

# InP solid state detector and the observation of low energy solar neutrinos

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## Abstract

A large volume radiation detectors using a semi-insulating Indium Phosphide (InP) wafer have been developed for Indium Project on Neutrino Observation for Solar interior (IPNOS) experiment. The volume has achieved to  $20\text{mm}^3$ , and this is world largest size among the detector observed gammas at hundred keV region. Although the depletion layer, most of charge are generated by an induction, and the charge collection efficiency achieves 50 to 60%, which is determined by the detector thickness and the carrier drift length ( $L_d = 120\text{ }\mu\text{m}$ ). The energy resolution is obtained by 25%. We measured actual backgrounds from  $^{115}\text{In}$  beta decay, and also the effect of radiative Bremsstrahlung from those betas. No significant event was found in the measurement and the radiation such as Bremsstrahlung from InP detector could be negligible.

**Key words** : low energy solar neutrinos (低エネルギー太陽ニュートリノ)  
neutrino oscillation (ニュートリノ振動)  
stellar evolution (恒星進化)  
indium (インジウム)  
solid state detector (半導体検出器)

## 1. Introduction

In 1998, Super-Kamiokande has reported an evidence of atmospheric  $\mu$  neutrino oscillation [1] for the first of the world, and the K2K experiment has confirmed the oscillation using  $\nu_\mu$  beam produced by KEK 1 GeV Proton Synchrotron [2] in 2005. On the other hands, Super-Kamiokande and Sudbery Neutrino Observatory experiment has established the  $\nu_e$  oscillation from solar neutrinos in 2001 [3, 4], and a long way problem so called Solar Neutrino Problem in past 30 years was almost solved by LMA oscillation. Independently, KamLAND experiment confirmed the oscillation using reactor  $\bar{\nu}_e$  in sense of  $\Delta m^2$  [5]. However, the oscillation mixing angel ( $\theta_{12}$ ) was not pointed out as well as  $\theta_{23}$  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  $\theta_{13}$  measurement should be done as soon as possible by T2K experiment and the reactor experiment such as Double Chooz. For the future solar neutrino experiment, a precise  $\theta_{12}$  measurement would be done with 1% accuracy. In this point of view, new experimental technique to measure not only flux but also energy of solar

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$pp/\bar{\nu}^7$  Be neutrinos will be necessary due to the direct observation of upturn of the neutrino spectrum. On the other hands, Helioseismology shows us the information of the interior of the Sun using observations of slight motion on the surface. Most of analytic results are consistent with predictions of the standard solar model, however, still small difference of frequency less 0.5% in the intrinsic mode between the observation and the model remains. Therefore, low energy neutrinos from not only  $pp$ -chain but CNO cycle are also important for direct investigation of solar interior on the stellar evolution theory. We are going to plan the experimet of low energy solar neutrino observation, so called, Indium Project on Neutrino Observation for Solar interior (IPNOS), for these objects.

## 2. Low energy solar neutrino experiment using $^{115}\text{In}$

Traditional technique used in KamLAND, Borexino [6] and Super-K is an elastic scattering of electron with induced neutrinos. Radio-chemical technique used in  $^{37}\text{Cl}$  and  $^{71}\text{Ga}$  is a neutrino capture using special nuclei which has a large cross section. Former case could measure both flux and energy of incident neutrinos with relatively higher energy, but later could only averaged flux. Most difficult problem is caused by natural radio activity backgrounds which emit low energy gammas and betas. In 1976, R.Raghavan proposed new technique for the measurement of low energy  $pp/\bar{\nu}^7$  Be solar neutrinos [7] via following reaction;



The prompt electron has an energy with  $E_\nu - 125$  keV, here  $E_\nu$  is an energy of incident neutrinos. Therefore the neutrino spectroscopy can be realized. An excited state of  $^{115}\text{Sn}$  shown in Eq. (1) decays into the ground state with a lifetime of  $4.7 \mu\text{s}$ , and emits two gammas (116 keV and 497 keV). This signature is also able to use for a triple-coincidence to extract neutrino signal from huge backgrounds. However,  $^{115}\text{In}$  itself has natural beta decay into the ground state of  $^{115}\text{Sn}$  with a lifetime of  $4.4 \times 10^{14}$  years. The radiative Bremsstrahlung could produce fake coincidence for neutrino signal. To avoid this, a fine segmented with well energy resolution detector is necessary [8].

