Low energy solar neutrino detectors with scintillators

Molybdenum Observatory Of Neutrinos

http://ewi.npl.washington.edu

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MOON is a “hybrid” solar $\nu$ & $\beta\beta$ experiment

Experimental evidences for oscillations in the $\nu_{\text{atm}}$, $\nu_{\text{solar}}$ & $\nu_{\text{reactor}}$ strongly indicate $\nu$ have mass and mixing, but tell only $\Delta m^2$

The absolute $\nu$ mass

$\Delta m_{\text{solar}}$

$\Delta m_{\text{atm}}$

normal

inverted

$\langle m_{\nu} \rangle \sim 0.01-0.06 \text{ eV}$

LMA region

Single and double beta decay


$\sqrt{\Delta m_{\text{atm}}^2}$

(0.35 to 1.3)

Current 0$\nu\beta\beta$ limit (68% C.L.)

$0.23 \text{ eV}$

WMAP
What’s next

Why perform low-energy solar neutrino experiments?

• Next I SNO 2nd phase
  - Status of maximal mixing
  - Matter effects
• Next I KamLAND reactor: $\Delta m^2$ determination

• Next II Low energy: challenge $\theta_{12}$
  - 99.99% of solar neutrinos $E < 5$ MeV
  - Redundancy + improvement: Identify the unexpected
  - Vacuum osc.
  - Luminosity constraint + $[^{7}\text{Be}]$ 5% + [p-p] 1-3%

Bahcall & Pena-Garay
hep-ph/0305159
Why $\nu_{\text{solar}}$ below 1 MeV

$^{100}\text{Mo}$

$^{176}\text{Yb}$
Low Energy exps: ES, CC

Small ES uncertainty

\[
[X]_{\nu-e} \sim P_{ee} + f(1-P_{ee})
\]

Better sensibility

\[
[X]_{CC} \sim P_{ee}
\]
+ p-p (pep) measurement

$\theta$ : Significant improvement

$\tan^2 \theta : 11\% \rightarrow 5\%$

and...

SSM independent at $< 0.01\%$

Bahcall & Pena-Garay
hep-ph/0305159
Exotic solutions

\[ R(^{7}\text{Be}) + 2R(\text{pp}) \sim 2 \cdot 0.2 \]

MOON: their ratio is independent of the B(GT)
# Real-time \textit{pp} solar-$\nu$ detector

<table>
<thead>
<tr>
<th>Detectors</th>
<th>Target</th>
<th>Detection Mechanism</th>
<th>Mass(T)</th>
<th>Threshold (keV)</th>
<th>SSM Rates/Yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOON</td>
<td>$^{100}$Mo</td>
<td>Solid/Liquid Scintillator</td>
<td>3.3 of $^{100}$Mo</td>
<td>168</td>
<td>399 \textit{pp}, 129 $^7$Be</td>
</tr>
<tr>
<td>LENS</td>
<td>$^{176}$Yb</td>
<td>Loaded Liquid Scintillator</td>
<td>10 Yb(nat)</td>
<td>301,445</td>
<td>146 \textit{pp}, 140 $^7$Be</td>
</tr>
<tr>
<td>LENS</td>
<td>$^{115}$In</td>
<td>Loaded Liquid Scintillator</td>
<td>4 In(nat)</td>
<td>118</td>
<td>365 \textit{pp}</td>
</tr>
<tr>
<td>InP</td>
<td>$^{115}$In</td>
<td>Solid state detector</td>
<td></td>
<td>118</td>
<td></td>
</tr>
<tr>
<td>SIREN</td>
<td>$^{160}$Gd</td>
<td>Loaded Liquid Scintillator</td>
<td>10 Gd(nat)</td>
<td>244</td>
<td></td>
</tr>
</tbody>
</table>

Radiochemical ---> HYBRID($^{37}$Cl), $^7$Li (for pep & CNO)

ES  XMASS, CLEAN, HERON, TPC, GENIUS etc....
Unique features for solar $\nu$

- CC real-time spectroscopic detector
- Low threshold $E_{th} = 0.168$ MeV
- Large matrix element, $0^+ \rightarrow 1^+$
- Ground state transition - matrix element can be measured
- $^{100}\text{Tc}$ decay (3.2 MeV-$\beta$, 15 s) tag large solar-$\nu$ capture rates

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>-Q(MeV)</th>
<th>pp</th>
<th>$^7\text{Be}$</th>
<th>$^{13}\text{N}$</th>
<th>pep</th>
<th>$^{15}\text{O}$</th>
<th>$^8\text{B}$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{71}\text{Ga}^c$</td>
<td>0.236</td>
<td>70.8</td>
<td>35</td>
<td>3.7</td>
<td>2.9</td>
<td>5.8</td>
<td>12.9</td>
<td>132</td>
</tr>
<tr>
<td>$^{100}\text{Mo}^d$</td>
<td>0.168</td>
<td>639</td>
<td>206</td>
<td>22</td>
<td>13</td>
<td>32</td>
<td>27</td>
<td>965</td>
</tr>
</tbody>
</table>

Charged-Current sub-MeV Real-Time:

**LENS:** Low Energy Neutrino Spectroscopy

**Method**
- charged current (CC) transition (inverse $\beta$-decay) to excited level ($\nu_e$ – only!)
- low-energy threshold: pp-, Be-7, pep,...
- $\nu_e$ – tag to discriminate against background
- $\nu_e$ – target (=Yb, In) loaded into liquid scintillator

\[ E_e = E_{\nu e} - E_{\text{thr}} \]

