Development of InP detector for solar pp/^{7}Be neutrino measurement

Y.Fukuda[a] T.Izawa[d] Y.Koshino[b] S.Moriyama[b] T.Namba[c] S.Sakaihara[a] T.Sato[a] M.Shiozawa[b]
[a] Miyagi University of Education [b] ICRR, University of Tokyo [c] ICEPP, University of Tokyo [d] Solid state division, Hamamatsu Photonics K.K.

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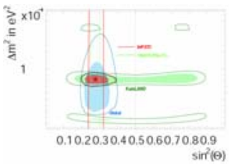
1. Introduction

◆ Purpose : Precise measurement of ν oscillation mixing angle θ_{12}

◆ Status of determination for ν oscillation parameter

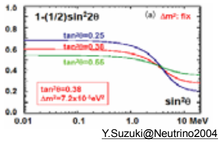


- 96%C.L. allowed region obtained by global fit
  LMA solution (blue) : Cl + Ga + SK (D/N spectrum)
  KamLAND (green) → confirm Δm_{12}^2

$27° < \theta_{12} < 37°$

mixing angle θ_{12} is not constrained compared with θ_{23} (obtained by Atm. ν)

Survival probability tends to increase in 5MeV or less in case of LMA solution, and shapes depend on θ_{12}.

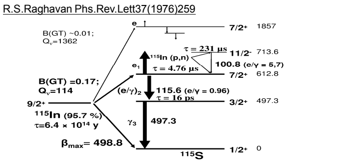


Amount of pp/^{7}Be ν should be observed

- **on-going solar pp/7Be experiment**
  - KamLAND (Liquid scintillator, electron elastic scattering (ES))
  - Borexino (Liquid scintillator, ES)
- **future solar pp/7Be experiment**
  - XMASS (LXe, ES, DIRK MATTER)
  - LENS (Liquid scintillator loaded In/Ye, charged current (CC))
  - CLEAN (LNe, ES)
  - MOON (^{100}Mo,CC)
  - SIREN (^{160}Gd, CC)

◆ Technique of low energy solar neutrino detection

R.S.Raghavan Phys.Rev.Lett37(1976)259



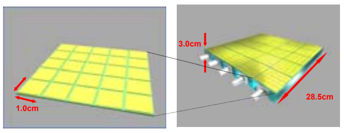
$^{115}In + \nu_e \rightarrow {}^{115}Sn^* + e^-$
$^{115}Sn^*(4.76\mu s) \rightarrow {}^{115}Sn + \gamma_1(115keV) + \gamma_2(497keV)$

- **Advantage**
  - direct counting
  - sensitive to low energy ν_e ($E_\nu \geqq 125$keV)
  - measuring the energy ($E_e = E_\nu - 125$keV)
  - Triple fold coincidence to extract neutrino signal from huge BG ($e_1 + \gamma_2 + \gamma_3$)
- **Disadvantage**
  - natural β-decay of ^{115}In ($\tau_{1/2} = 4.4 \times 10^{14}$ yr , Ee≧498keV)
  - Possible BG due to correlated accidental coincidence by Bremsstrahlung

◆Possible detector with 4tons of ^{115}In assuming 5 years operation

- Number of expected events assuming no ν oscillation → 1885
- Number of expected event assuming LMA solution with Ee≧100keV → 720

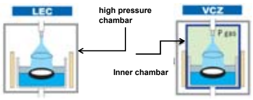
Statistical and theoretical error in total → ~3.9 % ⇒ θ_{12} = 29° - 34°



- **Hybrid structure of InP and solid scintillator**
  - InP detector module 10mmX10mmX0.2mm cell
  - Solid scintillator surrounding InP detector to detect γs
- **4tons of ^{115}In detector for solar ν experiment**
  InP : 5.1tons (2.1X10^6 modules)
  solid scintillator (ex. CsI) : 934tons
  total size : 6.3m X 6.3m X 5.3m

2. Semi-Insulating(SI) InP semi-conductor

● **VCZ (Vapor Pressure Controlled Czochralski)**

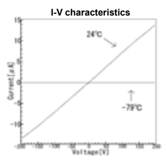


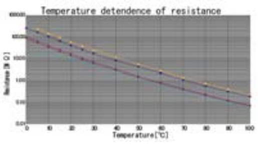
http://www.sei.co.jp/sc/technical/inp.html

- **Product : Sumitomo Electric Industries, Ltd.**
- **Process**
  In inner chamber controlled by steam pressure of As or P, covering material melt by B_2O_3 like LEC method and pulling up single crystal growth from it. Because of crystal growth in low temperature gradient, transition density can reduce.

● **Characteristic table**

EPD	~5,000cm^{-2}
Conduct	Semi-insulation
Dopant	InP(Fe)
Resistivity	(4.9~5.2)×10^{7}Ωcm
Mobility	(2.8~2.7)×10^{3}Ωcm
Thickness	456~459μm
Diameter	50.00mm
Orientation	(100)±0.03°





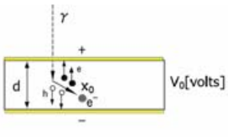
$I\,[A] \propto T^{2/3} \exp(-E_g/2k_\beta T)$

E_g : band gap (1.29eV)
k_β : Boltzmann constant
T : element temperature

Dark current could be reduced by lowering temperature

● **Characteristic of SI InP semi-conductor is both target and detector**

3. Proto-type detector with SI InP



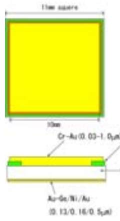
μ : mobility [m²V⁻¹s⁻¹]
v : carrier velocity [ms⁻¹]
E : electric field [vm⁻¹]
d : thickness of SI InP
x_0 : range of electron