Many possible detectors using indium were designed in last few decade, however, no realistic detector has been made. 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 [9]. The detector size was very small ( $1\text{mm}^2 \times 10 \mu\text{m}$ ), however, the prototype detector could observe the low energy 60 keV gammas with the energy resolution of 5.5% . For large volume detector, a liquid scintillator solved indium was developed by Suzuki [10] and LENS project [11]. Recently LENS group presented the feasibility of realistic way to build a big scale detector [12], but there might be exist the difficulties of the transparency with respect to the weight of solvent.

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  $-60^\circ\text{C}$  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  $-60^\circ\text{C}$  [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  $1\text{mm}^3$  or less except us, and it seems to hard to use for solar neutrino experiment.

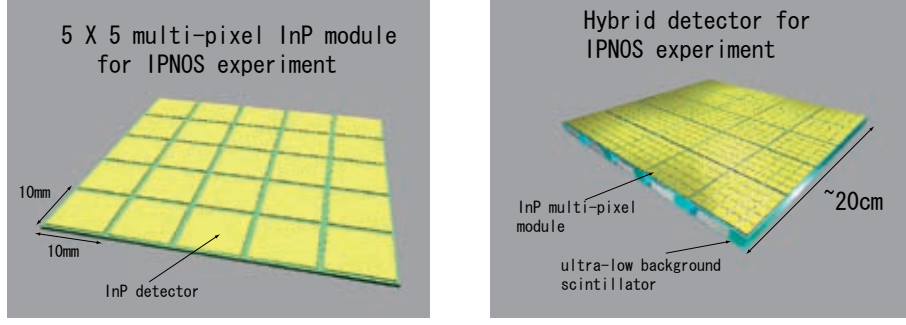


Figure 1. Possible detector design for IPNOS experiment. Left figure shows one module as multi-pixel combination, and right figure shows the hybrid structure consist of multi-pixel InP module surrounded by scintillator for detection of two gammas.

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  $10\text{ mm} \times 10\text{ mm} \times 0.2\text{ mm}$ , 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,  $5 \times 5$  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  $\nu_e$  capture process by  $^{115}\text{In}$  nuclei. These 116 keV and 497 keV gammas could escape from the original wafer of InP, so other calorimeter should detect them efficiently. The IPNOS detector will consist of a hybrid structure that InP modules surrounded by the ultra-low background (solid) scintillator as shown in right side of Fig. 1.

### 3. Performance of InP detector

We have chosen another wafer produced by Sumitomo Electrical Industry Co. LTD with the method of Vapor pressure controlled Czochralski (VCZ). Hamamatsu Co. LTD developed InP detector with  $10\text{ mm} \times 10\text{ mm}$  in surface, and  $0.2\text{ mm}$  in thickness. The electrodes consist of Cr-Au with  $1\text{ }\mu\text{m}$  thickness for top and Au-Ge/Ni/Au with  $0.13/0.015/0.5\text{ }\mu\text{m}$  thickness for bottom as shown in Fig. 2. The junction between electrode and InP are ohmic contact in room temperature, however actually a Schottky barrier could be formed at low temperature, because of the rectification in the measurement of Hall effect.

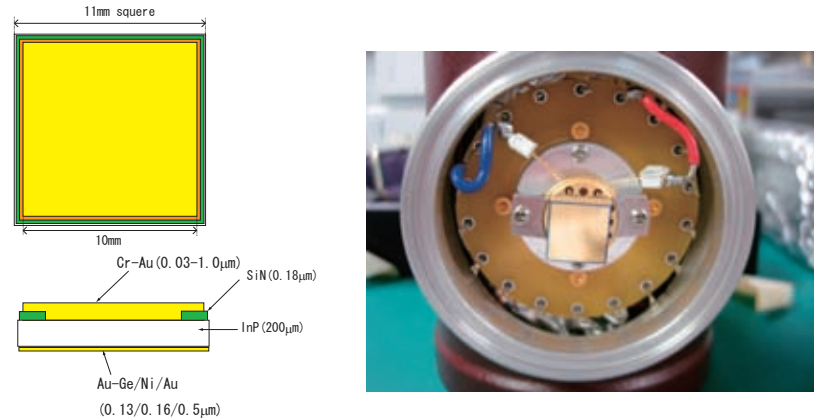


Figure 2. Left figure shows the schematic view of the proto-type detector. The detector size is  $10\text{ mm} \times 10\text{ mm}$  in surface, and  $0.2\text{ mm}$  in thickness.

