SNO+ from water to scintillator

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A matter/antimatter asymmetry search

- The neutrino could be a Majorana fermion
  - Only possible for neutral particles
  - Would be its own antiparticle
- Some isotopes undergo double beta decay
  - If the neutrino is Majorana, the decay can produce zero neutrinos
- $2\nu2\beta$ is rare; $0\nu2\beta$ would be even rarer. Detection requires to:
  - Achieve (and understand) very low background
  - Accurately determine detector response
  - Consider scalability of the technique
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http://next.ific.uv.es/
The SNO+ detector

- Very low background neutrino detector
- Located in SNOLAB
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- At a depth of 2km (rock, 5900 mwe)
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The SNO+ detector

- Detector itself is over 9000 PMTs monitoring an acrylic vessel
  - Mounted at 8.5m radius
  - 54% of photocoverage
  - Cavity is flooded with ultra-pure water

- Fiducial volume: spherical acrylic vessel
  - Radius of 6m
  - Held in place by tensylon rope systems
  - Access via neck at the top
Fiducial volume material

Material in vessel sets the physics goal

1. Ultra-pure water phase
   - Recording 7 hits/MeV deposited energy (Cherenkov)
   - Physics goals are nucleon decay, solar and reactor neutrinos
   - Understanding of detector optics and external backgrounds

2. Intermediate stage: scintillator
   - Estimated 500 hits/MeV deposited energy
   - Studies of solar, geo and reactor neutrinos
   - Understanding of scintillator backgrounds

3. Ultimate goal: Tellurium-loaded scintillator
   - Search for $0\nu2\beta$ in 130-Te (Q value 2.5 MeV)
   - Expect 400 hits/MeV deposited energy
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Current status

- Taking water data since early 2017
- Physics results include 114.7 days of livetime (of 235 calendar days)
  - Twice the amount of data collected in the mean time
- Extensive detector calibration with deployed and mounted sources
Optical calibration

• Isotropic light source deployed at multiple positions/wavelengths
• Full analysis of optical response in water conducted
  • Attenuation, group velocity, relative angular acceptance of optical sensors
• LED/laser systems mounted and being tested to do constant monitoring
Detector response

• Response calibrated using an $^{16}$N source
  • Producing two gammas $\rightarrow$ Compton scatter $e^-$
  • Data used to characterize energy response and fit algorithms (position, direction)
Solar flux measurement in water

- Neutrinos from $^8\text{B}$ observed

- Flux
  \[ \Phi_{^8\text{B}} = (5.95^{+0.75}_{-0.71}\text{ (stat.)}^{+0.28}_{-0.30}\text{ (syst.)}) \times 10^6 \text{ cm}^{-2}\text{s}^{-1}. \]
  consistent with SNO

- Fit in direction of $\cos(\theta_{\text{sun}})$, backgrounds are flat

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Background levels

• Internal backgrounds
  • Intrinsic radioactivity of water in the vessel

• External backgrounds
  • Intrinsic radioactivity in vessel, ropes, PMTs and water
  • Will not change in between phases

• Observables to identify backgrounds
  • Energy, position, isotropy and direction
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External background results

• Multiple analyses constrain the backgrounds
  • Fit to spectral shapes, counting events within a region
• Results are consistent, indicate external background at expectation

<table>
<thead>
<tr>
<th>Background source</th>
<th>Results (observed / expected) for latest period analyzed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>z &gt; 0 (upper hemisphere)</td>
</tr>
<tr>
<td>Acrylic vessel + rope system</td>
<td>2.2 ± 0.08 (stat) +2.4-1.9 (syst)</td>
</tr>
<tr>
<td>External water</td>
<td>0.6 ± 0.06 (stat) +1.9-0.6 (syst)</td>
</tr>
<tr>
<td>PMTs</td>
<td>1.2 ± 0.02 (stat) +1.1-0.5 (syst)</td>
</tr>
</tbody>
</table>
Invisible nucleon decay search

• Never observed baryon-number violating process

• Theories propose invisible decay modes (e.g. \( n \to 3\nu \))

• Decay could be observed indirectly with gammas
Results from nucleon decay search

- Selection based on straight cuts to remove backgrounds
- Two analysis performed: cut & count and likelihood fit
- No excesses, only limits

