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

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Abstract. A radiation detectors used a semi-insulating Indium Phosphide (InP) wafer for measurement of solar $pp/^7$Be neutrinos have been developed in last a few years. A volume of the detector has achieved to $20mm^3$. This detector observed γ-rays, and measured a peak for the photoelectric effect at -79 °C. The charge seems to be mainlly collected due to a carrier drift along to the electric field at outside of the depletion layer, and the efficiency is achieved by 60 to 70%. No clear Bremsstrahlung coincidence was seen in the background measurement.

1. Introduction

In 1998, Super-Kamiokande has reported an evidence that the atmospheric μ neutrinos oscillate into τ neutrinos [1], and the K2K experiment has confirmed the oscillation using ν_μ beam produced by KEK 1GeV Proton Synchrotron[2] in 2005. On the other hands, Super-Kamiokande and Sudbery Neutrino Observatory experiment has established the ν_e oscillation for the solar neutrino observation in 2001, and a long way problem called Solar Neutrino Problem in past 30years was almost resolved by LMA oscillation. Independently, KamLAND experiment confirmed the oscillation in the LMA using reactor $\overline{\nu_e}$ in sense of Δm^2 [5]. However, the oscillation mixing angel (θ_{12}) was not pointed out as well as θ_{23} observed in the atmospheric neutrino data. Next step of neutrino physics should be to measure the precise oscillation parameter and CP phase. For instance, a valuable θ_{13} measurement should be done as soon as possible by J-PARC accelerator experiment nor the reactor experiment such as Double Chooz.

For the future solar neutrino experiment, a presise θ_{12} measurement should be done with 1% accuracy for restriction of GUT model. For that purpose, not only a flux but also the spectral shape of solar $pp/^7$Be neutrinos will be necessary.

2. Solar $pp/^7$Be neutrino experiment using ^{115}In

Recently Borexino has reported that the first detection of ^{7}Be neutrinos signal using low background liquid scintillator [6]. Because of precise analysis for low energy background, they will give us clear spectrum of recoiled electrons in near future. However it seems to be very difficult to detect *pp* neutrinos even though they establish the finite value of ^{7}Be neutrinos flux.

In 1976, R.Raghavan proposed the measurement of low energy solar $pp/^7$Be neutrinos [7] via following reaction $^{115}\text{In} + \nu_e \rightarrow^{115} \text{Sn}^* + e^-$. The prompt electron has an energy with $E_\nu - 125keV$, here E_ν is an energy of incident neutrinos, therefore the neutrino spectroscopy would be realized. An excited state of ^{115}Sn decays into the ground state with a lifetime of 4.7 μs, and emits two gammas (116keV and 487keV). This signature is also able to use for a triple-coincidence to extract neutrino signal from huge backgrounds. However, ^{115}In itself has natural beta decay into the ground state of ^{115}Sn with a lifetime of 4.41×10^{14} years. The Bremsstrahlung could produce fake coincidence for neutrino signal. Therefore a fine segmented with well energy resolution detector is necessary [8].

3. InP solid state detector

Many possible detectors using indium were designed in last few decade, however, no realistic detector has been made. A liquid scintillator solved indium was developed by Suzuki [9]*et. al* and LENS project [10]. Recently the LENS group presented the feasibility of realistic way to build a big scale detector [11], but there might be exist the difficulties of the transparency with respect to the weight of solvent. In 1988, Suzuki and Fukuda developed the InP solid state detector with the pn-junction and the detector observed the gammas from the radioactive sources. [12]. The detector size was very small($1mm^2 \times 10\mu m$), however, the prototype detector could observe the low energy 60keV gammas with the energy resolution of 5.5%.