The performance of InP detector was measured by using gammas emitted by usual radio active sources. Carriers generated by the energy deposit of an electron via photoelectric process or Compton scattering are drifted along to electric field. Assuming a drift chamber in case of solid state, the charge are induced by the polarized carrier at the surface of electrode. The induced charge is evaluated by

$$Q [C] = \int_0^R \frac{dE/dx}{\epsilon} \frac{L_d}{d} dx. \quad (2)$$

Here,  $L_d$  is the carrier drift length,  $\epsilon$  is an average energy for electron/hole pair production,  $R$  is the carrier range, and  $d$  is thickness of InP detector. Generally speaking, the carrier drift length is expressed by  $L_d \equiv \mu \tau \frac{V_0}{d}$ , here  $\mu$  is the carrier mobility,  $\tau$  is life-time of the carrier trapping and  $V_0$  is the bias voltage. In order to get longer life time, the detector should be cooled. Figure. 3 shows that the observed charge distribution

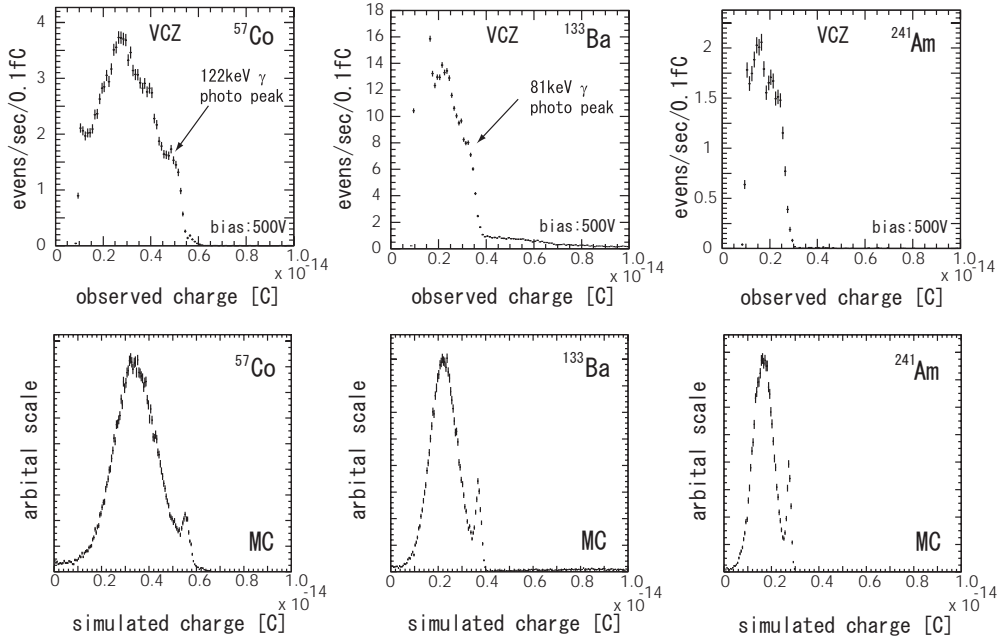


Figure 3. Observed and simulated charge distributions for gammas obtained by VCZ InP detector ( $10\text{mm} \times 10\text{mm} \times 0.2\text{mm}$ ) are shown.

measured at  $-79^\circ\text{C}$  for several radio-isotopes. There found two peaks in each spectra. For instance, photo peak for 122 keV gamma in  $^{57}\text{Co}$  appears around  $0.3 \times 10^{-14} \text{ C}$  and  $0.55 \times 10^{-14} \text{ C}$ . Higher peak is produced by the charge collection in the depletion layer (thickness =  $x_0$ ), and it is consistent with other sources assuming by an average energy for electron/hole pair production to be 3.5 eV. This assumption is also confirmed by the fact that the higher peak position was not changed as increasing bias voltage. On the other hands, lower peak moves to higher position as increasing bias voltage. This is naturally explained by above formula. The collection efficiency for lower peak corresponds to 50% to 60%. According to a simulation using Eq. (2) with the energy resolution of 25% at 122 keV for a lower peak, the spectral shape could reproduce assuming both  $L_d \sim 120 \mu\text{m}$  and  $x_0 \sim 20 \mu\text{m}$  as shown in Fig. 3. An intrinsic energy resolution for a higher peak was also determined by 3% at 122 keV in this simulation. This induced charge were also found in the another sample, which had a 500  $\mu\text{m}$  thickness and growth by Vertical Gradient Freeze (VGF) method produced by American Xtal Technology Inc. The observed charge spectra were well reproduced by same simulation but no depletion layer as shown in Fig. 4.