$E = V_0/d \quad v = \mu E = \mu V_0/d$

drift length : $L_d = \tau v = \mu\tau V_0/d$ τ : carrier lifetime [s]
e/h creatrion energy : ε_{eh}
charge $Q_{total}[C]$=(electron energy)/$\varepsilon_{eh} \times e$
$L_d \fallingdotseq \infty$ $Q_{obs}[C] = \int_0^{x_0} (dE/dx)/\varepsilon_{eh}\, e^{-x(x)/L_d}\, dx \times e$

- Produced electron loses its energy, and creates electron-hole pair as carrier.
- Carrier moves along electric field.
- If drift length is enough to the thickness, charge collection efficiency achieves 100%.
- If the drift length is not enough, the carrier might be trapped by the impurity before the collection.
- Drift length is proportional to carrier mobility and electric field.

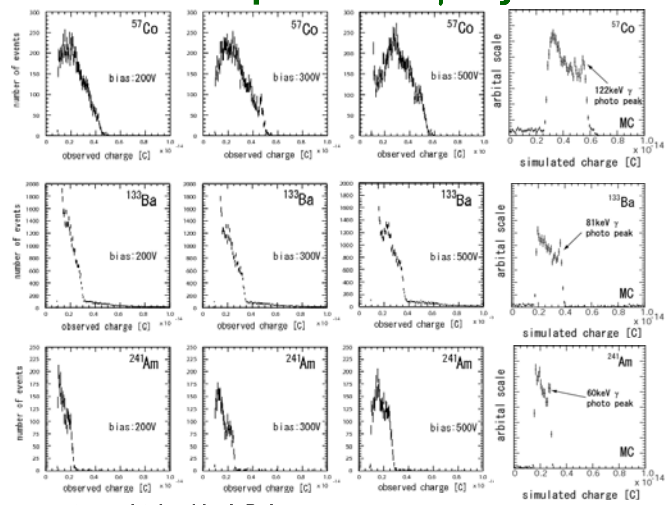
● **InP detector with cooling dewar**



Size:
10mm×10mm×0.2mm
Electrode :
- Ohmic contact
- Vacuum evaporation of Au base

Schematic view of InP detector

4.Response for γ-rays



γ spectrum obtained by InP detector

- Photo electric peak for 81keV (^{133}Ba), 122keV (^{57}Co) and 60keV (^{241}Am) were observed.
- However, two peaks were found.
- Lower peak position moved by increasing bias voltage.
- Lower peak was obtained by the carrier drift at outside of depletion layer.
- Higher peak corresponds to photo electric peak with charge collection.
- Average energy of electron/hole pair production is assumed by 3.5eV-4.0eV.
- Intrinsic energy resolution was obtained by MC σ=5%@122keV

Succeeded to develop InP detector used for hybrid detector module.

5. Background measurement

◆ Purpose : Measurement the natural β decay of ^{115}In and the Bremsstrahlung

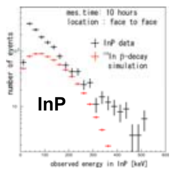
●Expected number of events

β decay : 68events/hour Bremsstrahlung : 0.0006 - 0.714 events/hour

●Configuration of InP detector and CsI scintillator

- CsI(Tl) scintillator : to detect Bremsstrahlung and other coincidence events with InP detector
  CsI crystal size : 50mm×50mm×20mm
  radiation shield : lead in 5cm thickness and oxygen free copper in 1cm thickness
- 4-π active veto plastic counter : to veto the cosmic ray

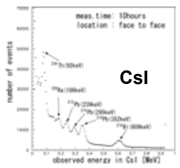
●Observed energy spectrum in InP detector



Observed spectrum has different shape from expected by β decay of ^{115}In

This could be explained by following noise

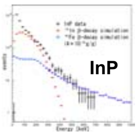
●Observed energy spectrum in CsI scintillator



Several peaks of γ rays caused by U/Th series were found

Background amount was calculated as a few 10^{-10}g/g

- **Observed events above 300keV**



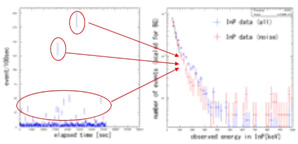
Semi-Insulating InP has Fe dopant

$^{60}Fe \rightarrow {}^{60}Co + e^- + \nu_e$
(Ee≦3.978MeV , $\tau_{1/2} = 1.5 \times 10^6$ yr)

Assuming 4×10^{-10} g/g ^{60}Fe contamination

⇓ consistent with ^{60}Fe of β decay

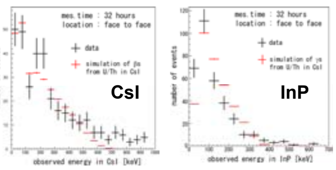
- **Observed events below 100keV**



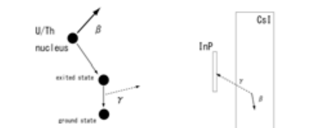
Low energy events contain human walking noise

⇓ might be due to the vibration

●Energy spectrum of coincidence events for CsI scintillator and InP detector



■ β , γ coincidence scheme



Some γs could escape from CsI scintillator and then InP detector detected them.

- Observed CsI scintillator spectrum was higher energy than expected spectrum by Bremsstrahlung.
- Radiative Bremsstrahlung might not be able to explain the dip around 200keV.
- Simulation assuming above scheme can explain the shape of spectrum both CsI scintillator and InP detector.

Most of coincidence events might be explained by U/Th series in CsI scintillator