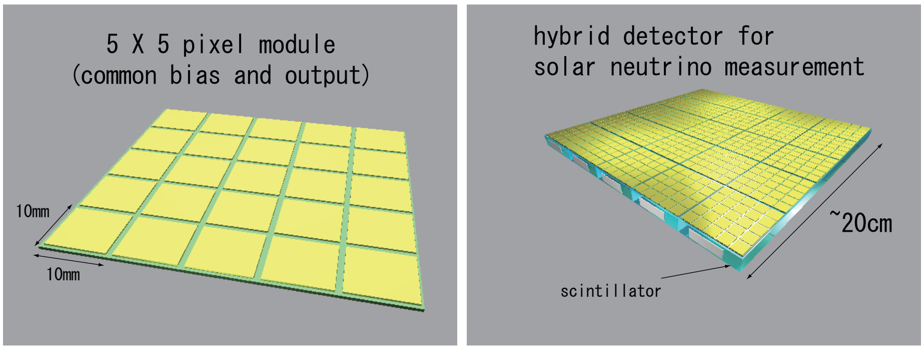

Figure 1. Possible detector design for $pp/^7$Be solar neutrino measurement. Left figure shows one module as multi-pixel combination, and right figure shows the hybrid structure consist of multi-pixel InP module surrounded by scintillation counter for detection of two gammas.

New detector using InP semi-conductor has been re-evaluated for last several years. The semi-insulating (SI) InP wafer is commercially produced for the optical devices. Typical dopant is Fe and the crystal is usually grown by the liquid encapsulated Czochralski (LEC). Some radiation detectors have been developed by the SI InP wafer. The ESTEC group have characterized a 0.18 mm thick of InP at -60 °C achieving 8.5 keV FWHM at 60 keV[13], and Italy group obtained 11 keV FWHM at 122 keV with 0.25 mm thick SI InP at -60 °C[14]. There is other crystal growth method, namely the Vertical Gradient Freeze (VGF), which is relatively higher resistance and naturally smaller EPD than LEC. A radiation detector using the VGF SI InP wafer is developed by UK group[15], and our group. All developed detectors, however, have a small volume of the order of $1mm^3$ or less except us, and it is hard to use for solar neutrino experiment.

It is possible to be solar neutrino detector using InP solid state detector, if the detector have a massive. If the InP detector have an order of 1g, which corresponds to $10mm \times 10mm \times 0.2mm$, then 10^6 order of detector are necessary for the actual detection of solar neutrinos. We need to combine such small detector as multi-pixel as shown in left side of Fig.1. According to this idea, 5×5 detectors are combined as one module, so same bias voltage should be applied and also the signal line also should be common. Another feature is the detection of gammas from ν_e capture process by ^{115}In nuclei. These 116 keV and 497keV gamma-ray could escape from the original wafer of InP, so other detector should detect them efficiently. Therefore we design a hybrid structure that the scintillation counter surrounded InP module as shown in right side of Fig.1.

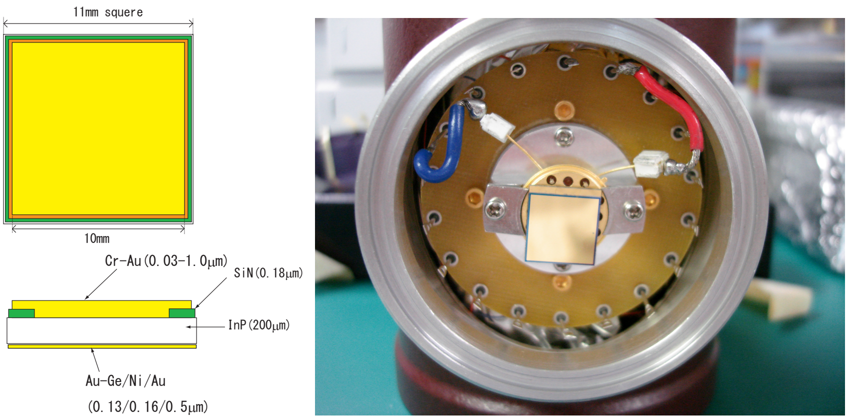

Figure 2. Left figure shows the schematic view of the proto-type detector. The detector size is $10mm \times 10mm$ in surface, and $0.2mm$ in thickness.

