Future Experiments on sub-MeV Solar Neutrinos

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Solar Neutrino Physics after 50 years
Workshop in honor of John Bahcall
6th May, 2004 @Milano

• What we know
• Remaining Problems
• Future sub-MeV Experiments
• XMASS
What we know Multi-MeV

All the measurements have smaller uncertainty than that of the prediction (BP2000, 2004).

\[ \phi_{ES}, \phi_{cc}, \phi_{NC} \rightarrow \text{established neutrino oscillation} \]
Sub-MeV solar neutrinos
Measurements are only for the integrated flux

\[\Delta_{\text{pp-\nu}} \rightarrow 1\% \text{ uncertainty and very robust}\]

\[\text{pp-\nu} \rightarrow \text{a precise (a few } \% \text{ level) study} \rightarrow \text{low energy spectrum measurement}\]
Oscillation Solutions

All solar neutrino experiments + KamLAND

Best Fit:

$\sin^2 \theta = 0.28$

$\tan^2 \theta = 0.38$

$\Delta m^2 = 7.2 \times 10^{-5}$ eV$^2$

KamLAND Analysis from:
hep-ph/0302230v2 (A. Ianni)
Flux suppressions for LMA

- **pp-neutrinos**  
  $\approx 55\text{~59\%}$

- **$^7\text{Be}$-neutrinos**  
  $\approx 52\text{~54\%}$

- **In the sun (for LMA solutions)**
  - Low energy $\nu$ below $\sim 1$ MeV, never pass the resonance:
    - $\theta_m \rightarrow \theta_v$ (E < 1 MeV)  \[ P=1-(1/2)\sin^22\theta \]
  - $E_\nu > a$ few MeV: adiabatic  
    \[ P=\cos^2\theta\cos^2\theta_m + \sin^2\theta\sin^2\theta_m \]
    - $\theta_m \rightarrow \pi/2 \implies P=\sin^2\theta$
Aims of the Future
Solar Neutrino Experiments
(Neutrino Physics)

• Confirm (?) LMA or find small sub-leading effects
  – $^8$B (Spectrum upturn in low energy, Day/Night)
  – Matter to Vacuum transition
    • Low energy spectrum measurement
  – CPT test comparing with KamLAND
  – Sterile neutrinos? (best by pp-neutrinos)
  – ?

• Precise determination of mixing angle $\theta_{12}$
  – Best by pp-neutrinos
\(^8\text{B} \quad \text{Spectrum upturn in lower energies}

- Not yet seen either in SK nor SNO

\[ \tan^2 \theta = 0.42, \Delta m^2 = 6.0 \times 10^{-5} \text{eV}^2 \]

\text{Super-K}

\[ \text{Energy in MeV} \]

\[ \text{Data/SSM} \]

\text{SNO}

\[ \text{Statistics Limited} \]

\[ \rightarrow \text{More data, and extend to low energy (4MeV for SK)} \]

\text{Oritz/Winter}

\text{Winter (PRL2003)}

\text{Spectrum calculations: not matter to study upturn in low energy}
Lowering threshold

After install the lower trigger system, the efficiency above 4.5MeV (total) became 100% (Sep. 2000~)

Remaining B.G. for lower energy →gamma from the rock →radio isotope (e.g. Rn)

Tight gamma cut and fiducial cut
Note: the oscillatory behavior of the atmospheric neutrino

- The first dip has been observed.
- This provide strong evidence of neutrino oscillation.
- The first dip observed cannot be explained by other hypotheses.

\[ \chi^2_{\text{min}} = 37.8 / 40 \text{ d.o.f} \]
\[ \chi^2_{\text{min}} = 49.2 / 40 \text{ d.o.f} \rightarrow \Delta \chi^2 = 11.4 \]
\[ \chi^2_{\text{min}} = 52.4 / 40 \text{ d.o.f} \rightarrow \Delta \chi^2 = 14.6 \]
$^{8}$B -- Day-Night effect

