

The recent results from KIMS experiment

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Abstract. In this paper, the recent results from KIMS (Korea invisible mass search) experiment are presented. KIMS has searched for WIMPs (Weakly Interacting Massive Particles) scattering off the nucleus by using the CsI(Tl) scintillator. The detector is an array of 12 CsI(Tl) scintillators, whose total mass is 103.4 kg. The results reported here used the exposure of 24524.3 kg-days. With pulse shape discrimination (PSD) analysis, we estimated the nuclear recoil (NR) event rate and no meaningful excess of NR events rate were found. From this, we derived the improved cross section limit for WIMP–nucleon interaction.

1. Introduction

Since the existence of the dark matter as the majority of the matter in the universe is widely supported by the astronomical observations [1], the explorations to discover the direct or indirect signal from the dark matter have been attempted in various ways. Since what the dark matter is not found yet, many candidates for it have been discussed. WIMP (Weakly Interacting Massive Particle) is one of good candidates, having two important merits. The first is its natural occurrence in the theories of particle physics which is independent on the dark matter problem. The next important thing is that it is supposed to leave tens of keV in the detector when it recoils the nucleus in the detector. The existence of this testable candidate has been pursued through several experiments and KIMS experiment is also searching for the direct signal from the WIMPs.

KIMS uses CsI(Tl) scintillator for WIMP search. CsI(Tl) scintillator is a very widely used, well-known detector. The ingredient elements, Cesium and Iodine have large atomic number (A), so that it gives large A^2 scaling effect when WIMP recoils the nucleus coherently. If WIMP nucleus interaction depends on the spin of the proton, because of the high spin expectation value for proton for both elements, this detector also has a good sensitivity. Furthermore, CsI(Tl) scintillator enables the pulse shape discrimination (PSD) so that the nuclear recoil (NR) event rate can be estimated statistically. Using PSD analysis, the background like electron recoil (ER) events can be subtracted. However, the weak point of CsI(Tl) is its inherent background such as Rb^{87} , Cs^{137} , Cs^{134} [2]. We had made an effort to reduce the internal backgrounds [3] and now we reached the background level of 2-3 count/day/kg/keV around 10 keV.

2. The experimental description

KIMS detector is an array of 3×4 CsI(Tl) scintillators. One module is composed of one crystal and two, 3 inch RbCs photo-cathode (green extended) photomultiplier tubes (PMTs) attached at both ends. The photoelectron yield is around 5 photoelectrons per keV. Figure. 1. shows the

result of ^{241}Am calibration for one detector module. The data is well fitted with various X-rays and gamma rays that are expected from ^{241}Am and X-ray escape peaks.

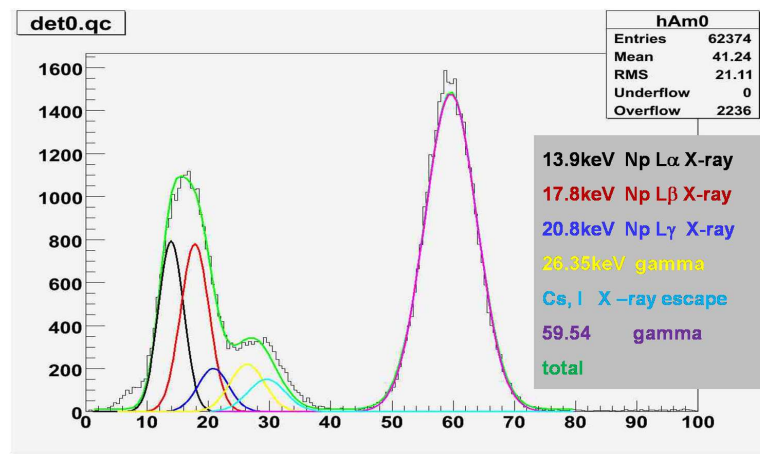


Figure 1. The energy spectrum with ^{241}Am source for one detector module

The size of one crystal is $8 \times 8 \times 30 \text{ cm}^3$ and its weight is around 8.6 kg. The mass of the whole detector array is 103.4 kg. The detector array is shown in Fig. 2 (a). The detector array enables vetoing multiple hit events, which is defined as the event triggering two or more detector modules like Compton scattering events. Because of the extremely low WIMP interaction rate, all multiple hit events are rejected in the analysis for WIMP. Figure 2 (b) shows the energy of one detector versus the energy detected by the others. Here, one can clearly see the structure from various decay modes of ^{134}Cs , one of the dominant backgrounds.