We have developed large volume detectors using another wafer produced by Sumitomo Electrical Industry Co. LTD with the method of Vapor Czochralski (VCZ). The schematic view and actual surface view of InP detector is shown in Fig.2. Hamamatsu Co. LTD actually produced two types of InP detector with $7mm \times 7mm$ and $10mm \times 10mm$ in surface, and $0.2mm$ in thickness. The detector volume corresponds to $10mm^3$ and $20mm^3$, respectively. The electrodes consist of Cr-Au with $1\mu m$ thickness for top and Au-Ge/Ni/Au with 0.13/0.015/0.5 μm thickness for bottom side. The junction between an electrode and the InP wafer are ohmic contact in room temperature, however actually a Schottky barrier has been formed at Dry-Ice temperature (-79 °C), because of the rectification in the Hall effect measurement. The InP detector is assembled in the vacuum chamber due to cooling by Dry-Ice as shown in photograph of Fig.2.

The leakage current as a function of the bias voltage which were measured at room temperature is shown in Fig.3. Typical current value is 40μA at 100V bias. The dark current could be reduced by lowering the temperature as followed formula; $I \propto T^{\frac{2}{3}} exp(-\frac{E_g}{2k_BT})$; here I[A], T[K], E_g, and k_B show dark current, temperature, band gap (1.29eV in case of InP), and Boltzmann constant, respectively. Typical value of dark current at -79°C is 5nA at 400V bias.

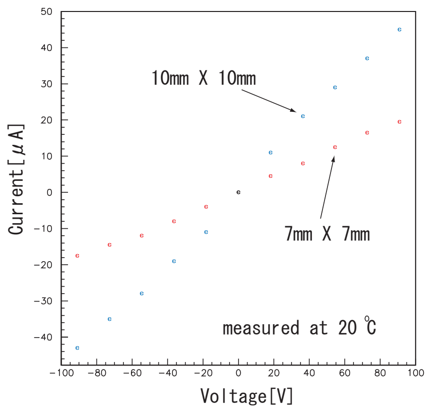

Figure 3. The leakage current as a function of bias voltage. Basically the current is same even though the positive or negative bias voltage.

4. Performance of InP detector

The performance of InP detector was measured by using gammas emitted by usual radio active sources. Carriers generated by the energy deposit of electrons via photoelectric process or Compton scattering are drifted along to electric field and reached the electrode. The expected charge could be evaluated by $Q[C] = \int_0^R \frac{dE/dx}{\epsilon} \mathrm{e}^{-\frac{r(x)}{L_d}} dx \times e$. Here, L_d is carrier drift length, ϵ is an average energy for electron/hole pair production, R is electron range, and $r(x)$ is distance from electrode. Generally speaking, the carrier drift length is expressed by $L_d \equiv \mu\tau\frac{V_0}{d}$, here μ is the carrier mobility, τ is life-time of the carrier trapping. V_0 is the bias voltage, and d is thickness of the wafer. In the depletion layer, carrier life time is long enough to the drift time, so the observed charge should be same as $N_{eh} \times e$. For the measurements of gammas, the detector should be cooled by -79 °C using Dry-Ice.

Figure.4 shows that the observed charge distribution of 122keV, 81keV and 60keV gammas using $7mm \times 7mm$ detector at several bias voltage. At lower bias voltage, there is no clear peak from the photo-electric interaction. As higher bias voltage applied, there found two peaks. For instance, the peak for 122keV gamma-ray appears around 0.3×10^{-14} C and 0.55×10^{-14} C. Higher charge peak is produced by the charge collection of depletion layer, and it is consistent with the charge collection assuming by 3.5eV for an average energy of electron/hole pair production. This assumption is also consistent with the fact that the peak position was not changed as increasing bias voltage. On the other hands, lower charge peak appeared above 400V and moves higher charge position rapidly. The collection efficiency for lower peak is obtained by the 56% in case of 122keV γ, and this peak was formed by charge collection due to carrier drift outside of the depletion layer.

Also Figure.5 shows that the observed and simulated charge distribution of each gamma using $20mm^3$ detector at 500V bias voltage. The spectral shape are almost same as ones obtained by $10mm^3$ InP detector, and therefore the charge collection should be same. According to the Monte Carlo simulation, the spectral shape could reproduce assuming both $L_d = 250\mu m$ and $20\mu m$ for the thickness of depletion layer as shown in Fig.4 and Fig.5. The number of events form each isotopes are increased by 3.1 times as compared with 2.8 times larger surface area (solid angle). Therefore, an effective area actually spread out as expected, and the performance is stable.