- Not yet convincingly seen either in SK nor SNO

~1~2% effect

\[\Delta m^2 \text{ in } 10^{-4} \text{eV}^2\]

Solar & KamLAND

(SK Zenith Seasonal Spectrum)

\[\nu_e \rightarrow \nu_{\mu/\tau} (95\% \text{C.L.})\]

\[\sin^2(\Theta)\]

\[0.1 \quad 0.2 \quad 0.3 \quad 0.4\]

-0.6%
-1.0%
-1.8%
-3.2%
-5.6%
-10%

\[\Delta m^2 (\text{eV}^2)\]

\[10^{-5} \quad 10^{-4} \quad 10^{-3}\]

0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

\[0 \quad 0.01 \quad 0.1 \quad 0.5 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 10\]

\[0.013 \quad 0.013 \quad 0.013 \quad 0.013 \quad 0.013 \quad 0.013 \quad 0.013 \quad 0.013 \quad 0.013 \quad 0.013\]

\[0.007 \quad 0.007 \quad 0.007 \quad 0.007 \quad 0.007 \quad 0.007 \quad 0.007 \quad 0.007 \quad 0.007 \quad 0.007\]

\[0 \quad 0.013 \quad 0.013 \quad 0.013 \quad 0.013 \quad 0.013 \quad 0.013 \quad 0.013 \quad 0.013 \quad 0.013\]

\[-0.07 \pm 0.049 \quad +0.013 \quad -0.012\]

\[-0.018 \pm 0.016 \quad +0.013 \quad -0.012\]
Energy dependent suppression (Sub-MeV)

- **Ga measurement:** 72 ± 5 SNU
  - Prediction from Oscillation: 70 SNU
  - Consistent with Oscillation

- **Cl measurement:** 2.56 ± 0.23 SNU
  - Prediction from Oscillation: 2.98 SNU
  - 1.9 σ low
    - Contradict?, Hint?
    - Need more accuracy

➡️ Spectrum measurement in low energy
Search for sterile neutrinos

Charged Current (CC) $\rightarrow$ $\nu_e$ flux measurement
$\nu_e$ scattering (ES) $\rightarrow$ $\nu_e + \alpha(\nu_\mu + \nu_\tau)$ flux measurement

$pp \nu (\sigma = \pm 1\%)$ is the best for the search.

Note: Precise NC experiment in Low energy is also valuable
Sensitivity to the sterile neutrinos
(5yrs of data: ES & CC)

- ES: 10 ton Xe (XMASS) – 3300 events/year
- CC: 60 ton In (LENS) – 1477 events/year

Example (pp-\(\nu\))
- ES: 10 ton Xe (XMASS)
  - 3300 events/year
- CC: 60 ton In (LENS)
  - 1477 events/year

Depending on the experimental errors

< 5~6 % sensitivity for the sterile contribution

Current limit on sterile contribution: < 13% (1\(\sigma\))
(Bahcall and Pena-Garay, JHEP 0311:004, 2003)
Precise determination of $\theta_{12}$

- $\theta_{12}$ determination via KamLAND + pp experiments
  - $\nu_e$ scattering experiment
  - 10 ton (Xe) detector
  - 5 years data
  - Statistical error + SSM flux error

Accuracy of mixing angle:
$$\sin^2 \theta = 0.28 \pm 0.015 \text{ (stat.+SSM)}$$

KamLAND contour from K.Inoue

Precise determination of oscillation parameters by KamLAND + pp experiments
Importance for Astrophysics