<table>
<thead>
<tr>
<th>Data set</th>
<th>Observed events</th>
<th>Expected events</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>$1.17^{+4.60}<em>{-0.05}^{+1.33}</em>{-0.39}$</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>$2.35^{+4.62}<em>{-0.40}^{+3.44}</em>{-0.81}$</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>$3.47^{+4.60}<em>{-0.15}^{+3.11}</em>{-0.96}$</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>$3.37^{+4.60}<em>{-0.17}^{+2.70}</em>{-0.98}$</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>$1.46^{+4.60}<em>{-0.13}^{+2.17}</em>{-0.60}$</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>$5.84^{+7.40}<em>{-2.31}^{+2.68}</em>{-0.62}$</td>
</tr>
<tr>
<td>Total</td>
<td>22</td>
<td>$17.65^{+12.68}<em>{-2.36}^{+6.51}</em>{-1.85}$</td>
</tr>
</tbody>
</table>

Limits on nucleon decay

- Results and comparison with existing limits

<table>
<thead>
<tr>
<th></th>
<th>Spectral analysis</th>
<th>Counting analysis</th>
<th>Existing limits</th>
</tr>
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<tbody>
<tr>
<td>$n$</td>
<td>$2.5 \times 10^{29}$ y</td>
<td>$2.6 \times 10^{29}$ y</td>
<td>$5.8 \times 10^{29}$ y [KamLAND]</td>
</tr>
<tr>
<td>$p$</td>
<td>$3.6 \times 10^{29}$ y</td>
<td>$3.4 \times 10^{29}$ y</td>
<td>$2.1 \times 10^{29}$ y [SNO]</td>
</tr>
<tr>
<td>$pp$</td>
<td>$4.7 \times 10^{28}$ y</td>
<td>$4.1 \times 10^{28}$ y</td>
<td>$5.0 \times 10^{28}$ y [Borexino]</td>
</tr>
<tr>
<td>$pn$</td>
<td>$2.6 \times 10^{28}$ y</td>
<td>$2.3 \times 10^{28}$ y</td>
<td>$2.1 \times 10^{28}$ y [Treyak et al.]</td>
</tr>
<tr>
<td>$nn$</td>
<td>$1.3 \times 10^{28}$ y</td>
<td>$0.6 \times 10^{28}$ y</td>
<td>$1.4 \times 10^{30}$ y [KamLAND]</td>
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Next: scintillator fill

• Cover-gas system in place to seal the vessel
• Radon monitor in place to follow activity
• Liquid scintillator purification plant being tested
  • About 1.8 tonnes injected in the vessel thus far
• Fill had to be halted several months due to a leak in the distillation column
• Leak has been repaired – about to restart fill very soon
Tellurium process systems installed

- TeA and TeDiol plants moving to commissioning

Telluric acid plant
Tellurium process systems installed

- TeA and TeDiol plants moving to commissioning
Majorana neutrino search

- Signal of Majorana neutrinos in the energy spectrum
- Using best knowledge of background levels
- Two analyses planned
  - Cut&count
  - Likelihood
Majorana neutrino search

ROI: 2.42 - 2.56 MeV [-0.5σ - 1.5σ]
Counts/Year: 9.47

- Cosmogenic
- $^{8}\text{B}\nu\text{ES}$
- $2\nu\beta\beta$
- $(\alpha, n)$
- External $\gamma$
- Internal Th chain
- Internal U

Counts/5y/20keV bin

Graph showing reconstructed energy vs counts/5y/20keV bin for various sources:
- $0\nu\beta\beta$ (100 meV)
- $2\nu\beta\beta$
- $(\alpha, n)$
- U chain
- Th chain
- External
- $^{8}\text{B}\nu\text{ES}$
- Cosmogenic
Majorana neutrino search

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Cosmogenic
2νββ
(α, n)
External γ
Internal Th chain
Internal U chain

Projected 2024 0νββ Sensitivities

$\mathcal{M}_{\beta\beta}$ (meV)

$T_{1/2}^{0\nu}$ (yrs)
Towards the future

• SNO+ Phase I is 0.5% Te-loaded
  • Main backgrounds aren’t from loading
  • Test-bed for a multi-ton experiment

• Telluric acid loading R&D
  • Chemistry studies to increase light yield

• Detector upgrade path
  • High QE PMTs being studied
  • Possible to replace PMT focusing
Summary

• Water phase wrapping up
  • Calibration systems tested
  • Detector response understood
  • Modeling of sub-leading effects with low background data

• Results from the water phase out
  • Nucleon decay limits and observation of solar neutrinos published
  • Working on neutron capture and reactor antineutrinos in water

• Scintillator phase to begin soon
  • Loading liquid scintillator this year
Thank you for your attention