Low-energy neutrino physics at Theia

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Theia: advanced optical multipurpose neutrino detector

Cutting edge developments in the target material and photodetection

Large scale, multipurpose detector
- Baseline: 25ktonne (17kt FV)
- Ideal: 100 ktonne (70kt FV)

Design options

Theia-25

Theia-100

Broad physics program: Studying neutrino fundamental properties and astrophysical objects

How to broaden the current physics reach

Scintillation Detectors:
- High light yield
- Low energy threshold
- Good energy and position resolutions
- Limited in size by absorption and cost
- Limited directionality

Cherenkov Detectors:
- Directional information
- Can be very large (low absorption)
- Particle ID at high energies
- No access to physics below the Cherenkov threshold
- Low light yield

Water-based Liquid Scintillation (WbLS) Detectors: Get best of two worlds
Water-based Liquid Scintillator - Basics

- Water-based Liquid Scintillator (WbLS) is a mixture of pure water and oil-based liquid scintillator
- WbLS is made using a surfactant (soap-like) such as PRS* (hydrophilic head and hydrophobic tail) to hold the scintillator molecules in water in a “micelle” structure
- Combines the advantages of water (transparency, low cost) and liquid scintillator (high light yield)
Cherenkov/scintillation photons separation

Cherenkov (Č)

Scintillation

Angular distribution

Timing

Wavelength

Angular resolution

Large area picosecond photodetectors LAPPDs (~70 ps TTS) or other fast photodetectors

• Dichroic filters
• Red-sensitive PMTs
• Filtering

See Tanner Kaptanoglu’s Talk for more info

Theia: multipurpose neutrino detector

- Large scale, multipurpose detector
  - Baseline: 25ktonne (17kt FV)
  - Ideal: 100 ktonne (70kt FV)
- Scintillator fraction tunable depending on the physics goal
- Staged approach

Design options:
- Theia-25
- Theia-100

Theia-25

- Neutrino mass ordering
- Neutrino CP-violating phase $\delta$
- Neutrinoless double beta decay
- Nucleon decay

- Solar neutrinos (CNO, $^8$B)
- Geoneutrinos
- Diffuse supernova neutrinos (DSNB)
- Supernova burst neutrinos

Theia: multipurpose neutrino detector

**Design options**

- Large scale, multipurpose detector
  - Baseline: 25ktonne (17kt FV)
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    -> staged approach

- **Theia-25**
  - 70m
  - 18m
  - 20m

**Theia-100**

**Theia-25**

**Theia-100**

**Design options**

- **solar neutrinos** (CNO, $^8$B)
- **geoneutrinos**
- **diffuse supernova neutrinos (DSNB)**
- **supernova burst neutrinos**
- **neutrino mass ordering**
- **neutrino CP-violating phase $\delta$**
- **neutrinoless double beta decay**
- **nucleon decay**

Solar neutrinos

**pp chain reaction (~99%)**

$pp \rightarrow ^4He + 2e^+ + 2\nu_e$

Released energy $\sim 26$ MeV

4p $\rightarrow ^4He + 2e^+ + 2\nu_e$


**CNO cycle (< 1%)**

$^{12}C + p \rightarrow ^{13}N + \gamma$

$^{13}N + p \rightarrow ^{14}N + e^+ + \nu_e$

$^{15}N + p \rightarrow ^{16}O + e^+ + \nu_e$

$^{16}O + p \rightarrow ^{17}F + e^+ + \nu_e$

$^{17}F \rightarrow ^{17}O + e^+ + \nu_e$

$^{16}O + p \rightarrow ^{17}F + \gamma$

$^{15}N + p \rightarrow ^{16}O + \gamma$

99.96% 0.04%
Theia: Solar neutrinos

Theia can significantly contribute to solar neutrinos studies:

- CNO neutrinos (directionality based background rejection, solar metallicity puzzle)

- $^8$B solar neutrinos high-statistics, low-threshold -> new physics in the MSW-vacuum transition region

