IPNOS for low energy solar neutrinos and ZICOS for neutrinoless double beta decay

Aspen Winter Workshop--New Directions in Neutrino Physics
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Indium Project on Neutrino Observation for Solar Interior (IPNOS) experiment for low energy solar neutrinos
Solar neutrino

Overall reaction: \(4p \rightarrow {}^4He + 2e^+ + 2\nu_e + 25\text{MeV}\)

- p-p chain
  - \(p^+ + p^+ \rightarrow ^2H + e^+ + \nu_e\) (99.77%)
  - \(^3H + p^+ \rightarrow ^3He + \gamma\) (15.08%)
  - \(^3He + p^+ \rightarrow ^4He + e^+ + \nu_e\) (0.23%)

- CNO cycle
  - \(^{15}N + p^+ \rightarrow ^{12}C + ^4He + \gamma\)
  - \(^{12}C + p^+ \rightarrow ^{13}N + \gamma\)

- Overall reactions: \(^3He + ^3He \rightarrow ^4He + 2p^+\) (84.92%)
  - \(^7Li + p^+ \rightarrow ^4He + ^4He\)
  - \(^8B \rightarrow ^8Be^* + e^+ + \nu_e\)
  - \(^8Be^* \rightarrow ^4He + ^4He\)

- Solar fusion cross sections are updated. (SF-II, Rev. of Mod. Phys. 83 (2011) 195)
- Solar abundances: GS98 (High metallicity), AGSS09 (Low metallicity)
Experimental status

- **pp (0.6%)**: SAGE (all: 5%, pp: 14%), Gallex/GNO
- **7Be (7%)**: Homestake, Borexino (5%)
- **pep (1.2%)**: Borexino (19%)
- **8B (14%)**: Kamiokande, Super-K, SNO (4%), Borexino, KamLAND
- **hep (30%)**: (SK, SNO, upper limit only)
  
  SK: $40 \times 10^3$ /cm$^2$/s (90%CL, w/o osc.) PRL 86, 5651 (2001)

- **CNO (14~17%)**: (Borexino, upper limit only)
  
  $7.7 \times 10^8$ /cm$^2$/s (95%CL, w/ osc.) arXiv:1110.3230

Radiochemical experiments

Theoretical/experimental uncertainties running

High precision spec. & d/n purification efforts are now on-going

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Current targets

Neutrino physics

- Vacuum-MSW transition
  - pep flux (ES, CC), 8B spectrum, ...
- Precise theta12
  - pp flux, 8B spectrum, ...

Astrophysics

- Separate solar models
  - CNO fluxes
- Solar core
  - high stat. solar $\nu$

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<table>
<thead>
<tr>
<th>project</th>
<th>target for solar (\nu)</th>
<th>current status / recent information</th>
</tr>
</thead>
<tbody>
<tr>
<td>pep/CNO (ES)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SNO+</td>
<td>1kt LS</td>
<td>under construction</td>
</tr>
<tr>
<td>KamLAND2</td>
<td>1kt LS</td>
<td>will be after KamLAND-Zen</td>
</tr>
<tr>
<td>pp(ES)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>XMASS</td>
<td>10 ton(FV) Lq. Xe</td>
<td>commissioning of XMASS-I (total 1ton, ~0.1ton FV)</td>
</tr>
<tr>
<td>CLEAN</td>
<td>50 ton Lq. Ne</td>
<td>MiniCLEAN is under construction</td>
</tr>
<tr>
<td>HERON</td>
<td>10 ton Lq. He</td>
<td>will not built a full detector (Astropart. Phys. 30, 1 (2008))</td>
</tr>
<tr>
<td>pp/7Be(CC)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LENS</td>
<td>10ton 115In</td>
<td>R&amp;D (In loaded LS)</td>
</tr>
<tr>
<td>IPNOS</td>
<td>115In</td>
<td>R&amp;D (InP cell + Lq. Xe detector)</td>
</tr>
<tr>
<td>MOON</td>
<td>1.5~3ton 100Mo</td>
<td>R&amp;D (EC branch of 100Tc was measured)</td>
</tr>
</tbody>
</table>

Next generation

| Water Cherenkov      | Megaton water             | LOI from Hyper-K (arXiv:1109.3262)                                                                    |
| Lq. Scintillator     | ~0.1Mton LS               | white paper from LENA (arXiv:1104.5620)                                                                |
Capture of low energy solar neutrinos by $^{115}$In


**Advantage**
- large cross section (~640SNU)
- direct counting for solar neutrinos
- sensitive to low energy region ($E_\nu \geq 125$keV)
- energy measurement ($E_e = E_\nu - 125$keV)
- triple fold coincidence to extract neutrino signal from huge BG ($\gamma_1 + \gamma_2 + \gamma_3$)

**Disadvantage**
- natural $\beta$-decay of $^{115}$In ($\tau_{1/2} = 4.4 \times 10^{14}$ yr, $E_{e} \geq 498$keV)
- possible BG due to correlated coincidence by radiative Bremsstrahlung

**Goal**
1. Good energy resolution : $10\%$(FWHM)
2. Fine segmentation ($10^4$-$10^5$)
3. High efficiency $\gamma$ detection
Semi-insulating InP detector

- Mounted in vacuum dewar
- Semi-insulating InP VCZ substrate by Sumitomo Electric Industrials
- Assembled by Hamamatsu Photonics
- Operation at -79degree

Surface size:
- 10mm × 10mm × 0.2mm
- 6mm × 6mm × 0.2/0.23/0.28/0.45mm

Electrode:
- Ohmic contact
- evaporated Au/Cr base metal
- Insulator (SiN) to avoid leak current
Gamma ray spectrum observed by InP