- Photon luminosity and neutrino luminosity are consistent?
  - Is the sun a stable burning star?
  - Any other source of energy?
- How much fraction of solar energy come from CNO?
  - CNO is the next burning phase after pp-chain. Test CNO burning using the sun.
- Nuclear cross section in dense plasma and at very low energy is consistent with laboratory experiments?
  - e.g. S17 obtained by solar neutrinos is already as good as laboratory experiments
- Input parameters of SSM are correct?
  - Uncertainties in Z/X, opacity, ....
# Future low energy solar neutrino experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>reaction</th>
<th>detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>LENS</td>
<td>$\nu_e^{115}\text{In} \to e^{115}\text{Sn}, e\gamma$</td>
<td>60 tons In-loaded scintillator</td>
</tr>
<tr>
<td>MOON</td>
<td>$\nu_e^{100}\text{Mo} \to e^{100}\text{Tc}(\beta -)$</td>
<td>3.3 ton $^{100}\text{Mo}$ foil + plastic scintillator</td>
</tr>
<tr>
<td>Lithium</td>
<td>$\nu_e^{7}\text{Li} \to e^{-}^{7}\text{Be}$</td>
<td>Radiochemical, 10 ton lithium</td>
</tr>
<tr>
<td>BOREXINO</td>
<td>$\nu e^{-} \to \nu e^{-}$</td>
<td>100 ton Liquid scintillator ($^{7}\text{Be}$ only)</td>
</tr>
<tr>
<td>KAMLAND</td>
<td>$\nu e^{-} \to \nu e^{-}$</td>
<td>1000 ton Liquid scintillator ($^{7}\text{Be}$ only)</td>
</tr>
<tr>
<td>XMASS</td>
<td>$\nu e^{-} \to \nu e^{-}$</td>
<td>10 ton Liquid Xe (pp, $^{7}\text{Be}$)</td>
</tr>
<tr>
<td>HERON</td>
<td>$\nu e^{-} \to \nu e^{-}$</td>
<td>10 ton super-fluid He (pp, $^{7}\text{Be}$)</td>
</tr>
<tr>
<td>CLEAN</td>
<td>$\nu e^{-} \to \nu e^{-}$</td>
<td>10 ton Liquid Ne (pp, $^{7}\text{Be}$)</td>
</tr>
<tr>
<td>TPC type</td>
<td>$\nu e^{-} \to \nu e^{-}$</td>
<td>Tracking electron in gas target (pp, $^{7}\text{Be}$)</td>
</tr>
<tr>
<td>SNO</td>
<td>$\nu e^{-} \to \nu e^{-}$</td>
<td>1000 ton Liquid scintillator (pep, CNO)</td>
</tr>
</tbody>
</table>

- **CC experiments**
- **$\nu + e$ scattering experiments**
KamLAND ($^7$Be) status

(background spectrum)

$^7$Be $\nu$
KamLAND purification study

- Studying the efficient way to remove Pb210
  - Water extraction
  - Adsorption
  - Distillation

Most likely it will be funded this year??
SNO filled with liquid scintillator for pep, CNO neutrino (M.Chen in WIN03)

- $^{7}\text{Be}$, pep and CNO Recoil Electron Spectrum

Expected oscillated rate:
- $\sim 3000 \text{ pep/year/600ton} (> 0.8\text{MeV})$
- $\sim 3900 \text{ CNO/year/600ton} (> 0.8\text{MeV})$
SNO filled with liquid scintillator

$^{11}$C Cosmogenic Background

Estimated background after statistical subtraction

Muon rate:
- 70/day @SNO
- ~26000/day @KamLAND

from KamLAND proposal

M.Chen
XMASS

- Xenon MASSive Detector for Solar Neutrinos ($pp/^{7}\text{Be}$)
- Xenon Detector for Weakly Interacting MASSive Particles (Dark Matter Search)
- Xenon Neutrino MASS Detector (Double Beta Decay)
Why Liquid Xenon

- ~160°K; (LNe~27°K; LHe~40°K)
- Scintillation(~173nm;~42000photon/MeV ~ NaI) and Ionization
- Density ~3g, Z=56, radiation length ~2.4cm
  - Self-shields (against external incoming BG)
  - compact (2.44 m diameter for 23 tons)
- Low backgrounds
  - Various purification methods
    - Distillation, circulation during the experiment
    - bubbling, centrifugal, absorption column
    - Ion sweeping by the electric fields
  - No long life isotopes
- Reasonable Price ($1M~1ton: natural)
- Easy for isotope separation

We have 10kg enriched isotopes.