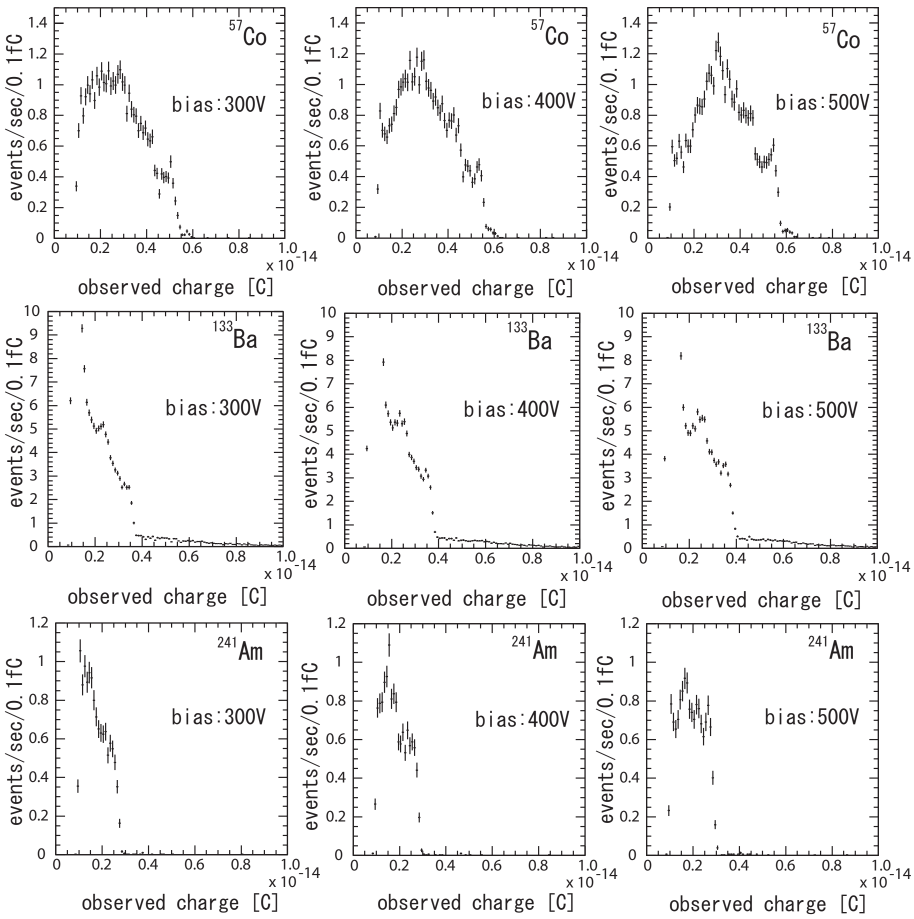

Figure 4. Observed and simulated charge distributions for gamma-rays are shown.

5. Background measurement

Using $20mm^3$ InP detector, we tried measured the natural beta decay of ^{115}In and the effect of Bremsstrahlung as fake coincidental backgrounds. In order to detect Bremsstrahlung and other coincident events from InP detector, we used CsI(Tl) scintillator produced by SCIONIX for detection of such backgrounds. The CsI size is $50mm \times 50mm \times 20mm$ and assembled by the photomultiplier. Figure6 shows the configuration of InP detector and CsI scintillation counter. These two detectors are located by face to face for measurement of ^{115}In β decay and the effect of Bremsstrahlung. For the accidental events, these are located by back to back. These detectors are located in the radio-active shield which consist of the lead in 5cm thickness and the Oxygen free copper in 1cm thickness for the low radio-active background environment. Also, in order to avoid the background due to the cosmic ray and the external radiation, 4-π active veto plastic counter surround the shield.

