The existence of dark matter has been widely supported by many astronomical observations on various scales [1][2][3]. Weakly interacting massive particles (WIMPs) are a good candidate for dark matter well motivated by cosmology and supersymmetric models [3]. The Korea Invisible Mass Search (KIMS) experiment has developed low-background CsI(Tl) crystals to detect the signals from the elastic scattering of WIMP off the nucleus [1][6][7]. Both $^{133}\text{Cs}$ and $^{127}\text{I}$ are sensitive to the spin-independent (SI) and spin-dependent (SD) interactions of WIMPs. Recently, the role of CsI in the direct search for SD WIMP for pure proton coupling has been pointed out [3]. It is worth noting that $^{127}\text{I}$ is the dominant target for the SI interactions in the DAMA experiment. The pulse shape discrimination (PSD) technique allows us to statistically separate nuclear recoil (NR) signals of WIMP interactions from the electron recoil (ER) signals due to the gamma ray background [8][9].

The KIMS experiment is located at the Yangyang Underground Laboratory (Y2L) at a depth of 700 m under an earth overburden. Details of the KIMS experiment and the first limit with 237 kg·d exposure data can be found in the previous publication [11]. Four low-background CsI(Tl) crystals are installed in the Y2L and operated at a temperature of $T = 0{}^\circ\text{C}$. Throughout the exposure period, the temperature of the detector was kept stable to within ±0.1°C. Green-enhanced photomultiplier tubes (PMTs) are mounted at both ends of each crystal. The signals from the PMTs are amplified and recorded by a 500 MHz FADC. Each event is recorded for a period of 32 $\mu$s. Both PMTs on each crystal must have at least two photoelectrons within a 2 $\mu$s window to form an event trigger. We obtained 3409 kg·d WIMP search data with four crystals, as shown in Table I. The energy is calibrated using 59.5 keV gamma rays from an $^{241}\text{Am}$ source. For calibration of the mean time, a variable used for the PSD, NR events are obtained with small crystals (3 cm × 3 cm × 3 cm) using an Am-Be neutron source. Compton scattering events taken with the WIMP search crystals using the $^{137}\text{Cs}$ source are used to determine the mean time distribution of the gamma background. Compton scattering events are also taken with the small crystals to verify that the mean time distributions for both the test crystals and the WIMP search crystals are the same. In order to understand the nature of the PMT background, a dominant background at low energies, acrylic boxes are mounted on the same PMTs used for the crystals. The data obtained using this setup is used to develop the cuts for the rejection of PMT background.

Since the decay time of the scintillation light in the CsI(Tl) crystal is rather long, photoelectrons are well separated at low energies and thereby enabling reconstruction of each photoelectron. The time distribution of photoelectrons in an event is fitted to a double exponen-
distributions. An unbinned maximum likelihood fit is performed with the log(MT) distribution of the WIMP search data using the likelihood function,

$$L_i = \frac{1}{n!} \times \exp\left\{-(N_{NR,i} + N_{ER,i})\right\} \times \prod_{k=1}^{n} \left[PDF_{NR,i}(x_k) + PDF_{ER,i}(x_k)\right],$$

where the index $i$ denotes the $i$-th energy bin; $n = N_{NR,i} + N_{ER,i}$ is the total number of events; $N_{NR,i}$ and $N_{ER,i}$ are the numbers of NR and ER events, respectively; $PDF_{NR,i}$ and $PDF_{ER,i}$ are PDFs of NR and ER events, respectively; and $x_k = \log(MT)$ for each event. The NR event rates obtained for each bin and for each crystal after efficiency correction are shown in Fig. 2. The extracted NR event rates are consistent with a null observation of the WIMP signal.

In order to obtain the expected measured energy spectrum of a WIMP signal including instrumental effects, a Monte Carlo (MC) simulation with GEANT4 [12] is used. A recoil energy spectrum is generated for each WIMP mass with the differential cross section, form factor, and quenching factor, as described in Ref. [13]. The spin-dependent form factor for $^{133}$Cs calculated by Toivanen [14] is used, while for $^{127}$I, Ressell and Dean’s calculation [15] is used. The photons generated with the fitted decay function described above are propagated to the PMT and digitized in the same manner as in the experiment. Subsequently, the photoelectrons within given time windows are counted to check the trigger condition and to calculate energy. In this manner, the trigger efficiency and energy resolution is accounted for in the expected energy spectrum. The trigger efficiency is found to be higher than 99% above 3 keV. The simulation is verified with the energy spectrum obtained using $^{241}$Am. The peak position and
The total WIMP rate, $R$, for each WIMP mass is obtained by fitting the measured energy spectrum to the simulated one. The 90% confidence level (CL) limit on $R$ is calculated by the Feldman-Cousins’s approach in the case of Gaussian with a boundary at the origin [17] and then converted to the WIMP-nucleus cross section, $\sigma_{W-A}$. Subsequently, the limits on WIMP-nucleon cross section is obtained from Ref. [13][18] as follows:

$$\sigma_{W-n} = \sigma_{W-A} \frac{\mu_n^2}{\mu_A^2} \frac{C_n}{C_A},$$

where $\mu_{n,A}$ are the reduced masses of the WIMP-nucleon and WIMP-target nucleus of mass number $A$. $C_A/C_n = A^2$ for SI interactions and $C_A/C_n = 4/3\{a_p < S_p > + a_n < S_n >\}^2(J + 1)/J$ for SD interactions. Here $a_p$, $a_n$ are WIMP-proton and WIMP-neutron SD couplings respectively. The spin expectation values used for this analysis are shown in Table II. Following the “model-independent” framework [18], we report the allowed region in two cases for SD interaction: one for $a_n = 0$, and the other for $a_p = 0$. We express the WIMP-nucleon cross section as follows:

$$\sigma_{W-n}^{SI} = \sigma_{W-A} \frac{\mu_n^2}{\mu_A^2} \frac{1}{A^2};$$

$$\sigma_{W-n,p}^{SD} = \sigma_{W-A} \frac{\mu_{n,p}^2}{\mu_A^2} \frac{3}{4} \frac{J}{(J + 1)} \frac{1}{< S_{n,p} >^2},$$

where we indicate pure proton ($p$, $a_n = 0$) and pure neutron ($n$, $a_p = 0$) coupling for SD interaction. We also present the allowed region in the $a_p - a_n$ plane with the following relation [18]:

$$\left( \frac{a_p}{\sqrt{\sigma_{W-p}}} \pm \frac{a_n}{\sqrt{\sigma_{W-n}}} \right)^2 \leq \frac{\pi}{24G_F^2\mu_p^2},$$

where $G_F$ is the Fermi coupling constant.

The uncertainty in the $MT$ distribution results in the uncertainty of the NR event rate. The limited statistics of the calibration data and different crystals used for the neutron calibration and WIMP search data are the major sources of this uncertainty. The former is investigated by varying the fitted parameters in PDF function within errors. The latter is estimated by changing the mean of $MT$ by the difference between the crystals. The systematic uncertainties from these two sources are combined in quadrature resulting in 20-30% of statistical uncertainties depending on the energy bins. In addition, there are uncertainties in the MC estimation of the expected event rates due to the uncertainties in the quenching factors and the difference of energy resolution between the MC simulation and the data. The systematic error from the MC simulation is estimated to be 13.3% of the limits. These systematic errors are combined with the statistical error in quadrature in the presented results.

The limits on the SD interactions are shown in Fig. 3 and 4 in the cases of pure proton coupling and pure neutron coupling, respectively. We also show the results obtained from CDMS [19], NAIAD [20], SIMPLE [21], and

| Isotope | J   | $< S_n >$ | $< S_p >$ | Reference |
|---------|-----|-----------|-----------|-----------|
| $^{133}$Cs | 7/2 | -0.370    | 0.003     | [16]      |
| $^{127}$I | 5/2 | 0.309     | 0.075     | [15]      |
FIG. 5: (color online). Allowed region (90% confidence level) in $a_p - a_n$ plane by KIMS data (inside the solid line contour) for 50 GeV WIMP mass. Results of CDMS [19](dotted line) and NAIAD [20](dot-dashed line) are also shown.

FIG. 6: (color online). Exclusion plot for the SI interactions at the 90% confidence level.

PICASSO [22]. The DAMA signal region is taken from Ref [23]. Our limit provides the lowest bound on the SD interaction in the case of pure proton coupling for a WIMP mass greater than 30 GeV/$c^2$. The allowed region in the $a_p - a_n$ plane for the WIMP mass of 50 GeV/$c^2$ is also shown in Fig. 5 together with the limits from CDMS and NAIAD. The limit for the SI interactions is shown in Fig. 6 together with the results of CDMS [24], EDELWEISS [25], CRESST [26], ZEPLIN I [27], and the 3σ signal region of DAMA (1-4) [28]. Although there are several experiments that reject the DAMA signal region, this is the first time that it is ruled out by a crystal detector containing $^{127}$I, which is the dominant nucleus for the SI interactions in the NaI(Tl) crystal.

In summary, we report new limits on the WIMP-nucleon cross section with CsI(Tl) crystal detectors using 3409 kg·d exposure data. The DAMA signal regions for both SI and SD interactions are excluded for the WIMP masses higher than 20 GeV/$c^2$ by the single experiment. The most stringent limit on the SD interaction in the case of purely WIMP-proton coupling is obtained.

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