<table>
<thead>
<tr>
<th></th>
<th>124</th>
<th>126</th>
<th>128</th>
<th>129</th>
<th>130</th>
<th>131</th>
<th>132</th>
<th>134</th>
<th>136</th>
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</thead>
<tbody>
<tr>
<td>Natural</td>
<td>0.096</td>
<td>0.089</td>
<td>1.919</td>
<td>26.4</td>
<td>4.07</td>
<td>21.18</td>
<td>26.89</td>
<td>10.44</td>
<td>8.87</td>
</tr>
<tr>
<td>136 enriched (Even)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>136 depleted (Odd)</td>
<td>14.2</td>
<td>84.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

We have 10kg enriched isotopes.
Keys for the experiment (Challenge)

- \( \gamma \) (U/Th/K/Co/Cs/…)
- Self-shield
- Low energy thres.: High energy res.: Large photons: 70~80% PMT coverage
- External BG:
  - Self-Shield (effective also for the PMT BG)
  - Water tank
- Internal BG:
  - Distillation, Getter, and others
  - Possible to circulate
- \( \mu \)
- \( H_2O \) shield
- Neutron
- \( \alpha, \beta, \gamma \) rays from \( ^{85}Kr, ^{42}Ar, U/Th \)
Self-shield

• Quite effective for the events below ~500 keV (Solar neutrino and Dark Matter)
• Not effective for double beta decay experiment
Detector

- 10 ton fiducial mass
- 30 cm self-shields
- Total 23 ton

Solar Neutrino

expected spectrum

10 ton /5 yr

- Diameter:
  - 1.84 m for fiducial
  - 2.44 m for entire volume

- 3280 3” PMTs for 80% coverage

- 42,000 photons /MeV
  - QE 30%
  - Coll. eff. 70%
  \[ \Rightarrow 360 \text{ p.e. @}50\text{keV} \]
Event rate for 10 ton detector

- $\nu + e \rightarrow \nu + e$ scattering
- 10 pp and 5 $^7$Be ev/day/10ton (x ~ 60% (osc)) > 50 keV

C.f. SK : 13 events/day
Strategy for XMASS

100 kg detector
R & D

~ 1 ton (800 kg) detector
Dark matter search

~ 10 ton detector
Solar neutrinos
Dark matter search

dedicated detector for
Double beta decay search
R&D by the 100kg detector

- 30 litter liquid Xenon
- Oxygen free copper: 31cm
- 54 2 inch- PM T
  - Photo coverage ~ 16%
- 0.6p.e./keV
  (1/10 of the next stage 800kg detector)

**Proof of the Feasibility**
- Vertex and energy resolution
- Proof of the shelf-shields
- Characteristics of Xenon
  - Light yield, absorption length
- External and internal BG
- Creation of the Low BG environment
  - shield
  - Test of the purification system
• Shield for 100kg detector

- Polyethylene (15cm)
- Boracic acid (5cm)
- Lead (15cm)
- EVOH sheets (30µm)
- OFC (5cm)
- Rn free air (~3mBq/m³)
Development of the low BG PMT

Q.E. ~ 30% @ 175nm
Collection efficiency ~ 90%
Quartz window
Metal tube (low backgrounds)
Selection of the parts (measured by HPGe)
→ Low BG PMT base
~1/10 of the usual ones

| PMT base | U     | 1.5 ± 0.3x10^{-3} Bq |
|          | Th    | 3.2 ± 4.6x10^{-4} Bq |
|          | ^{40}\text{K} | 1.7 ± 2.9x10^{-3} Bq |

Aiming for another order of magnitudes improvement
Hexagonal PMT

Developing hexagonal PMT w/ Quartz window & metal tubes in order to increase the packing density
• Test experiment (100kg chamber) :
  
  December-2003

  - Data acquisition ~6 days (173°K, 1.5 atm)
    - Normal Run
    - γ-source run

[Diagram of the chamber setup with labels for pipe, lead, copper, source, vacuum chamber, and shielding.]
$^{137}$Cs photo-peak