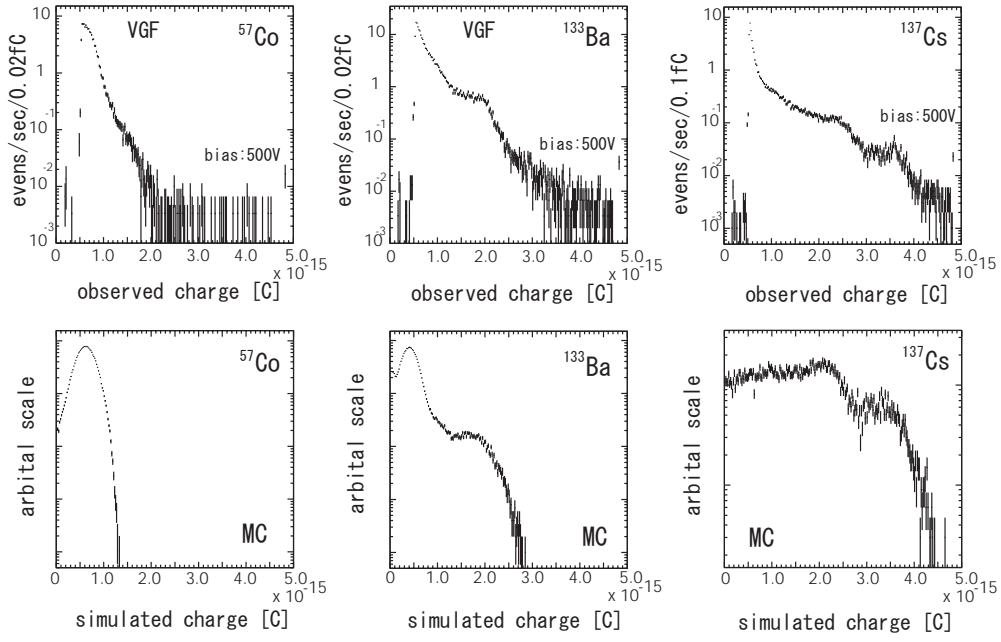


Figure 4. Observed and simulated charge distributions for gammas obtained by VGF InP detector ( $6\text{ mm} \times 6\text{ mm} \times 0.5\text{ mm}$ ) are shown.

#### 4. Measurement of backgrounds

As described in section 2,  $^{115}\text{In}$  decays naturally with beta emission, and it could be possible background in the observation of solar neutrinos. In order to measure the  $\beta$  decay from  $^{115}\text{In}$  and the effect of Bremsstrahlung, we used InP solid state detector for measurement of  $\beta$  spectra and CsI (TI) scintillator which was produced by SCIONIX for the measurement of radiative Bremsstrahlung. The CsI size was  $50\text{ mm} \times 50\text{ mm} \times 20\text{ mm}$ . These two detectors are located by face to face and set inside of radio-active shield which consist of the lead in 5 cm thickness and the oxygen free copper in 1 cm thickness. The 4- $\pi$  active veto plastic counter surrounded the shield rejected backgrounds due to the cosmic ray and the external radiation.

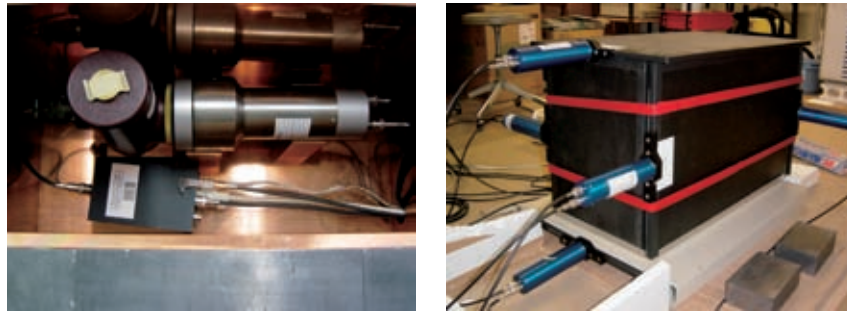


Figure 5. Configuration of InP and CsI detector, radio-active shield and 4- $\pi$  active veto plastic counter surrounded the shield