For the measurement of β decay of ^{115}In, the isolated events were observed in InP detector as seen in Fig.7. The coincident events are rejected in this figure. The measurement time is 10 hours, and the expected number of β decay is 680. The observed events are clearly larger than the expected number of β decay. The expected energy spectrum for ^{115}In β decay is also shown in left of Fig.7. For low energy events blow 100keV, we assume those as backgrounds due to the vibration. The detector was so cooled that the floated capacitance between InP detector and the charge amplifier affected to generate noise which is sensitive to the vibration. This is confirmed

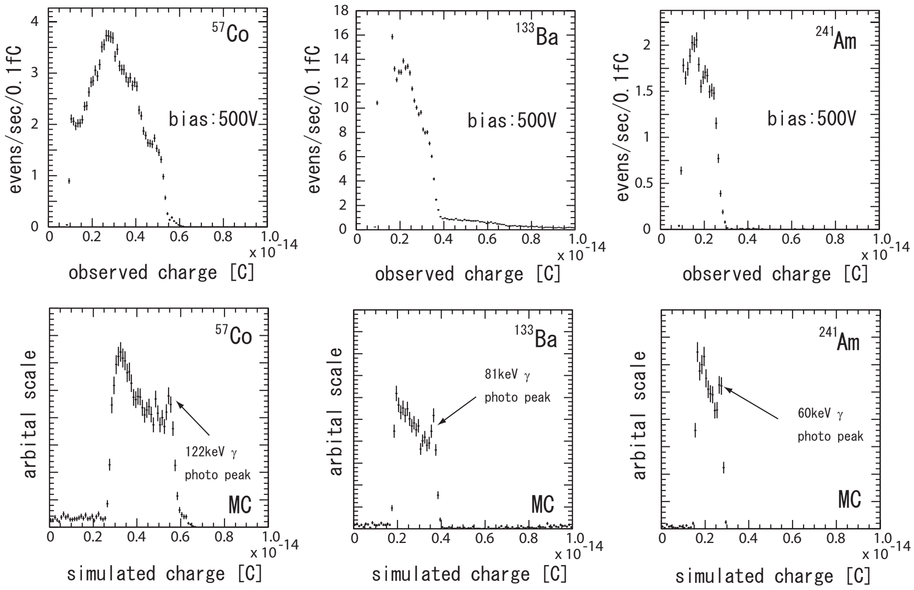

Figure 5. Observed and simulated charge distributions for gamma-rays are shown.

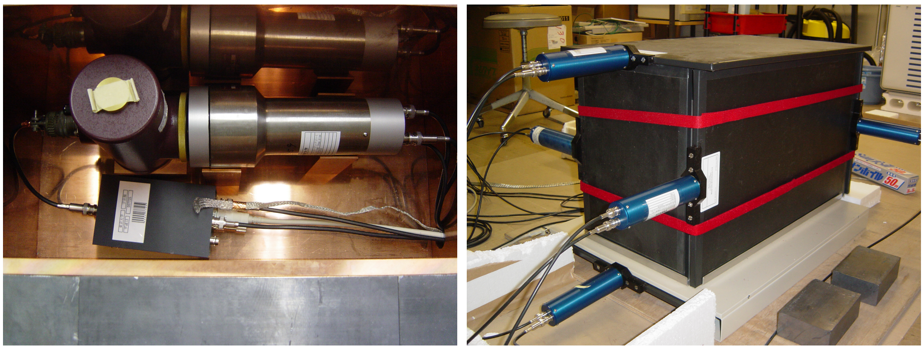

Figure 6. Configuration of InP and CsI detector. These are located face to face to detect ^{115}In β decay and the Bremsstrahlung from InP detector. For low radio-active background environment, the shield consist of lead in 5cm thickness and oxygen free copper in 1cm thickness. 4-π active veto plastic counter surrounded the shield in order to veto the cosmic ray and external incident radiation.

by main amount of fraction in those events due to the accidental vibration happened in other period as shown in right of Fig.7. Assuming the events blow 50keV to be noise events due to the vibration, the expected energy distribution is consistent with the observed distribution as shown in Fig.8. Observed events above 400keV in InP data is still inconsistent with the spectrum from β decay of ^{115}In. According to the measurement of U/Th natural activity using ultra-low background germanium detector located in Kamioka mine, the semi-insulated InP wafer contains those activity as order of 10^{-11}g/g. This amount of backgrounds could not explain these events. Another possibility is iron (Fe) which is used for the dopant of InP crystal. ^{60}Fe nuclei decays into ^{60}Mn with β^- ($E_e \leq 3.978$MeV, $T_{\frac{1}{2}} = 1.5 \times 10^6$years). Assuming ^{60}Fe radio-active background contaminated an order of 10^{-10} g/g, then the expected energy spectrum in InP detector are very consistent with the observed spectrum as shown in right of Fig.8.