Collimated gamma rays for three different positions

Real data

MC
Proof of the self-shield

Remove events w/ Saturation

Z = -15
Z = +15

137Cs (662keV)

60Co (1173 & 1333keV)

Data
MC
Data
MC

MC reproduces data very well.
We have demonstrated that the self-shield actually works.
• Energy Distribution

$^{137}\text{Cs (hole-A)}$  \hspace{1cm}  662 \text{ keV}

All volume

20cm fiducial

10cm fiducial

Resolution: $63 \text{keV@662keV}$

Energy scale & energy resolution

$\Rightarrow$ no significant position dependence
Background level

- MC calculation

\[ \gamma \text{-ray from outside of the shields} \]

\[ \text{from the PMT attached} \]

\[ \text{U-chain} \]

\[ \text{Th-chain} \]

\[ ^{40}\text{K} \]

\[ \text{Lead shield} \]
Data and effect of the self-shield

Central part of the detector is low BG due to the self-shield
Some excess around ~200~400keV

\[ 85\text{Kr at the level of 3ppb} \]

Please ignore excess at E < 100keV \[ \leftarrow \] Wall effect
Mis-reconstruction of the events near the corner
Typical for the cubic detector (100kg detector)
Do not exist for the spherical detector (~800kg detector)
\( ^{85}\text{Kr} \rightarrow ^{212}\text{Bi} \rightarrow ^{212}\text{Po} \rightarrow ^{208}\text{Pb} \)

\( ^{85}\text{Kr} \)

\( \tau_{1/2} = 10.756 \text{ year} \)

\( \beta \) (0.434\%) 173keV

\( ^{85}\text{Rb} \)

\( \beta \) (99.563\%) 687keV

\( \gamma \) 514keV

\( \tau_{1/2} = 1.015 \mu \text{s} \)

\( ^{212}\text{Bi} \)

\( \beta \) (Q=2.3MeV)

\( ^{212}\text{Po} \)

\( \alpha \) (8.8MeV)

\( ^{208}\text{Pb} \)

\( \tau_{1/2} = 299\text{ns} \)

\( ^{214}\text{Bi} \)

\( \beta \) (Q=3.3MeV)

\( ^{214}\text{Po} \)

\( \alpha \) (7.7MeV)

\( ^{210}\text{Pb} \)

\( \tau_{1/2} = 164\mu\text{s} \)
Summary of the internal BG of the 100kg detector

- The first measurements of the internal backgrounds in the 100kg detector were done.
- **Results**
  - $^{238}\text{U}$: $(48 \pm 8) \times 10^{-14}$ g/g
  - $^{232}\text{Th}$: $< 63 \times 10^{-14}$ g/g
  - Kr: $< 2.2\text{ppb}$ ($\beta+\gamma$)
  - $< 2\sim3\text{ppb}$ (687keV $\beta$)
Distillation to remove Kr

Boiling point is different

<table>
<thead>
<tr>
<th></th>
<th>Boiling P. (@1 atm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xe</td>
<td>165K</td>
</tr>
<tr>
<td>Kr</td>
<td>120K</td>
</tr>
</tbody>
</table>

Raw Xe

Processing speed: 0.6kg/hour

13 stage of

2cmφ

~3m

1/100

Off- gas (Kr rich)

Lower temp.

(2 atm)

Higher temp.

Purified Xe
Distillation

Test using 1.6kg Xe in Sep. 2003

Input Xe: 310ppb Kr

Gas-side Xe (1%):
45000 → 600 ppb Kr

Liq.-side Xe (99%):
< ~1ppb Kr

More than factor 300 (design:1/1000) reduction by one path.
Confirmed Krypton removal by distillation.

Below detection limit

2) Distillation of the 100kg Xe (in March)

Off-gas ~100 times concentration of Kr

Kr (in off-gas)
330 → 100 ppb

Raw Xe (100kg)
Kr ~3 ppb

Agreement with the spectrum data

Expected Kr concentration in Xe (single pass)
design value (~1/1000) → 0.003ppb
measurement (<1/300) → < 0.01ppb
Our target background levels for the 800kg detector would be feasible!