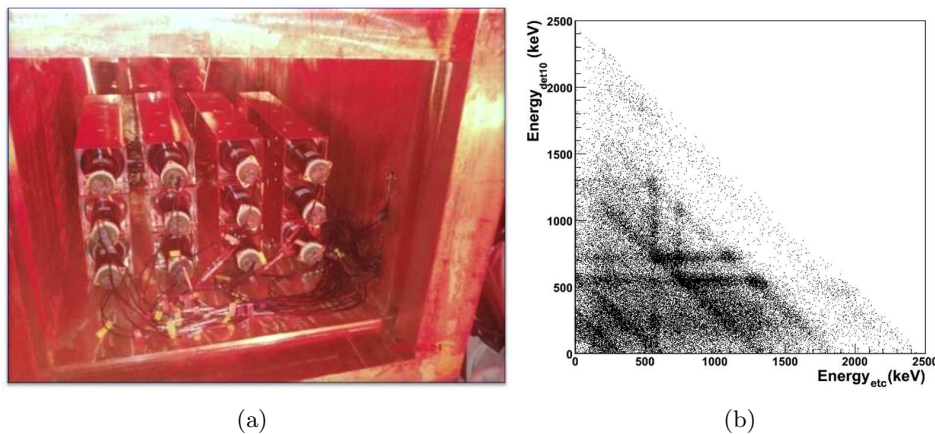


Figure 2. The detector array (a) The detector array of 12 CsI(Tl) scintillators. (b) The two dimensional plot of the energy of one detector and the sum of the energy of the others.

The array is mounted in the shield structure which consists of 10 cm of copper, 5 cm of polyethylene, 15 cm of lead and 30 cm of liquid scintillator based on mineral oil. The mineral oil layer not only moderates the external neutron flux but also serves as the muon veto. The experimental site is Yanyang underground laboratory (Y2L) located east of Gangwon province, South Korea. The experimental hall utilizes the space of the Yanyang pumped storage power plant. The muon flux at the experimental hall is $2.7 \times 10^{-7} / \text{cm}^2/\text{s}$.

3. The data analysis

Recently, as the exposure of the data increased, we noticed the new component of the background, surface alpha events. The ^{222}Rn gas in the air readily sticks to any surface. ^{222}Rn attached to the surface of the detector decays to ^{210}Pb via several decay steps, whose half-life is 22 years and produces ^{210}Po which emits a 5304 keV alpha particle with a half-life of 138 days. Since this alpha decays happen at the detector surface, the alpha particle can escape from the detector leaving only small portion of the full energy of 5 MeV. Therefore, this surface alpha (SA) events can show up even in the small energy region below 10 keV. Figure 3 shows the scatter plot of the energy deposits versus the PSD parameter—the characteristics to distinguish the type of particles, LMT10 (the logarithm of the mean time of each event estimated in 10 μs aperture) seen in the KIMS detector. Here, one can see the continuum of the SA events which appear down to the very low energy. In order to understand the characteristics of SA events,

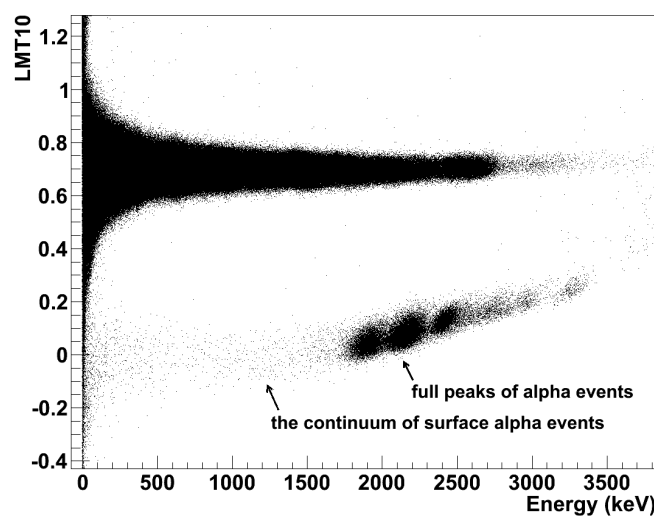


Figure 3. The energy versus the LMT10 (the logarithm of the mean time of each events estimated in 10 μs).