- Measured clear photo-peak
- Induced charge collection ($L_{ed} \sim 200\mu m$, $L_{he} \sim 30\mu m$)
- Energy of electron-hole pair production: $3.5eV$
- Energy resolution: $25%@122keV$
IPNOS phase-I experiment for low energy solar $\nu$ experiment

InP multi-pixel detector inside of Liquid Xenon (LXe) with PMTs

30cm cubic chamber (like XMASS 100kg prototype) includes $\sim$10kg InP detector

$\sim10^3$ modules will be needed in the final IPNOS ($\sim$10ton InP)

Need larger area InP detector
Development of LXe chamber for IPNOS phase-I proto-type

- 24cc Liquid Xenon (LXe) in inner chamber
- 4 InP detectors mounted inside of LXe
- PMT (used for XMASS) detects sci. light from gammas
Cooling test of Liquid Xenon chamber
New InP crystal (low etch pit density)

EPD related to Lattice Defect which generates significant dark current
Zirconium Complex in Organic liquid Scintillator (ZICOS) for double beta decay experiment
Neutrinoless double beta decay

\[ [T_{1/2}^{0\nu}(0^+ \rightarrow 0^+)]^{-1} = G_{0\nu}(E_0, Z)|M_{0\nu}|^2 <m_\nu>^2 \]

\[ T_{1/2} \sim a(M_t/\Delta EB) \]
a: abundance, M: mass, t: meas. time, \( \Delta E \): energy res., B: BG rate

Requirement: Low BG, Large target mass, High energy resolution

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For future experiments

~tons of target will be needed for next generation detector

http://kds.kek.jp/getFile.py/access?contribId=37&sessionId=16&resId=2&materialId=slides&confId=9151
Studied isotopes

116\(^{\text{Cd}}\) → COBRA CdWO\(_4\)
76\(^{\text{Ge}}\) → GERDA MAJORANA
82\(^{\text{Se}}\) → SuperNEMO LUCIFER
136\(^{\text{Xe}}\) → KamLAND-Zen EXO NEXT
100\(^{\text{Mo}}\) → ZnMoO\(_4\) AMoRE
130\(^{\text{Te}}\) → CUORE

Nat(48)\(^{\text{Ca}}\) → CANDLES
Nat(150)\(^{\text{Nd}}\) → SNO+ Borexino

A dream?

48\(^{\text{Ca}}\) → CANDLES SuperNEMO AMoRE
150\(^{\text{Nd}}\) → SNO+ SuperNEMO MTD Borexino
Neutrinoless double beta decay using liquid scintillator

- Experimental limits for neutrino mass
- Requirement for $\langle m_\nu \rangle$: 50~100 meV
  - high energy resolution
  - 4%@2.5 MeV
  - low background rate
  - 0.01 count kg$^{-1}$ y$^{-1}$
  - ton scale of target

Liq. Scintillator is easy to scale up target mass
Detector concept design

- Spherical structure (Zr loaded 100ton LS)

Assuming 10w.t.% solubility
What’s problem

- Absorption spectra of \( \text{In(acac)}_3 \) (indium acetyl acetone) was overlapped with the emission spectra from Anisole (Chem. Phys. Lett., 435(2007), 252)

Same overlap of the emission and the absorption spectrum would be occurred even if different metal (Zr) was used.
Scontillation Light yield (\(^{60}\)Co) with respect to concentration of Zr(acac)\(_4\)
Zr β-diketon complex introducing substituent groups (β-keto ester complex)

\[
\text{Zr(CH}_3\text{COCHCOOCH(\text{CH}_3)})_4 = \text{Zr(iprac)}_4 \\
mw : 711.92
\]

\[
\text{Zr(CH}_3\text{CCOCHCOOCH}_3)_4 = \text{Zr(etac)}_4 \\
mw : 665.81
\]
Zr β-keto ester complex

Zr(iprac)$_4$+(iprac)$_{1.5}$
state: powder

Zr(etac)$_4$
state: dry solid

Synthesized by Prof. Takahiro Gunji (Tokyo University of Science)

Solubility > 10 w.t.% for anisole
Absorption spectra
Overlap with emission peak

Absorption peak of keto-ester complex

No overlap between emission and absorption
Development for new LS for IPNOS phase-II

- Liquid Scintillator containing indium β-keto ester complex

- Advantages
  - Easy to scale up for 10ton In in 100ton LS
  - Possible same design as ZICOS
  - Low energy solar $\nu$
    - $pp/^{7}\text{Be}$ and CNO $\nu$
    - Modulation using $^{7}\text{Be}$ $\nu$
  - Supernova $\nu$ burst
    - $\nu_e$ burst form

Neutralization

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Neutrinos from Neutralization burst

- **ν-nucleus σ**

  - ¹¹⁵In has ~10⁻³⁹ cm² for 20-100MeV compared with σ_{ννν}~10⁻⁴³ cm²
  - Sensitive to neutralization burst

- Nuclear synthesis (r-process)

- ν mass hierarchy

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Summary

- InP detector for IPNOS phase-I needs more larger area to reduce the number of channel. A new substrate will solve them.

- High solubility of Zr β-keto ester in Anisole (>~10w.t.%) for ZICOS detector was achieved.

- Confirmed absorption peak of beta-keto ester complex moves to shorter wavelength (275nm → 245nm). No overlap with emission spectra from anisole.

- Indium β-keto ester complex will be developed for IPNOS phase-II to measure both low energy solar neutrinos and supernova neutralization burst.