Measurement of the Rayleigh Scattering length at SNO+

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31/03/2015
SNO+ The Scattering Module

Cut selection

Measurement Summary

- Neutrinoless double-beta decay search
- Solar neutrinos
- Reactor anti-neutrinos
- Geo neutrinos
- Supernova neutrinos
- Invisible Nucleon Decay

Acrylic Vessel (AV)

Water shielding

Scintillator Cocktail

~9500 PMTs within a geodesic support structure (PSUP)

S. Langrock


Event reconstruction using photon timing
Delay of scattered photons
Scattering level depends on scintillator composition

ELLIE (Embedded LED Light Injection Entity):
- Timing and charge calibration of the PMTs (JINST Vol. 10, P03002 (2015))
- Measurement of optical scattering properties as a function of wavelength
- Monitoring of the attenuation lengths

The Scattering Module of ELLIE:
- 12 fibres at 4 injection points
- 3 fibres at each point at different angles ($0^\circ$, $10^\circ$, $20^\circ$)
- Pulse diode lasers at 4 wavelengths (375 nm, 407 nm, 446 nm and 495 nm)

see also Krishanu Majumdar’s talk “THE OPTICAL SCATTERING CALIBRATION SYSTEM AT SNO+”
Calculate theoretical time for each optical interaction. Use these to define timing cuts.

Define spatial cuts for in-beam light and outer AV reflections:

- Beam angle (in-beam light: dependent on angular profile of fibre, outer AV reflections: dependent on fibre angle)
- Z-coordinate (dependent on fibre)

Timing for a photon reflected upon AV entry:

\[ t_{AV} = (|\vec{r}_{pmt} - \vec{r}_{AV}| + |\vec{r}_{AV} - \vec{r}_{fibre}|) \cdot n_{water}c \]

\[ t_{res} = t_{PMT} - t_{tof}, \quad t_{tof} \text{ photon time of flight} \]

Beam angle:

\[ \alpha = \arccos(\frac{\vec{a} \cdot \vec{b}}{|\vec{a}| \cdot |\vec{b}|}) \]

with \( \vec{a} = \vec{r}_{fibredir} \) and \( \vec{b} = \vec{r}_{pmt} - \vec{r}_{fibre} \)

all vectors with respect to the detector centre.
- Calculate theoretical time for each optical interaction
- Use these to define timing cuts

Timing for a photon reflected upon AV entry:

\[ t_{AV} = \left( |\vec{r}_{pmt} - \vec{r}_{AV}| + |\vec{r}_{AV} - \vec{r}_{fibre}| \right) \cdot \frac{n_{\text{water}}}{c} \]

\[ t_{\text{res}} = t_{\text{PMT}} - t_{\text{tof}}, \quad t_{\text{tof}} = \text{photon time of flight} \]

All vectors with respect to the detector centre
- Define spatial cuts for in-beam light and outer AV reflections:

- Z-coordinate (dependent on fibre)
Define spatial cuts for in-beam light and outer AV reflections:

- Beam angle (in-beam light: dependent on angular profile of fibre, outer AV reflections: dependent on fibre angle)

beam angle:

\[ \alpha = \arccos \left( \frac{\vec{a} \cdot \vec{b}}{||\vec{a}|| \cdot ||\vec{b}||} \right) \]

with \( \vec{a} = \vec{r}_{\text{fibredir}} \) and \( \vec{b} = \vec{r}_{\text{pmt}} - \vec{r}_{\text{fibre}} \)

all vectors with respect to the detector centre
Cut adjustment and verification using Monte Carlo simulations for a water-filled detector:

Switching off the Rayleigh scattering:

Removing the AV:

10° fibre at 495 nm
Simulation parameters:

- 10000 events per fibre and wavelength
- Water-filled detector
- 2000 photons per beam pulse

Scaling factor, \( s \), ranging from 0.2 to 2.0

Scaling factor \( s \): \( SL(\lambda) = \frac{SL_{\text{nom}}(\lambda)}{s} \)
(SL - scattering length)

0° fibre at 375 nm with \( s = 0.2 \)

0° fibre at 375 nm with \( s = 2.0 \)
Apply cut selection to water-fill data:

\[
\begin{align*}
    c_{\text{scatt}} &= \frac{N_{\text{scatt}}}{N_{\text{total}}} \\
    c_{\text{in-beam}} &= \frac{N_{\text{in-beam}}}{N_{\text{total}}}
\end{align*}
\]

simulations: \( f_1(x) = ax + b \)

data: \( f_2(x) = c \)

\[ s = \frac{c - b}{a} \]