we obtained a small piece of CsI(Tl) crystal ($3 \times 3 \times 1.5 \text{ cm}^3$, test crystal 1) cut from the large crystal, from which the crystals used in KIMS experiment were also cut and contaminated it with ^{222}Rn progenies by putting it in a special chamber filled with ^{222}Rn gases at the concentration of 4.33 MBq/m^3 . By tagging the alpha particle going out of the crystal, we have collected the SA events [4]. The characteristic of SA events is seen in Fig. 4, which shows the LMT10 distribution of SA events as well as NR and ER events. To obtain the reference data sample for NR events, we used another piece of crystal (test crystal 2) and exposed it to Am-Be neutron source. This figure shows the SA events are distinctively fast compared to other type of events. As the LMT10 distributions of ER events obtained with various crystals including the KIMS detector show good agreements, we adopted the distribution for SA (and NR) obtained from the test crystal for the PSD analysis of the KIMS detector. The crystal-to-crystal variation is a few percent and it is taken into account as the systematic effect.

Since the energy range of the interest is below 10 keV and the signal event happens rarely, the PMT noise also become a serious background. To investigate the PMT noise background, we developed the PMT Dummy Detector (PDD), which is the same with one CsI(Tl) detector module except that the crystal is replaced with the clean, hollow acrylic box. We installed this detector besides the detector array and have taken the data at the same time. In the light of the

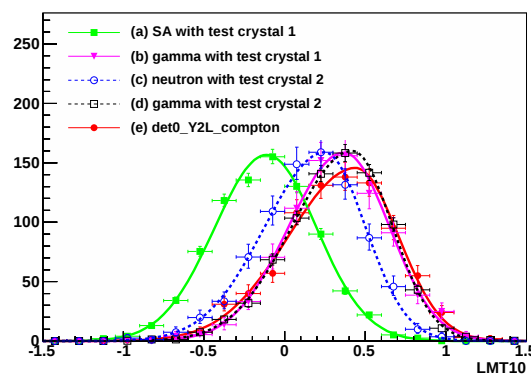


Figure 4. LMT10 distributions at 3 keV (a) SA with test crystal 1, (b) gammas with test crystal 1, (c) neutrons with test crystal 2, (d) gammas with test crystal 2 (e) Compton scattering events in detector 0 used in the WIMP search.

PDD data, we developed the event selection criteria to reject the PMT noise. In general, PMT noise event is the random coincidence between two coupled PMTs. Therefore, the signal size and its start time in two PMTs is asymmetric compared to the real signal. And, PMT noise event have the big spike signal in it. A typical event consists of a series of the photo-electrons, which we named clusters. The PMT noise event usually accompanies the abnormally big cluster. From the signal asymmetry along the two PMTs and the presence of an abnormal big cluster signal, we can reject the PMT noise events effectively. The major event selection criteria are shown in Fig. 5. In Fig. 5 (a), qc asymmetry means the signal size asymmetry between two PMTs. The x-axis label, fit quality is the value related the goodness of fitting each event with the two exponential functions. As the tail events following the very high energy events such as the muon event show the bad fit quality, we used this variable to reject the tails of the high energy events. The vertical blue line and horizontal green line shows the event selection criteria. Figure 5 (b) shows the two dimensional distribution of the ratio of the whole signal to the biggest cluster by area for two PMTs. As shown in the figure, the PMT noise events are populated around the origin and we rejected the events whose x-value or y-value is smaller than the value marked by the green lines. The event selection criteria for this is marked with two green lines. The event selection efficiency ranges from 20~40 % at 3 keV to 40~70 % at 10 keV.

With the reference distribution of LMT10 for SA, NR and ER events, we have tried to fit the LMT10 distribution of the selected events for the WIMP search. To estimate the fraction of SA and NR events in the data, we used the bayesian analysis method [5]. The most probable value and the 90 % confidence limit (C.L.) value can be estimated from the posterior PDF for NR (SA) components. Figure 6 shows the estimated NR event rate for twelve detectors. We also estimated SA event rate for each detector and found the SA background level of detector 0, 8 and 11 is about three times as high as the average of the remaining detectors. For this reason, in drawing the overall NR event rate, we excluded the detector 0, 8 and 11. Figure. 7 shows the NR event rate combined from the remaining nine detectors. As one can see, there is no clear excess NR signal. This NR event rate is incompatible with the WIMP-Iodine interaction interpretation for DAMA signal [7]. The annual modulation amplitude claimed by DAMA is 0.0183 ± 0.0022 counts/day/kg/keV in 2-4 keV. Considering the quenching factor of NaI(Tl) and CsI(Tl) [2, 8], 2-4 keV energy range in NaI(Tl) corresponds to the 3.6-5.8 keV in CsI(Tl). In this energy range, we calculated the 90 % C.L. limit of NR event rate and the result is 0.0098 counts/day/kg/keV, which is well below the DAMA signal amplitude. Therefore, any scenario involving Iodine target such as iDM model are inconsistent with our results. As an example, we

