Limits on the WIMPs density by annual modulation with large-volume NaI(Tl) scintillators

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1 Introduction

Experimental and theoretical studies for the universe indicate that the mass of the universe is composed mostly of invisible dark matters (DM). Cold dark matter (CDM) is of current interest from view points of particle physics, nuclear physics and astrophysics. New candidates of DM particles (SUSY etc.) lead to new theories beyond the minimal standard theory, and to possible solutions for the long-standing puzzle of the missing mass in the universe[1].

The purpose of the present work is to search for weakly interacting massive particles (WIMPs), which are considered to be convincing candidates for CDM. Investigating the annual modulation of the energy spectrum is one of the most convincing evidence for WIMPs signal [2, 3]. Recently, several groups report the annual modulation of WIMPs signal by means of large volume detectors [4, 5]. It should be noted that a large volume detector has a great advantage for studies of the annual modulation because of good statistical accuracy. However, the stability of the detector system should be taken into account. The high-sensitivity NaI detector array of ELEGANT V, which has been used primarily for studies of double beta decays [6], is quite suitable for this purpose. The NaI crystal has merits of the large volume, the low background, the easy handling, the large light output and the low noise. In this work, a search for WIMPs was made by investigating the annual modulation of the energy spectrum by means of huge NaI array.

2 Limits on WIMPs by the modulation significance

The earth's motion around the sun gives rise to the annual modulation of the WIMPs energy spectrum. The relative velocity of the earth to the galactic halo oscillates between 215km/s in June and 245km/s in December. Consequently both the WIMPs flux and their mean incident energy oscillate. Then one expect an annual modulation for the energy spectrum of recoil nuclei scattered by WIMPs. The energy spectrum of WIMPs-nucleus elastic scattering is given as,

$$\frac{dR}{dE_R} = R_0 \frac{\sqrt{\pi}}{4E_0 r b}\{\mathrm{erf}(a+b) - \mathrm{erf}(a-b)\}|F(q)|^2. \quad (1)$$

Where E_R is the recoil energy of nuclei, $E_0 = m_\chi \beta^2/2$ with m_χ being the WIMPs mass, a is the dimensionless recoil energy, $a = (E_R/E_0 r)^{1/2}$, $r = m_\chi m_N/(m_\chi + m_N)^2$ and $\mathrm{erf}(x) = (2/\pi^{1/2})\int_0^x \exp(-t^2)dt$. $b = \beta_{\mathrm{earth}}/\beta_0$. The modulation factor b has its maximum in June

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($b = 0.81$) and its minimum in December ($b = 0.92$). The difference of the energy spectrum between June and December is too small to give a significant limit by a few years measurement. Thus the bulk of the modulation in the optimum energy range must be investigated during the whole year. The statistical analysis of the annual modulation by the whole year data can be performed if the background condition is stable all over the year. The observed event rate of the WIMPs signal in the analyzing energy window is given as, $S(d) = S_0 + S_m \cos(2\pi d/365)$, where S_0, S_m and d are the non-modulating, the modulating components and the number of days from June 2nd, respectively. The indicator of the modulation significance is defined as $R = X/\sigma(X)$ where $X = \sum_d 2\cos(2\pi d/365)(S(d)+BG(d))$. $S(d)$ and $BG(d)$ are Poisson random variables of the signal and the background, respectively. The measured value of X should be compared with the measured value of the standard deviation of $\sigma(X)$ in order to obtain the modulation significance as $r = x/\sqrt{4\alpha D}$, where D is the measured value of $\sum(S(d) + BG(d))$ and x is the measured value of $\sum X$. The modulation significance is indicated by a confidence level (CL) which is given by $\mathrm{CL} = \frac{1}{2} + \frac{1}{2}\mathrm{erf}(\frac{r}{\sqrt{2}})$. The 90% CL ($r \geq 1.29$) is used as a fairly reliable evidence for the annual modulation.