In the measurement of  $\beta$  decay of  $^{115}\text{In}$ , the events without any coincidence between InP and CsI detector nor veto counter. The spectra of observed events and expected  $\beta$  decay are shown in Fig. 6. The event rate of  $\beta$  decay was expected by 68 per hour. For low energy events below 100 keV, the backgrounds due to the

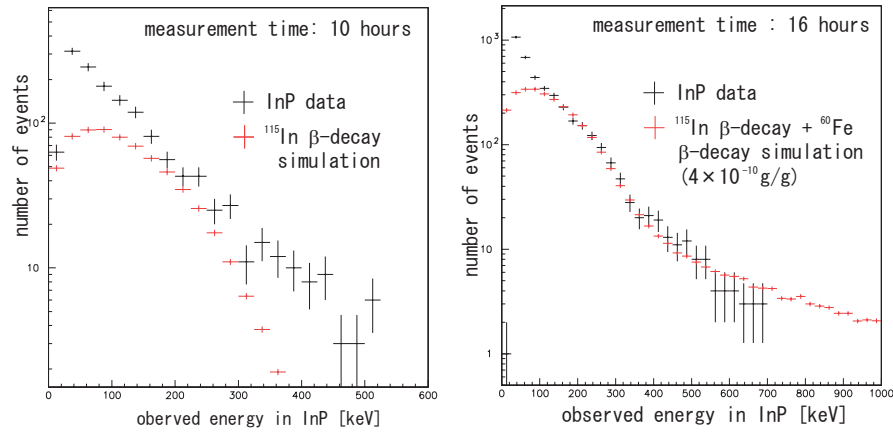


Figure 6. Observed energy distribution of InP detector and the expected  $\beta$  decay spectrum. Residual events above 400 keV was consistent with the  $^{60}\text{Fe}$   $\beta$  decay.

vibration seems to be dominated. The InP detector was so cooled that a floated capacitance between the InP detector and the charge amplifier made it sensitive to external vibration. Observed events above 400 keV were still inconsistent with the spectrum of  $\beta$  decay of  $^{115}\text{In}$ . According to the measurement of U/Th activity using ultra-low background germanium detector located in Kamioka mine, the semi-insulated InP wafer contains those activities as order of  $10^{-11}$  g/g. This amount of backgrounds could not explain both the number of these events nor the spectral shape. Another possibility was iron (Fe) which is used for the dopant of semi-insulating InP crystal. The  $^{60}\text{Fe}$  nuclei decay into  $^{60}\text{Mn}$  with  $\beta^-$  decay ( $E_e \leq 3.978$  MeV,  $T_{1/2} = 1.5 \times 10^6$  years). Assuming  $^{60}\text{Fe}$  contamination at an order of  $10^{-10}$  g/g, then the expected energy spectrum in InP detector is almost consistent with the observed spectrum as shown in Fig. 6.

For a measurement of radiative Bremsstrahlung from  $\beta$  decay of  $^{115}\text{In}$ , it should take a coincidence between InP and CsI detector within 10  $\mu\text{sec}$ . The radiative Bremsstrahlung is different from usual one, because the radiation emits due to  $\beta$  nuclei, not a free electron. The Coulomb potential is so stronger that the energy of the radiation could be higher ( $\sim 100$  keV) than usual X-ray with less than 10 keV. In case of 10 hours measurement, totally 105 events were found. The observed number of events looks larger than the expected number of events of  $\beta$  decays. Before concerning coincidence events, it is necessary to take into account the U/Th natural backgrounds in CsI scintillator. Figure 7 shows the energy spectrum of CsI detector obtained by the self

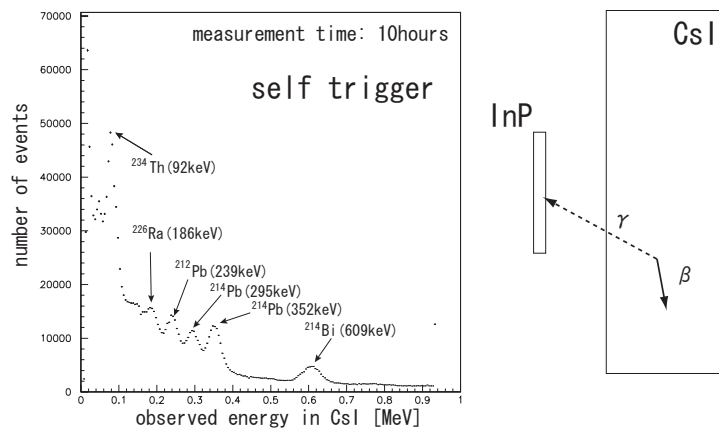


Figure 7. Energy spectrum of natural U/Th series observed in CsI detector. Due to these backgrounds, some gammas could escape from CsI scintillator and then enter into InP detector.