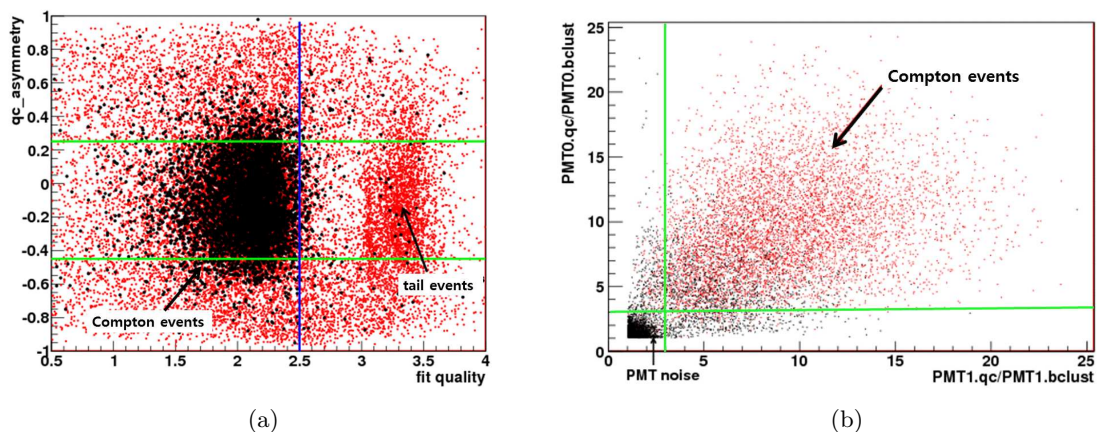


Figure 5. The event selection criteria (a) The qc asymmetry versus fit quality. (b) The two dimensional plot for the ratio of the whole signal to the biggest cluster by area for the two PMTs.

present the allowed parameter space for DAMA in iDM model and our exclusion limit for 70 GeV mass of WIMP in Fig. 8.

From the total 90 % C.L. limit of NR rate, we can derive cross section limits for the WIMP-nucleon spin independent (SI) and spin dependent (SD) interaction based on the standard halo model [6]. Our limits and other experimental results are presented in Fig. 9.

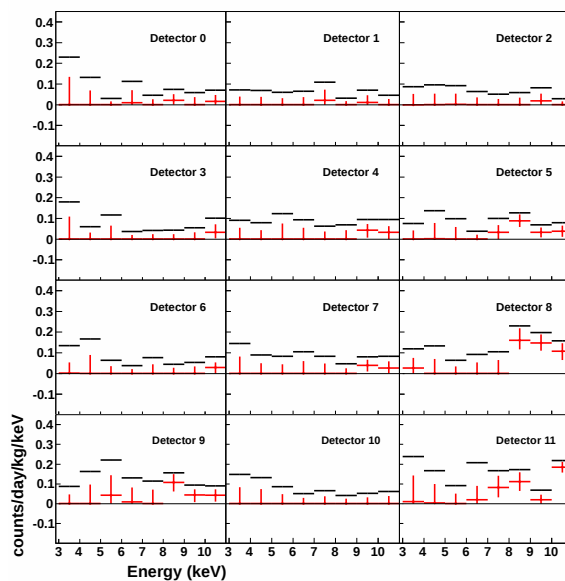


Figure 6. Nuclear recoil event rates for twelve detectors. The black horizontal bar indicate 90% C.L. upper limits, the red vertical lines denote the 68% C.L. interval, and the red horizontal bars the most probable values.

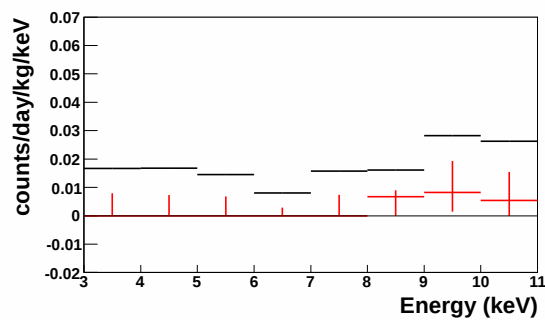


Figure 7. Total nuclear recoil event rates from the combined results from nine detectors (without detector 0, 8 and 11). The details are same with Fig. 6.

