Annual modulation study of dark matter using CsI(Tl) crystals in KIMS experiment

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The orbital motion of the Earth can result in annual modulation signatures of dark matter. The DAMA group reported a positive signal for an annual modulation with NaI(Tl) crystal detectors. The KIMS experiment uses a CsI(Tl) crystal detector array to search for dark matter and, if the DAMA result is in fact due to WIMP interactions, can be expected to see a similar annual modulation signal. This paper presents results of a search for a dark-matter-induced annual modulation of signals in CsI(Tl) detectors over a 2.5 year period.

1 Introduction

Common matter, so-called baryons, constitute only 4% of the energy density of the universe; the composition of the remaining 96% is unknown [1]. Today, we have various evidence that supports the existence of dark matter [2][3][4][5][6]. The Korea Invisible Mass Search (KIMS) group has carried out an experimental search for Weakly Interacting Massive Particles (WIMPs) using CsI(Tl) crystal detectors. This study used a 75.53-ton·day data-exposure that extended from Sep. 2009 to Feb. 2012, corresponding to 2.5 annual modulation cycles.

CsI(Tl) crystal pulse shapes can be used to discriminate nuclear recoil signals from gamma background, something that cannot be done with NaI(Tl) crystals. The KIMS experiment already reported lower limits than DAMA annual modulation signal in iodine using the pulse shape discrimination (PSD) method in 2007 [7] and 2012 [8]. However, DAMA argued that KIMS may lose some nuclear recoil events when PSD is used in crystal scintillators [9]. The annual modulation study of KIMS provides a more direct comparison compared to the non-PSD analysis.

2 Data analysis

2.1 Fitting Function

Because of the different characteristics of each CsI(Tl) detector module, this analysis is done separately for each detector and then the results are summed. Two-month-long time intervals are used for the study of the annual modulation as shown in Fig. 1.

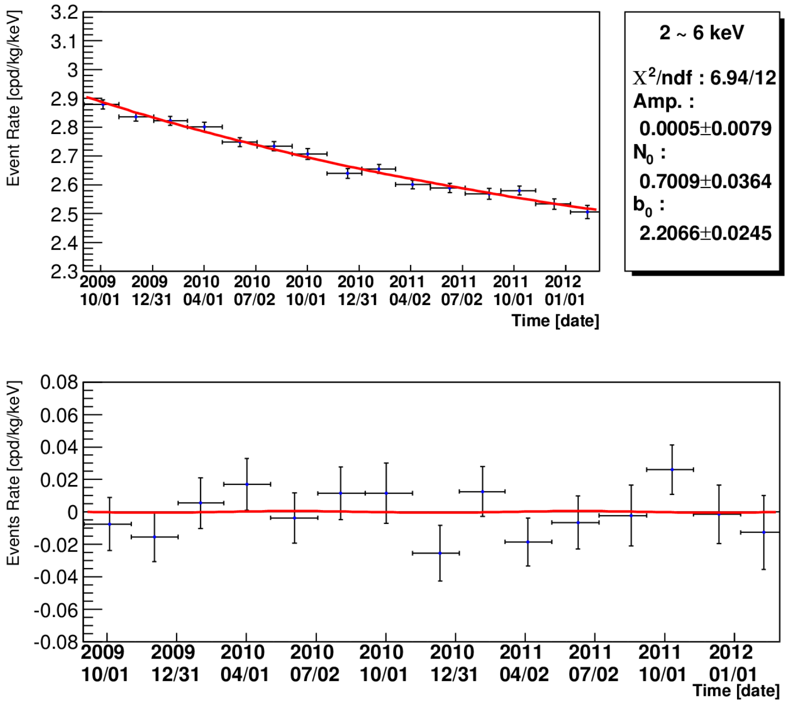

Figure 1: The preliminary result from the fit of an annual modulation function to the data. The fitted energy range is from 2 keV to 6 keV and the modulation phase is fixed to 2 June. The upper figure shows the best fit (red line) to the data. The lower figure shows the residuals, where the smooth background corresponding to the first and second terms of Eq. (1) are subtracted.

Equation (1) is used to fit the data. The first term is used to represent radioactive isotope decays, the second term is for the constant background level and the last term corresponds the annual modulation amplitude where the period is fixed at one year.

$$f(t) = A_{decay}e^{-\frac{t-t_0}{\tau}} + Bkg + A\cos\frac{2\pi}{T}(t-t_1)\,. \quad (1)$$

The decay constant of the first term is fixed at the ^{134}Cs lifetime of 2.065 y. Here, t_0 is fixed on the start time of data taking, and t_1 is 2 June and T is the cycle of the annual modulation. Equation (1) has three free parameters; A_{decay} (initial level of decay components), Bkg (constant background level) and A (annual modulation amplitude). The fitting result from each of the different detector modules are averaged to give the final value for each parameter.