**Spin independent**

**Spin dependent**

Seasonal effect

Rate (spectrum)
Towards solar neutrino measurements

- External BG → Idea of self-shields works as expected

Simulation of 10 ton detector (Cubic → wall effect)
Towards solar neutrino measurements

- Internal BG
  (compare to the 800kg detector)

  \[
  \frac{1}{250} < \frac{1}{100} \sim \frac{1}{200}
  \]

**Requirements on internal BG**

- **\(^{85}\text{Kr}\): 0.687 MeV \(\beta\)**
  - \(< 4 \times 10^{-15} \text{g/g for Kr/Xe}\)

- **\(^{39}\text{Ar}\) (0.57 MeV \(\beta\), \(^{42}\text{Ar}\) (0.6 MeV \(\beta\)):**
  - \(< 1 \times 10^{-9} \text{g/g for Ar/Xe}\)

- **U/Th:**
  - \(< 1 \times 10^{-16} \text{g/g for U, Th/Xe}\)

- **\(^{136}\text{Xe}\) \(\beta\beta\):**
  - Need isotope separation
  - \(\tau_{1/2}^{\beta\beta} \geq 8 \times 10^{23} \text{y}\)
Summary

• Low Energy Spectrum measurement of solar neutrinos is important
• Need both CC and ES measurement are necessary
• XMASS is a promising detector to measure low energy solar neutrinos and also to look for dark matter
Backup
Confirmation of LMA or Remaining Problems
Most preceding $^7$Be experiment: BOREXINO

Stainless Steel Water Tank 18m ∅
Stainless Steel Sphere 13.7m ∅
Nylon Sphere 8.5m ∅
2200 8” Thorn EMI PMTs
100 ton fiducial volume
Pseudocumene Buffer
Steel Shielding Plates 8m x 8m x 10cm and 4m x 4m x 4cm
Scintillator
Holding Strings
Water Buffer

Muon veto:
200 outward-pointing PMTs
Nylon film
Rn barrier

Position of the balloon which is being mounted

PMT and DAQ are ready to go.
214Po $\alpha$ : 343 p.e.;
$\sigma = 21$ p.e. (~6%)
$E = 7.69$ MeV
$E_{\text{vis}} = 751$ keV
$\sim 460$ p.e./MeV

214Bi $\beta$ spectrum: end point at 3270 keV

source at the center of tank

from S.Schoenert
**LENS-Experimental Plan**

**LENS-Sol**
Liquid scintillator based
CC Solar Nu Experiment at Kimballton (VA USA)
(60 ton In; 750 ton InLS; 3000 ton In-free LS)
CC parameter Known only from (p,n) reactions.
Direct measurement integral part of precision experiment.

**LENS-Cal**
Precision (<3%?) Calibration of In CC (GT) parameter
By MCi $\nu$ Source (37Ar?) -- in BAKSAN, Russia
In metal foil/Plastic or LS Scint. Sandwich Detector
(5 ton In; 15 ton Scint)
LENS-Sol-Goal

Solar Nu Spectrum
At <2 MeV to probe pp, pep, $^7$Be, CNO in Sun

\[ \nu + \text{In} \rightarrow e^- + 2 \gamma + \text{Sn} \]

\[ E(e^-) = E(\nu) - 114 \text{ keV} \]

\( e^- \) tagged by isomeric

2 \( \gamma \) cascade decay (\( \tau \))

• Update: Recent values
• \( \sim 440 \text{pe/MeV} \)
In Liq. Scint.
Solvent PC
Scint Yield 42% @ 7% wt In
L(1/e)(430 nm) = 10 m

Update
New Safe Solvent: Phenylcyclohexane
F.P. 100C
Non-toxic
InLS/PCH
Scint Yield 42% of Solvent @ 7% In
Transparency Same as PC

Data from BNL