarrow 3\nu$ becomes the dominant mode [2]. Thus, the search for any mode which may have been missed by previous experiments is of fundamental interest. In this Letter, the Sudbury Neutrino Observatory (SNO) [3] is used to search for what we refer to as invisible decay channels, i.e., those in which no visible energy is deposited in the detector via direct production of energetic, charged particles.

The search utilizes SNO's unique detection capabilities for γ rays in the region of 6 MeV, based on the Cherenkov light produced by the resulting Compton-scattered electron. A generic signature for nucleon disappearance in ^{16}O arises from the subsequent deexcitation of the residual nucleus [4,5]. Approximately 45% of the time, the deexcitation of either ^{15}O* or ^{15}N* results in the production of a γ ray of energy 6–7 MeV. SNO detects these γ rays with good efficiency. In fact, the primary energy calibration source used by SNO is the 6.13-MeV γ ray produced in the decay of ^{16}N.

A background to this nucleon-decay signal in SNO results from neutral current (NC) interactions of solar neutrinos. This is due to the γ rays of similar energies that are produced as a result of neutron captures on nuclei in the detector. In Phase I (D_2O), neutrons were detected through observation of the single 6.25-MeV γ ray resulting from neutron capture on deuterium. This capture efficiency is 0.29, but the threshold applied to the analysis to limit low energy backgrounds reduces the overall neutron detection efficiency to $\epsilon_n = 0.144 \pm 0.005$ [6]. In Phase II (D_2O + NaCl), 2 tons of NaCl were added to the 1 kiloton of D_2O. Neutron captures on ^{35}Cl release 8.6 MeV of energy in γ rays, with most capture events producing multiple γ rays. The corresponding capture efficiency in Phase II is 0.90 and, due to a relatively high analysis threshold, the overall neutron detection efficiency is $\epsilon_n' = 0.399 \pm 0.010$ [7]. The multiple γ rays from neutron captures in Phase II result in a more isotropic distribution of Cherenkov light, which can be used as a further discriminant for identifying the neutron-induced component. However, the principal advantage in comparing Phase I and Phase II data lies in the fact that γ rays from the nucleon-decay signal are detected with similar efficiencies in SNO, while neutrons produced by ^{8}B solar neutrinos are detected with very different efficiencies. These characteristics are used in what follows to measure an upper limit for nucleon disappearance.

In terms of the data from Phase I of SNO, the rate of nuclear γ-ray production can be related to the apparent production rate of neutrons by taking account of the detection efficiencies for neutrons, γ rays, and particle misidentification as follows:

$$R_\gamma \epsilon_\gamma f_{\gamma n} = R_n - \epsilon_n \mathcal{R}_{\mathrm{NC}}$$

where R_γ is the rate of nuclear γ-ray production due to nucleon decay, ϵ_γ is the efficiency for detecting the nuclear γ rays above the analysis energy threshold, $f_{\gamma n}$ is the fraction of the detected nuclear γ rays which are mistaken for neutrons, R_n is the extracted neutron detection rate nominally attributed to NC interactions, ϵ_n is the neutron detection efficiency for the fiducial volume and analysis energy threshold, and $\mathcal{R}_{\mathrm{NC}}$ is the actual production rate of neutrons due to solar neutrino NC interactions. Similarly, for Phase II data,

$$R_\gamma \epsilon_\gamma' f_{\gamma n}' = R_n' - \epsilon_n' \mathcal{R}_{\mathrm{NC}}.$$

Thus,

$$R_\gamma = \frac{R_n - \frac{\epsilon_n}{\epsilon_n'} R_n'}{\epsilon_\gamma f_{\gamma n} - \epsilon_\gamma' f_{\gamma n}' \frac{\epsilon_n}{\epsilon_n'}} \equiv \frac{\Delta R_n}{\epsilon_\gamma f_{\gamma n} - \epsilon_\gamma' f_{\gamma n}' \frac{\epsilon_n}{\epsilon_n'}},$$

where ΔR_n is the difference between the extracted neutron detection rate attributed to NC interactions in Phase I and that implied by data from Phase II.

In order to compare Phase I and Phase II rates under the same assumption for the underlying charged current (CC) spectrum, results from SNO data were used in which the CC component was constrained to follow the shape of a standard ^{8}B energy spectrum [8]. Table I summarizes the relevant results from these two phases. The extracted numbers of CC, NC, and ES (elastic scattering) events include the subtraction of all known backgrounds (as detailed in [6,7]), including atmospheric neutrino interactions which might identically mimic the nucleon-decay signal via the removal of a proton or neutron from ^{16}O.

The number of NC events extracted in Phase I [6] was 576.5 for a live time of 306.4 d, yielding a rate of $R_n = 686.8 \pm 83.9$ per year, with statistical and systematic uncertainties added in quadrature. Similarly, for Phase II, 1265.8 NC events were implied based on a live time of 254.2 d, yielding a rate of $R_n' = 1817.6 \pm 136.6$ per year. Thus, accounting for the relative neutron detection efficiencies,

$$\begin{aligned} \Delta R_n &= R_n - \frac{\epsilon_n}{\epsilon_n'} R_n' \\ &= (686.8 \pm 83.9) - (656.0 \pm 49.3) \\ &= 30.8 \pm 97.3 \end{aligned}$$

Thus, an upper limit of $\Delta R_n < 180.6$ per year at 90% confidence limit is obtained using a standard, Bayesian prescription (which is also in good agreement with frequentist prescriptions) [9].