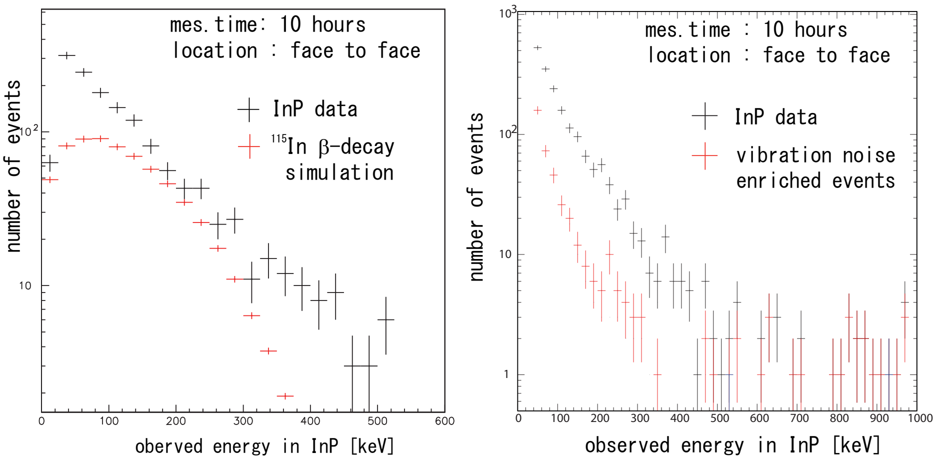

Figure 7. Observed energy distribution in InP detector. It is not consistent with the expected spectrum from β-decay of ^{115}In. Lower energy events with $E \leq 100$keV are consistent with the backgrounds due to the vibration.

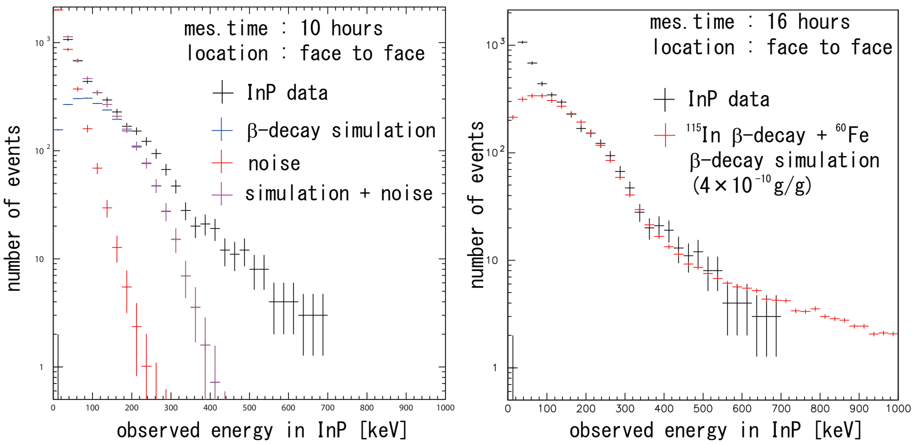

Figure 8. Observed energy distribution on InP detector assuming the noise due to the vibratio for the events blow 50 keV, and assuming ^{60}Fe nuclei decays.

