Super-K Gd Project: Detecting Anti-neutrinos from Pre-supernova Stars

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In a massive star (initial mass \(>8\text{M}_\odot\)), at the end of its life...

- H and He fusion rates are not high enough to stabilise star
- Star contracts and increases in temperature
- Heavier nuclei are fused up to iron until core collapse

Neutrino Interactions on Earth

- Depends on progenitor mass and model
- No oscillation or matter effect assumed here
- Lighter progenitors increase in rate earlier, but will produce less events in total
- Masses are zero age main sequence masses, not current masses

Data sources
- Odrzywolek et al.
  [http://th.if.uj.edu.pl/~odrzywolek/]
<table>
<thead>
<tr>
<th>Supernova Neutrinos</th>
<th>Silicon Burning Neutrinos</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy $&gt;10$ MeV</td>
<td>Energy $&lt;3$ MeV</td>
</tr>
<tr>
<td>Hours before light from SN</td>
<td>Days before light from SN</td>
</tr>
<tr>
<td>Detected in 1987</td>
<td>Never detected before</td>
</tr>
<tr>
<td>1000s of events in seconds at SK at $&gt;10kpc$</td>
<td>100s of events in a day at SK-Gd for stars at $&lt;1kpc$</td>
</tr>
</tbody>
</table>
Benefits

• Avoid detector maintenance and calibration immediately before supernova – “Early Warning”

• Never before seen astrophysical object, not visible to EM astronomy
Inverse Beta Decay at SK-Gd

- Energy threshold 0.8 MeV
- Neutron capture on Gd gives an average 4-5 MeV visible energy
- Look for sudden increase in rate of candidates
- No pointing information
Neutron Singles and Gadolinium

- Detecting low energy positrons at SK is difficult!
  - Cherenkov threshold 0.8 MeV
  - Detector trigger threshold ~2.5 MeV – below this there simply aren’t enough photons detected to reconstruct reliably

- Captures on Gadolinium will reduce background for low energy positrons

- Most of the time positron will not be detected, so we need to detect neutron captures alone
Neutron Singles Efficiency

• Background is estimated using 30 days trigger data from SK
• Signal is simulated
  • Gamma rays generated according to the spectrum (see *)
  • Propagated in SK detector simulation
• Signal is distinguished by energy, reconstruction quality, light pattern

• Estimated ~36% signal efficiency, with ~170 background events per day
• Low energy background could be higher following tank open work and Gd addition
• Some prompt positrons will be detected, but this is not considered in the following slides

* http://neutrino.phys.ksu.edu/~GLG4sim/Gd.html
Sensitivity

<table>
<thead>
<tr>
<th>Poisson False Alarm Rate</th>
<th>Signal events required over 170 background</th>
<th>Early warning across all models at 150 parsecs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 per 100 years</td>
<td>55</td>
<td>3-17 hours</td>
</tr>
<tr>
<td>1 per 10 years</td>
<td>46</td>
<td>6-19 hours</td>
</tr>
<tr>
<td>1 per year</td>
<td>37</td>
<td>8-22 hours</td>
</tr>
<tr>
<td>1 per month</td>
<td>23</td>
<td>13-30 hours</td>
</tr>
</tbody>
</table>

Assumed:
- signal efficiency 36%
- background 168 per day
- 90% capture efficiency
- normal hierarchy survival fraction 0.74
  (Note that inverted hierarchy could greatly reduce the number of events detected)
- Star is 150 parsecs away (very close)
Range for minimal alarm

Number of events $\propto \frac{1}{\text{distance}^2}$

<table>
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<tr>
<th>Poisson False Alarm Rate</th>
<th>Signal events required over 170 background</th>
<th>Max range for warning</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 per 100 years</td>
<td>55</td>
<td>210-510 parsec</td>
</tr>
<tr>
<td>1 per 10 years</td>
<td>46</td>
<td>230-550 parsec</td>
</tr>
<tr>
<td>1 per year</td>
<td>37</td>
<td>260-610 parsec</td>
</tr>
<tr>
<td>1 per month</td>
<td>23</td>
<td>330-780 parsec</td>
</tr>
</tbody>
</table>

Assumed:
- signal efficiency 36%
- background 168 per day
- 90% capture efficiency
- normal hierarchy survival fraction 0.74

- Maximum range is comparable to KamLAND published

(red is underneath magenta)
Summary

• Final stages of fusion in a massive star produces a rapid increase in the flux of electron antineutrinos
• SK-Gd will have improved detection of electron antineutrinos
• SK-Gd will be able to detect silicon burning in nearby stars
• This would give some early warning of supernova, and be interesting astrophysically
• Tentative ranges were estimated for detection
• Sensitivity will be improved by prompt positrons that are detected
Data Sources

• Odrzywolek astrophysical model
  http://th.if.uj.edu.pl/~odrzywolek/

• T. Yoshida et al. astrophysical model
  arXiv:1606.04915v2

• Stumia and Vissani, cross section
  arxiv:astro-ph/0302055
Comparison to KamLAND

• KamLAND has a published sensitivity to pre supernova neutrinos arXiv:1506.01175

• KamLAND sees roughly 1/10th as many events as SK, but has much lower backgrounds

• KamLAND uses a 48 hour window so $5\sigma \sim 1$ in 96,000 years, SK-Gd would use a 24 hour window

• Maximum range for this threshold very similar between SK-Gd and KamLAND (e.g. 460 parsec for NH, 25 M☉)