2.2 Fitting results

The left panel of Fig. 2 shows the averaged parameters for each 1 keV energy interval. The amplitude at each energy is consistent with zero within 2 standard deviations. The right panel of Fig. 2 shows the phase shift of the annual modulation for each energy bin. All of phases are concentrated within 2 standard deviations of the origin, and the results do not show the significant shift toward the right side, which would indicate a summer's positive amplitude. The fitted values of A_{decay} and Bkg indicate a smooth background that is slightly less than

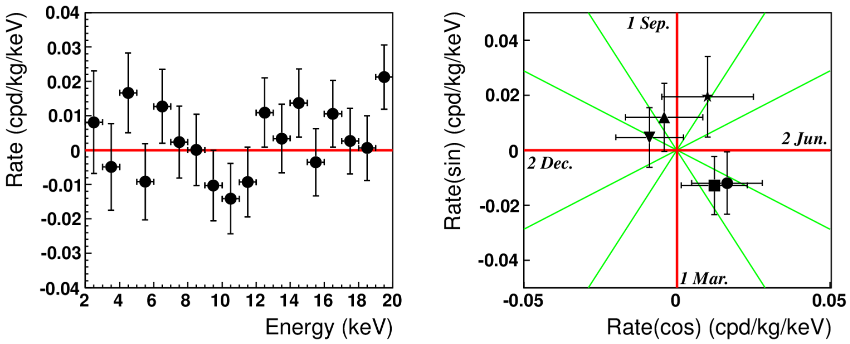

Figure 2: The preliminary result of the annual modulation amplitudes. The left spectrum of energy results in the fixed phase and the right shows the phase distribution of the annual modulation amplitude (Star-2 keV, Triangle-3 keV, Circle-4 keV, Inverted triangle-5 keV, Square-6 keV).

3 cpd/kg/keV. The fitted values of the annual modulation amplitude A are 0.0021 ± 0.0062 cpd/kg/keV (2 keV-6 keV) and 0.0008 ± 0.0068 cpd/kg/keV (3 keV-6keV). These amplitudes are consistent with a null signal within 1 standard deviation. The 90% confidence level (C.L.) upper limits of the annual modulation amplitudes are 0.0122 cpd/kg/keV for 2 keV-6 keV and 0.0119 cpd/kg/keV for 3 keV-6keV. This results can be compared with DAMA modulation signature, 0.0183 ± 0.0082 cpd/kg/keV (2 keV-4 keV, 8.3σ). If the interaction is caused by the WIMP-iodine scattering, the 2 keV-4 keV energy range of NaI(Tl) should be compared with 3 keV-6 keV of CsI(Tl) to account for the slight difference in the quenching factors [13]. The 90% C.L. upper limit of this result is inconsistent with DAMA modulation signature.

2.3 Cross-section limits

The well-defined WIMP model, which gives the rate of the momentum transfers between WIMPs and detectors, and the Standard Halo Model (SHM) are used to convert from event rates to cross-sections. The SHM is well described in [10], [11] and [12]. The cross-sections are combined for both isotopes of ^{133}Cs and ^{126}I according to $1/\sigma = 1/\sigma_{Cs} + 1/\sigma_I$. Figure 3 shows the 90% C.L. upper limit of the cross-section for the cases of the spin-independent WIMP-nucleon, the spin-dependent WIMP-proton and the spin-dependent WIMP-neutron, respectively. The sensitivity becomes worse near 100 GeV/c^2 mass at the left panel of Fig. 3 because the positive (maximum in 2 June) and negative (maximum in 2 December) amplitudes have zero amplitudes averaged over this range. Reference [10] briefly discusses the negative amplitude possibility. This broadens and shifts the limits toward higher WIMP masses in the spin-dependent case.

3 Conclusion

In this report, the spin-independent cross-section limits exclude a large part of DAMA's WIMP signal area for iodine. Furthermore, the spin-dependent cross-section limits rule out completely the iodine island that corresponds to the DAMA's annual modulation. Previous KIMS results ([7] and [8]) could not provide cross-section limits for very low mass WIMPs because the PSD technique requires a 3 keV threshold energy. In contrast, the annual modulation study does not use the PSD technique and, therefore, has a lower threshold of 2 keV. Because of this point, the spin-independent and spin-dependent limits can also exclude large parts of DAMA's sodium island.

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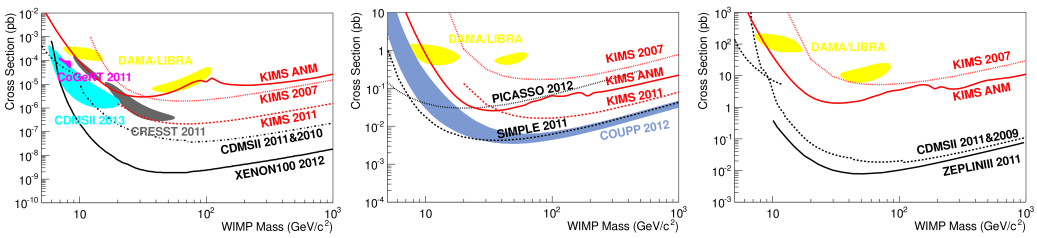

Figure 3: The preliminary results of the spin-independent (left), the spin-dependent WIMP-proton (middle) and the spin-dependent WIMP-neutron (right) cross-section limit.