From [4], a vanishing neutron from the ^{16}O nucleus results in an excited state which has a branching ratio of 44% for producing a 6.18-MeV γ and 2% for a 7.03-MeV γ. For a vanishing proton, the distribution is nearly the same, with a branching ratio of 41% for a 6.32-MeV γ and 4% for a 7.0-MeV γ. The signal extraction procedures previously used for solar neutrino analyses were applied to simulated nuclear γ-ray lines of these energies, combined with a simulated solar neutrino signal. The numbers of additional NC events extracted relative to the actual NC signals generated were then expressed as fractions of the generated nuclear γ-ray signals. The values of $f_{\gamma n}$ and $f_{\gamma n}'$ were then determined by the appropriate weighting of

TABLE I. Signal extraction results for CC constrained to ^{8}B shape. Error bars are the quadrature sum of statistical and systematic uncertainties.

Analysis parameter	Phase I (pure D_2O)	Phase II[a] (D_2O + NaCl)
Fiducial volume	6.97×10^8 cm^3	6.97×10^8 cm^3
Energy threshold	$T_{\mathrm{eff}} > 5$ MeV	$T_{\mathrm{eff}} > 5.5$ MeV
Live time	306.4 d	254.2 d
CC events	1967.7 ± 117.9	1430.3 ± 97.1
ES events	263.6 ± 29.2	163.7 ± 23.8
NC events	576.5 ± 70.4	1265.8 ± 95.2
Neutron detection efficiency	0.144 ± 0.005	0.399 ± 0.010
NC event rate (R_n & R_n')	686.8 ± 83.9 yr^{-1}	1817.6 ± 136.6 yr^{-1}
Equivalent Phase I NC rate (R_n and $\frac{\epsilon_n}{\epsilon_n'} R_n'$)	686.8 ± 83.9 yr^{-1}	656.0 ± 49.3 yr^{-1}

[a] The Phase II data set used for this analysis is identical to that presented in [7].

these fractions in accordance with the relative branching ratios given above. For Phase I data, it was found that $f_{\gamma n} = 0.99^{+0.01}_{-0.02}$ for both neutron- and proton-decay modes. This is as expected since the neutron signal in pure D_2O results from a 6.25-MeV γ ray, which is virtually indistinguishable from either 6.18 or 6.32 MeV within the energy resolution of the detector. The distributions are, therefore, nearly 100% covariant. For Phase II data, $f_{\gamma n}' = 0.75^{+0.01}_{-0.01}$ (again, nearly identical for either decay mode). Once more, this is roughly what is expected given the additional isotropy information. The lower value of $f_{\gamma n}'$ derived reflects a compromise within the fitting procedure between providing a good description of the isotropy distribution and the energy spectrum expected for neutrons. These same simulated nuclear γ-ray lines were also used to determine ϵ_γ and ϵ_γ'. For neutron- (proton-) decay modes, these were found to be 0.51 ± 0.01 (0.59 ± 0.01) and 0.361 ± 0.005 (0.425 ± 0.006), respectively.

Thus, an upper limit can be deduced for the number of decay γ rays at greater than 90% confidence level of $R_\gamma^{\mathrm{lim}} < 443$ per year for neutron decay and $R_\gamma^{\mathrm{lim}} < 385$ per year for proton decay. An upper bound to invisible modes of nucleon decay can now be established as follows:

$$\tau_{\mathrm{inv}} > \frac{N_{np}}{R_\gamma^{\mathrm{lim}}} \varepsilon_\gamma,$$

where N_{np} is the number of neutrons or protons (depending on decay mode) within the D_2O fiducial volume which are bound in ^{16}O (1.85×10^{32}), and ε_γ is the efficiency for the decay to result in the release of a 6- or 7-MeV γ ray (0.46 for neutron modes and 0.45 for proton modes). Therefore, the comparison of Phase I and Phase II data from SNO implies that, at greater than 90% confidence level,

$$\text{for neutron modes}: \quad \tau_{\mathrm{inv}} > 1.9 \times 10^{29}\ \mathrm{yr};$$

$$\text{for proton modes}: \quad \tau_{\mathrm{inv}} > 2.1 \times 10^{29}\ \mathrm{yr}.$$

Prior to this Letter, the best constraint on $n \rightarrow 3\nu$ used by the Particle Data Group [9] was based on Kamiokande data in which higher energy, but much weaker, branches of the deexcitation of the oxygen nucleus were considered and yielded a limit of $\tau > 5 \times 10^{26}$ yr [5]. It has been proposed that a similar analysis could be carried out with data from Super-Kamiokande and, by making use of the carbon nucleus, possibly even in the KamLAND detector [10]. It has also been noted that the disappearance of a proton from the deuteron in heavy water detectors would result in a free neutron, which could then be captured to yield a detectable signal for invisible proton decay (see, for example, [11]). This has already been used to yield a lower bound to the proton lifetime in excess of 10^{28} yr for such modes [6,12]. Lead perchlorate has also been suggested as a possible future detector medium to search for invisible nucleon decay, making use of deexcitation of the nuclear hole that would be left in ^{35}Cl, with an estimated sensitivity on the order of 10^{30} yr for a 1 kiloton detector [13,14]. Owing to the extremely low background levels in SNO, the principal branches of the deexcitations for ^{16}O have been probed here and have yielded limits which are within a factor of 5 of this level. Thus, the constraint presented here is about an order of magnitude more stringent than the recently published limits on invisible proton decay and 400 times more stringent than previous limits on neutron modes, such as $n \rightarrow 3\nu$.

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*Deceased.

†Present Address: Department of Physics and Astronomy, Indiana University, South Bend, IN 46615.

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