For a measurement of Bremsstrahlung effect from βdecay of ^{115}In, it should take a coincidence between InP detector and CsI counter. In case of location of those detectors as face to face, there was 105 events found in the 10 hours measurements as shown in Fig.9. On the other hands, the coincidence was taken however the location of those detectors as back to back should be accidental noise as shown in Fig.10. Number of those events was 15 during 10 hours. This is consistent with number expected by the accidental coincidence of event rate for each detector. The energy spectrum of InP detector also indicates that those should be noise due to the vibration. Before concerning of events shown in Fig.9, it is necessary to take into account the U/Th natural backgrounds in CsI counter, Figure 11 shows the energy spectrum of single triggered by CsI counter. It is clearly seen that characteristic photo peak due to specified U/Th nuclei as listed in Fig.11. This means that the several 10^{-10}g/g order of U/Th could be contaminated in CsI counter. The amount is usual however it becomes non negligible backgrounds. Those nuclei generally decay with both γ and β, so that the some *gamma* could

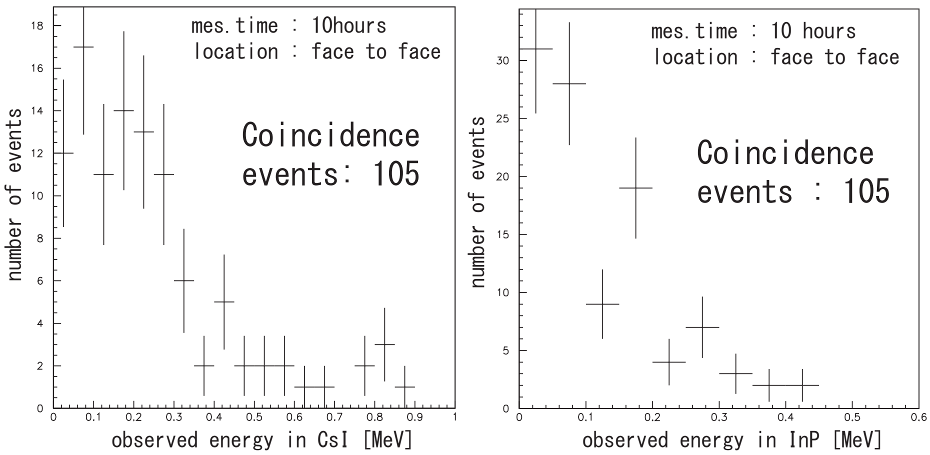

Figure 9. Energy spectrum of coincident events for CsI counter and InP detector located by face to face.

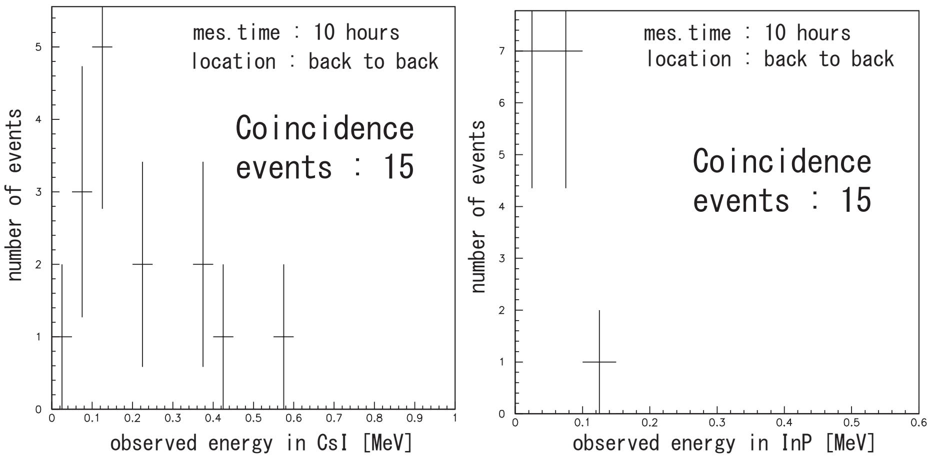

Figure 10. Energy spectrum of coincident events for CsI counter and InP detector located by back to back. These events should be accidental.

escape from CsI counter and enter into InP detector as shown in right figure of Fig.11. Using this scheme, Monte Carlo simulation was done inside of CsI counter to the InP detector. Figure12 shows the energy spectrum of coincident events between InP detector and CsI counter and the simulated energy spectrum are overlapped. According to these figures, most of coincident events between InP detector and CsI counter are caused by the U/Th natural backgrounds in CsI counter, and no clear evidence of Bremsstrahlung effect which should be observed blow 50keV was appeared. Another possible backgrounds to be concerned is radiative β decay from ^{115}In. This is similar to Bremsstrahlung however the much higher energy could be carried to the radiation. We concluded that this effect should be small because of spectral shape of InP detector for coincidence events is different from the expected shape of β decay, and small amount events can be seen in lower energy region. In the actual case for the measurement solar neutrinos, these kinds of related β decay backgrounds should be negligible due to a few μ seconds of time difference between InP detector and surrounded scintillator.