Theia: multipurpose neutrino detector

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    -> staged approach

Design options:
- Theia-25
- Theia-100

- solar neutrinos
  - (CNO, $^8$B)
- geoneutrinos
- diffuse supernova neutrinos (DSNB)
- supernova burst neutrinos

- neutrino mass ordering
- neutrino CP-violating phase $\delta$
- neutrinoless double beta decay
- nucleon decay

Geoneutrinos

Predictions by different models:
Radiogenic heat = 10 – 35 TW

Current only two measurements: Borexino (Italy), KamLAND (Japan)

\[
\begin{align*}
^{238}U \rightarrow ^{206}Pb + 8 \alpha + 6 e^- + 6 \nu + 51.7 \text{ MeV} \\
^{232}Th \rightarrow ^{208}Pb + 6 \alpha + 4 e^- + 6 \nu + 42.8 \text{ MeV} \\
^{40}K \rightarrow ^{40}Ca + e^- + \bar{\nu} + 1.32 \text{ MeV}
\end{align*}
\]
• Likelihood fit extracting geoneutrinos rate with 8.6% precision and reactor neutrons with 6.7% precision in just one year
• Extracting U and Th individual rates, and measuring Th/U ratio with 56%-15% precision
• First high statistics measurement in a new geographical location useful to extract mantle contribution
Theia: multipurpose neutrino detector

**Large scale, multipurpose detector**
- **Baseline:** 25ktonne (17kt FV)
- **Ideal:** 100 ktonne (70kt FV)

Scintillator fraction tunable depending on the physics goal -> staged approach

**Design options**

- **Theia-25**
- **Theia-100**

**Theia-25**

- **Theia-100**

**Theia: multipurpose neutrino detector**

Theia: supernova burst neutrinos

- **dynamics of the core collapse** (neutronization, reheating, proto-neutron star cooling)
- **the properties of the neutrinos themselves** (mass hierarchy, absolute mass scale, collective oscillations)

**Only one observed: SN1987A**

- Flavor-resolved neutrino spectra
- low energy threshold/good energy resolutions
- Supernova pointing
- Separate ES from IBD events for directionality.

**Expected event rates in 100kt 10% WbLS for SN at 10kpc:**

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{\nu}_e + p \rightarrow n + e^+$</td>
<td>19,800</td>
</tr>
<tr>
<td>(ES) $\nu + e \rightarrow e + \nu$</td>
<td>960</td>
</tr>
<tr>
<td>($\nu_e$O)</td>
<td>340</td>
</tr>
<tr>
<td>($\bar{\nu}_e$O)</td>
<td>440</td>
</tr>
<tr>
<td>(NCO)</td>
<td>1,100</td>
</tr>
</tbody>
</table>

- **At LBNF:** the combination of WbLS (THEIA) and liquid argon (DUNE) detectors at the same site -> high-statistics co-detection of neutrinos and antineutrinos.
- Complementarity to JUNO and Hyper-K: opposite side of the Earth -> Earth matter effects
- Pre-supernova neutrinos
Theia: Diffuse supernova neutrino background (DSNB)

Diffuse, isotropic flux of $\nu$ from all SN explosions in the Universe.

Not yet experimentally observed

- **Cherenkov/Scintillation (C/S) ratio** gives a powerful handle to discriminate atmospheric neutral current background signals;
- substantial increase in event statistics when added to Super-K and JUNO;
- $5\sigma$ discovery (125 kton-year): $\sim$8 years (Theia-25) or $\sim$2 years (Theia-100)


Conclusions

• Broad low energy program to complement the high-energy program (see next talk by Leon)

• Directionality in solar neutrino analysis

• Likelihood fit extracting geoneutrinos rate with 8.6% precision and reactor neutrons with 6.7% precision in just one year. Extracting U and Th individual rates, and measuring Th/U ratio with 56%-15% precision

• High-statistics and reach physics potential for supernova burst neutrinos

• High-statistics diffuse supernova neutrino background (currently not observed)
QUESTIONS ARE WELCOME
now
or later
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