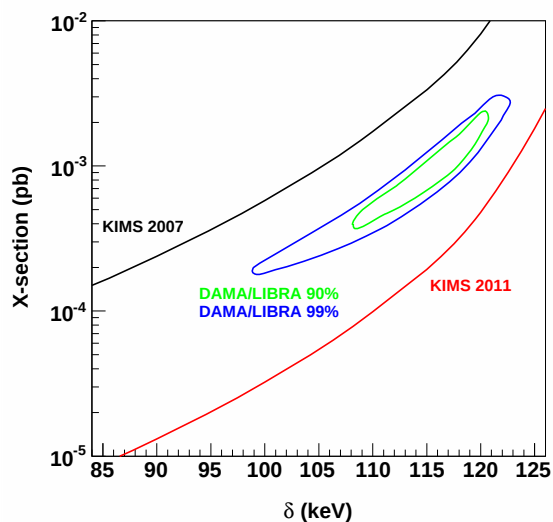


Figure 8. The allowed parameter space for DAMA [9] and the limits reported here for a 70 GeV WIMP mass in iDM model. δ is the mass split between the ground and excited states of the WIMP. The astronomical parameters from Ref. [9] are used.

4. Conclusion

KIMS experiment has been carried out with an array of twelve CsI(Tl) scintillators whose total mass is 103.4 kg. From the exposure of 24524.3 kg·days, we estimated the NR event rate in the data with PSD analysis method. We identified and characterized the background from the alpha decay that occurs at the surface of the detector and incorporated it in the PSD analysis. As no excess signal of NR events are seen in the data, we set 90 % C.L. limit for NR event rate. This result is inconsistent with the DAMA annual modulation amplitude and disfavors any WIMP-Iodine interaction scenario including iDM. We derived the improved cross section limit for WIMP-nucleon scattering. Especially, for the WIMP-proton SD scattering, we obtained very competitive result.

References

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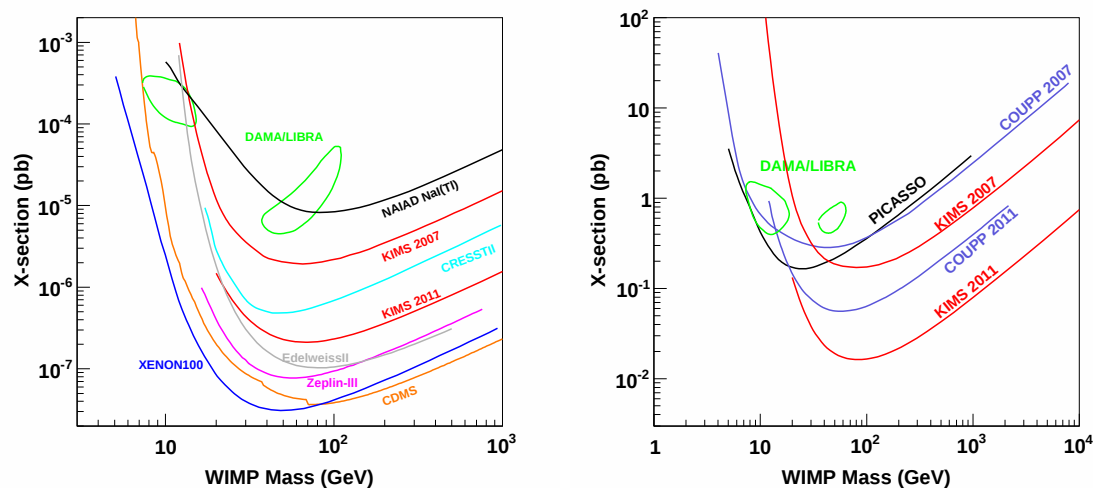


Figure 9. The 90 % exclusion limits on **(Left)** SI WIMP-nucleon and **(Right)** SD WIMP-proton cross sections. In both plots DAMA results interpreted by Savage *et al.* [18] are used (3σ contours are drawn). The SI plot includes NAIAD [10], CRESST [11], Edelweiss [12], Zeplin [13], XENON100 [14] and CDMS [15] limits. The SD plot includes PICASSO [16] and COUPP [17] limits.

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