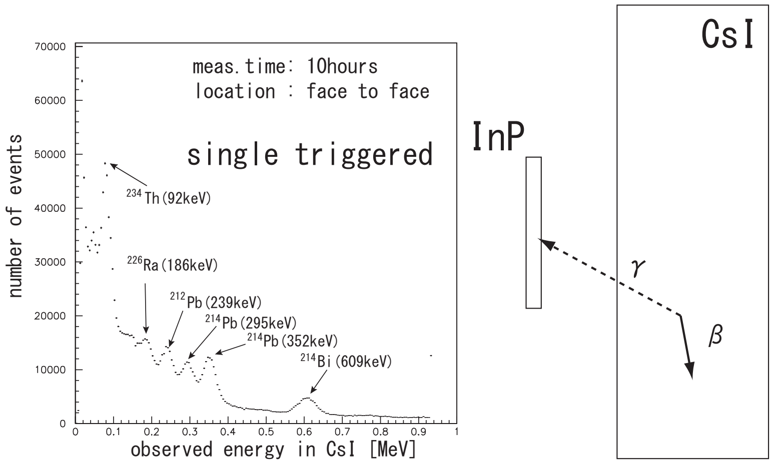

Figure 11. Energy spectrum of natural U/Th series observed in CsI counter. Due to these backgrounds, some *gamma* could escape from CsI counter and then enter into InP detector as shown in right figure. This is scheme that coincident events in face to face.

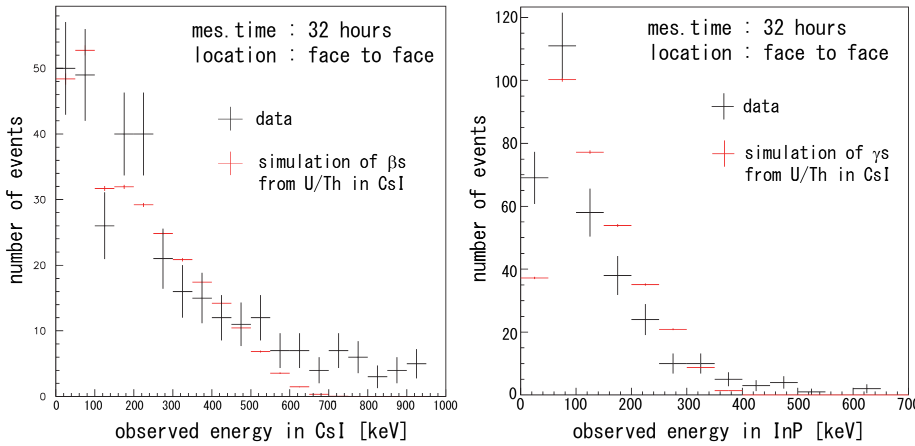

Figure 12. Energy spectrum of coincident events for CsI counter and InP detector for 32 hours data, and the expected spectrum from above scheme is overlapped.

6. Conclusion

An InP detector with large volume has been developed, and obtained good performance as concerned with radiation detector. Observed charge spectra could be explained by the carrier drift with $250\mu m$ and the collection efficiency is achieved by 60 to 70 %. This is the first time to demonstrate InP detector with a bulk size crystal, and the detector performance shows us that it is possible to use for solar $pp/^7$Be neutrino measurement. Backgrounds in InP detector seems to be very small even though amount of ^{60}Fe is order of 10^{-10}g/g. No effect of Bremsstrahlung can be seen in the background measurement, and it is very important that the low level of radio activity for surrounded scintillator should be selected.

Acknowledgments

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