Invisible Nucleon Decay in SNO+ Water Phase

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Overview

- The SNO+ experiment, detector
- Status, run plan
- Invisible nucleon decay
- Likelihood approach
SNO+ is a multi-purpose neutrino experiment, reusing the infrastructure of SNO, located 2 km underground in Vale’s Creighton nickel mine.

Physics goals:
- neutrinoless double beta decay
- supernova neutrinos
- solar, reactor, geoneutrinos
- exotic searches
Collaboration

Queen's
Alberta
Laurentian
SNOLAB
TRIUMF

BNL, AASU
U Penn, UNC
U Washington
UC Berkeley/LBNL
Chicago, UC Davis

Oxford
Sussex
Lancaster
Liverpool
QMUL

LIP Lisboa
LIP Coimbra

TU Dresden

UNAM
The Detector

Inner volume (900 m$^3$)
*scintillator or water*

Acrylic Vessel ($r = 6$ m)

Outer volume (1700 m$^3$)
*water*

PMTs (9300, $r = 8.5$ m)

Water shielding (5700 m$^3$)
We have made significant upgrades to the detector since the end of SNO:

- New calibration systems
- Improvements to the DAQ
- Hold-down rope net to enable the use of liquid scintillator
- Scintillator purification plant
- Covergas system
- PMT repairs
Run Plan

- Water phase, \( \sim \) 6 months
  - backgrounds, reactor, supernovae, nucleon decay
- Scintillator phase, \( \sim \) 6 months
  - backgrounds, reactor, solar, geo, supernovae
- Loaded scintillator phase, \( \sim \) 3 years
  - reactor, geo, supernovae, neutrinoless double beta decay
Invisible Nucleon Decay

Invisible nucleon decay is the model-independent class of hypothetical decays of protons or neutrons to undetected products. The best limits on this process come from SNO and KamLAND:

\[ \tau_p > 2.1 \times 10^{29} \text{ years} \quad (90\% \text{ CL - SNO [1]}) \]
\[ \tau_n > 5.8 \times 10^{29} \text{ years} \quad (90\% \text{ CL - KamLAND [2]}) \]

Possible examples:
\[ n \rightarrow \nu\nu\nu \]
extra dimensions
dark matter decays

Nucleon disappearance in $^{16}\text{O}$ can lead to excited states of $^{15}\text{O}$ or $^{15}\text{N}$. These deexcite via $\gamma$ decay. In roughly 40% of such decays, this results in a $\gamma$ of 6-9 MeV.
Strength of SNO+

Why can SNO+ improve on the limits of SNO and KamLAND?
- SNO limited by neutron capture on deuterium (NC solar signal)
- Branching ratio to signal significantly higher from oxygen than carbon
Counting Experiment Approach

Cuts:

- energy: $5.4 \text{ MeV} \leq E \leq 10 \text{ MeV}$
- radius: $r \leq 5.5 \text{ m}$
- direction: $\cos \theta_{\odot} > -0.8$

Backgrounds after cuts

<table>
<thead>
<tr>
<th>Decay Source</th>
<th>Events in 6 mo run</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{214} \text{Bi}$</td>
<td>0</td>
</tr>
<tr>
<td>$^{208} \text{Tl}$</td>
<td>0.6</td>
</tr>
<tr>
<td>solar $\nu$</td>
<td>17.7</td>
</tr>
<tr>
<td>reactor $\bar{\nu}$</td>
<td>1.3</td>
</tr>
<tr>
<td>external Bi-Tl</td>
<td>8.9</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>28.5</strong></td>
</tr>
</tbody>
</table>

| $\epsilon(n)$ | 0.1017 |
| $\epsilon(p)$ | 0.1129 |

90% CL sensitivity:

- SNO+
  - $\tau_p > 1.4 \times 10^{30} \text{ years}$
  - $\tau_n > 1.3 \times 10^{30} \text{ years}$

- Existing Limits
  - $\tau_p > 0.2 \times 10^{30} \text{ years}$
  - $\tau_n > 0.6 \times 10^{30} \text{ years}$
Likelihood Approach

- Replace cut in energy with fit from 5 to 10 MeV
- Binned likelihood fit in energy
  \[ \ln L = - \sum_{\text{bins}} (x - d + d \ln \left( \frac{d}{x} \right)) \]
- Sample from background and fit to energy templates
- Assume 10% constraints on reactors, solars, 100% uncertainty on radioactive backgrounds
- Assume uniform prior on nucleon decay rate above 0
Example Spectral Fit — MC background only
Conclusion

- With 6 months of water data, SNO+ will improve the world limits on invisible nucleon decay by a factor of 2 – 7, with a sensitivity of $1.4 \times 10^{30}$ years.
- Additional improvements to sensitivity through a likelihood approach are under development.