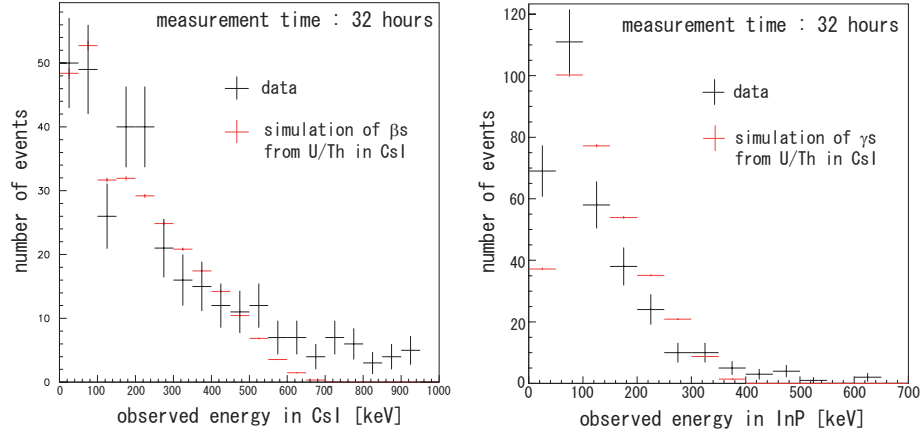


Figure 8. Energy spectrum of coincident events for CsI and InP detector for 32 hours data, and the expected spectrum from above scheme is overlapped.

trigger. It is clearly seen that the photo-electric peak due to some nuclei in the U/Th decay chain. The amount corresponds to several  $10^{-10}$  g/g order of U/Th contaminated in the CsI scintillator or the photo multiplier. This amount is quite adequate, however it becomes non-negligible backgrounds. Those nucleus generally decay with both gamma and beta, so that some gammas could escape from CsI scintillator and enter into InP detector as described in Fig. 7. Applying the simulation using this scheme, the energy spectrum of InP and CsI detector taken the coincidence was obtained as shown in Fig. 8.

According to these figures, most of coincident events between InP and CsI detector looks consistent with  $\beta - \gamma$  coincidence of U/Th backgrounds in CsI scintillator, and no clear evidence for the effect of radiative Bremsstrahlung could be observed. However, this was not completely confirmed by the radiative Bremsstrahlung, because of difficulties to separate them. We have to measure same spectrum using other solid state detector such as CdTe, and confirm them caused by U/Th series in CsI scintillator. However, these radiative Bremsstrahlung backgrounds could be eliminated by the timing difference, because of few  $\mu$  seconds in the case of  $^{115}\text{In}$  decay.

Another possible background should be concerned by neutron capture ( $n, \gamma$ ) reaction by  $^{115}\text{In}$ . The cross section is quite large (an order of 100 barn) and some resonances have a peak value (an order of 1000  $\sim$  10000 barn)  $^{116m}\text{In}$  nuclei decays into  $^{116}\text{Sn}$  with  $\beta^-$  decay ( $T_{1/2} = 54.2$  min) and emits gammas such as 1.29 MeV, 0.42 MeV and 2.11 MeV. We will measure this effect using natural neutron background and nuclear neutron source like  $^{252}\text{Cf}$ , however it will not be also severe background for IPNOS experiment due to an efficient neutron shield.

## 5. Conclusion

An InP solid state detector has been developed and obtained suitable performance. Observed charge spectra could be explained by the carrier drift length as  $L_d = 120 \mu\text{m}$ , and the collection efficiency is achieved by 50 to 60 %, which corresponds to the induced charge. This is the first time to demonstrate InP detector with a bulk size crystal, and detector performances including the background measurements show us that an InP detector is actually possible to use for IPNOS experiment.



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