\( a, b \) - fit parameters
No actual water-fill data yet
Produced fake data sample with $s = 0.786$

Averaging over all three fibres of one injection point at all four wavelengths:

$$s_{\text{data}} = 0.78 \pm (0.01)_{\text{stat.}}$$

Statistical Uncertainties:
- Statistical uncertainty on amount of hits: $\sqrt{N}$
- Statistical uncertainty on fit parameters $a$ and $b$ taken from fit
Systematic Uncertainties to be considered (work in progress):

- AV position → measurements with the Timing Module of ELLIE
- Fibre directions → measurements using data
- Angular profile of the fibre beams → measurements using data
- Beam intensity → measurements from the SMELLIE hardware & a number-of-hits based evaluation process

<table>
<thead>
<tr>
<th>Systematic Uncertainty</th>
<th>Absolute Value</th>
<th>Relative Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>AV position</td>
<td>0.02</td>
<td>2.6</td>
</tr>
<tr>
<td>Fibre direction</td>
<td>0.01</td>
<td>1.3</td>
</tr>
<tr>
<td>Angular profile</td>
<td>0.02</td>
<td>2.6</td>
</tr>
<tr>
<td>Intensity</td>
<td>yet to be determined</td>
<td>yet to be determined</td>
</tr>
<tr>
<td>Total</td>
<td>0.03</td>
<td>3.8</td>
</tr>
</tbody>
</table>

Table: Systematic error evaluation using conservative estimates of the uncertainty on each systematic. The estimates will be adjusted once the uncertainties from their measurements are known.
Accurate measurement of scaling factor in a water-filled detector
Framework ready for water-fill data
Systematic uncertainties are not expected to exceed 5% based on previous studies
Adaption of framework for scintillator fill underway
Thank you for your attention!
Back Up
Table: Number of hits selected by each cut and the number of Rayleigh scattered photons in each cut for a 20° fibre at 446 nm.

<table>
<thead>
<tr>
<th>Cut</th>
<th>Number of Hits</th>
<th>Scattered photons</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-beam</td>
<td>1193818</td>
<td>8533</td>
</tr>
<tr>
<td>Outer AV reflections</td>
<td>14599</td>
<td>2268</td>
</tr>
<tr>
<td>Scattering</td>
<td>53392</td>
<td>38983</td>
</tr>
<tr>
<td>Inner AV reflections</td>
<td>9155</td>
<td>5938</td>
</tr>
<tr>
<td>PSUP reflections</td>
<td>114509</td>
<td>12279</td>
</tr>
<tr>
<td>Multiple deflections</td>
<td>30475</td>
<td>71</td>
</tr>
<tr>
<td>Total</td>
<td>1415948</td>
<td>68072</td>
</tr>
</tbody>
</table>

- Wavelength dependence of Rayleigh scattering ($I \propto \frac{1}{\lambda^4}$)
- Overall good purity in in-beam region

Table: Cut evaluations for all four wavelengths for a 0° fibre.
<table>
<thead>
<tr>
<th>Wavelength [nm]</th>
<th>$SL_{\text{nom}}(\lambda)$ [m]</th>
<th>$SL_{s=0.2}(\lambda)$ [m]</th>
<th>$SL_{s=2.0}(\lambda)$ [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>360</td>
<td>119</td>
<td>5963</td>
<td>60</td>
</tr>
<tr>
<td>400</td>
<td>182</td>
<td>9089</td>
<td>91</td>
</tr>
<tr>
<td>440</td>
<td>266</td>
<td>1331</td>
<td>133</td>
</tr>
<tr>
<td>500</td>
<td>444</td>
<td>2219</td>
<td>222</td>
</tr>
</tbody>
</table>

**Table:** Rayleigh scattering length for water and for two different scaling factors for a range of wavelengths.

<table>
<thead>
<tr>
<th>Wavelength [nm]</th>
<th>$SL_{\text{nom}}(\lambda)$ [m]</th>
<th>$SL_{s=0.2}(\lambda)$ [m]</th>
<th>$SL_{s=2.0}(\lambda)$ [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>360</td>
<td>13.5</td>
<td>67.3</td>
<td>6.7</td>
</tr>
<tr>
<td>400</td>
<td>20.5</td>
<td>103</td>
<td>10.3</td>
</tr>
<tr>
<td>440</td>
<td>30.1</td>
<td>150</td>
<td>15</td>
</tr>
<tr>
<td>500</td>
<td>48.5</td>
<td>243</td>
<td>24.3</td>
</tr>
</tbody>
</table>

**Table:** Rayleigh scattering length for the scintillator cocktail and for two different scaling factors for a range of wavelengths.