$\nu_e + (A,Z) \Rightarrow e^- + (A,Z+1)^* \quad \text{delay} \quad (A,Z+1) + \gamma$
The major BG

$^{100}\text{Mo}; \text{accidental coincidence } 2\nu\beta\beta \rightarrow 10^{19}$ y

$^{115}\text{In}; \text{that of the single } \beta \text{ decay } \rightarrow 4 \times 10^{14}$ y

The accidental rate $\propto (R_{\beta\beta})^2$ or $R_{\beta}^2$, $\Delta T$, $(N_0/K)$

$(R_{\beta\beta})^2$ is smaller by a factor $10^{-8}$ than $R_{\beta}^2$

$\Delta T$ for $^{100}\text{Mo}$ is longer by $3 \times 10^6$ than that for $^{115}\text{In}$

$N_0/K$ for $^{100}\text{Mo}$ with two $\beta$; smaller by $10^{-5} \sim 10^{-4}$

than $^{115}\text{In}$ with $\beta-\gamma$

$^{100}\text{Mo}$ better than $^{115}\text{In}$ by a several orders of magnitude

$^{176}\text{Yb}$ uses 50 ns delayed soft ($\sim 0.1$ MeV) $\gamma$-rays for tagging

$^{100}\text{Mo}$ uses 16 s delayed hard ($\sim 1.5$ MeV) $\beta$-rays
Requirements for MOON

- Large volume/mass of $^{100}$Mo $M \sim 1$ ton
- Two $\beta$ coin. $\Delta t \sim$ ns for $\beta\beta$, $\Delta t \sim 1$-30s solar-$\nu$.
- Dynamic range $E_\beta \sim 0.1$-40 MeV
- Energy resolution FWHM $\Delta E \sim 0.12/(E \text{ MeV})^{1/2}$
  - 7% for 3MeV ov$\beta\beta$.
- Position resolution $x \sim y \sim z = 2$-3 mm. $1/K \sim 10^{-9}$.
- Purity 0.1 ppt $10^{-3}$ Bq/ton for U, Th isotops.
Ongoing R&D:

• Mo Loaded Liquid Scintillator
  0.3 - 0.7% Mo by weight
  ~3.5 $\times$ $10^3$ photons/MeV

• Wavelength shifting fiber-readout

  $\Delta E \sim 2E^{-1/2} \sim 11\%$ at 3MeV
  $\Delta X \sim 0.8 \ E^{-1/2} \sim 0.5$cm

Need to increase photon yield by 2.5

• Hybrid(SciFi&Sci) detector

  Photon yields check

Anticipate ~2 year R&D, then freeze detector design
Hybrid detector

1. Position read-out by fibers with 2.2 m – 2.2 m - 0.4 mm
2. Energy read-out by 2–dimensional plane scintillator with 
   \( E \) resolution; \( \sigma \sim 2\% \), FWHM \( \sim 4.5\% \) including the Mo film.
3. Modest volume with enriched Mo and modest cost of MA / PM

One unit  2.2 m – 2.2 m – 2.2 m :  257 modules
One module  2.2 m – 2.2 m – 7.6 mm
PL 31.3 x 16.5 x 3 cm$^3$

PMT 2” (H1161)

$^{137}$Cs

LED & optical fiber
Multi-p.e. fit
$^{137}\text{Cs}$ Compton edge

PL 12 $\square$ 100 $\square$ 1.5cm$^3$
EL-V; NIMA302(1991) 304

$^{137}\text{Cs}(478\text{keV}) \sim 5736\text{photon}$
$\sim 4/18? \square \text{Q.E.(0.22)} \sim 280\text{ p.e.}$

PMT 2"(H1161) $\square$ 4
FWHM $\sim 12\%$
(7% @ 3MeV)

PMT 31.3 $\square$ 16.5 $\square$ 3cm$^3$
1 PMT
4 PMT

FWHM $\sim 12.6\% (348\text{p.e.})$
We can measure the energy by using Scintillator.

We can measure the position by using “Scintillation-Fiber”.

Size; Plastic Scintillator ~ 50cm × 50cm

$^{100}$Mo foil ~ 30cm × 30cm
MOON-I design

Good energy photon collection!

Scintillation Fiber readout (multi channel readout)
GEANT Simulation

*Energy loss of Mo-foil*

50 $\square$ 50cm$^2$ $^{100}$Mo

Hybrid detector
(PL + SciFi)

0.4 mm (x,y)

$\varepsilon_{\max}(E_{th}=0) \sim 28 \%$ with 6.6 mg/cm$^2$
(previously 20% with 50 mg/cm$^2$)
Summary

• Physics Objectives of low energy (Low-E) solar-ν well founded and defined

  *Ideal Wrap up for 35y Solar-ν program*

• MOON & LENS are both real-time Low-E CC experiment and complementary to each other to tackle in many issues.

• MOON is the **HYBRID** detector! **the key!**

  *Multi-purpose(ββ, solar-ν, SN-ν) & SciFi(position)+Sci(energy)*

• High position resolution and adequate time window for two β rays reduce all kinds of correlated and accidental BG.

• Following R&D, freeze the detector design, MOON-I will start soon
Welcome to MOON !!!