The data acquisition of annual modulation was started in the middle of May and continued for one year at the Kamioka underground laboratory. The energy calibration is most important task for the study of annual modulation. Many peaks of gamma rays (242keV,295keV,352keV) and X rays (12keV,77keV) were observed when the background condition was bad. These peaks were used for energy calibration. The peak positions of 46.5keV,242keV,295keV and 352keV γ rays were continuously monitored in order to check if the energy calibration is stable. The measured values of x and D were summed if the another data were taken 183 day (half year) after or before the day. The factor $\alpha = 0.5146$ is the correction factor for the present analyzed data. The analyzed energy windows are 8keV$\sim$15keV(A), 15keV$\sim$30keV(B) and 8keV$\sim$30keV(A+B). These energy windows correspond to the recoil energy 20keV $\leq E_{R,\mathrm{Na}} \leq$ 37.5keV(A) and 140keV $\leq E_{R,\mathrm{I}} \leq$ 300keV(B), respectively.

The results for these energy windows are 68%CL(A), 54%CL(B) and 64%CL(A+B) respectively, which showed no significant annual modulation.

The another analysis was performed by investigating the variation of the event rate in the energy windows A and B. The variation of event rates in the energy windows A and B are shown in Fig.1. The modulating component S_m in the energy windows A and B were 0.63$\pm$0.86 and 1.24$\pm$0.89, respectively. The modulating components in the energy windows A and B showed no significant modulation. Thus the upper limits on the modulating component for each energy window are $S_{m,\mathrm{limit}} = 1.86\mathrm{kg}^{-1}\mathrm{day}^{-1}$ for window A and $S_{m,\mathrm{limit}} = 2.42\mathrm{kg}^{-1}\mathrm{day}^{-1}$ for window B.

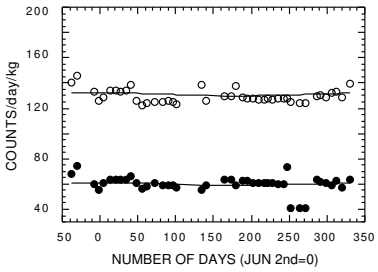

Fig.1: The changes of the event rate in the energy windows, A (closed circle) and B (open circle). The well-known backgrounds are already subtracted from the raw data. The expected annual modulations with the calculated upper limits on the modulating amplitudes are shown by solid lines.

3 Discussion

The exclusion plot on the cross section and WIMPs mass is evaluated by using the relation

$$\sigma_{p-\chi} = \frac{[\lambda^2 J(J+1)]_p}{[\lambda^2 J(J+1)]_N} \cdot \frac{\mu_p}{\mu_N} \cdot \frac{S_{\rm limit}}{S_m} \sigma_{N-\chi}. \qquad (2)$$

Where $\sigma_{\rm N-\chi} = 3.38 \times 10^{-5} \mu_N^2 g_A^2$ nb, $\mu_N = \frac{m_N m_\chi}{m_N + m_\chi}$ and $g_A^2 = C^2 J(J+1)$. In the case of WIMPs being the Majorana neutrino, $g_A^2 = |\sum_q T_q^3 \Delta q|^2 \lambda^2 J(J+1)$, where $|\sum_q T_q^3 \Delta q| = 0.4624$ is the hadronic matrix element for proton[7]. The spin matrix elements $\lambda^2 J(J+1)$ are 0.089 for ^{23}Na and 0.126 for ^{127}I [8].

The nuclear spin matrix element, $\lambda^2 J(J+1)$ for ^{23}Na and ^{127}I has been calculated by shell model calculation. The values used for the nuclear spin matrix element $\lambda^2 J(J+1)$ Other results of annual modulation search for ν_M are shown in Fig.2. Canfranc NaI [4] reported no significant annual modulation for spin-dependent WIMPs candidates. The present work gives very stringent limits for the light WIMPs with mass below 120GeV, ads shown in Fig.2. Recently, DAMA group reported the possibility of a significant annual modulation for spin-independent WIMPs candidates [5].

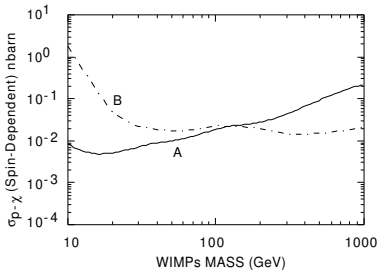

Fig.2: The exclusion plot on $\sigma_{p-\chi}$ for spin-dependent case. A: The present result; B: Exclusion plot which was derived from the subtraction between June and December by Canfranc NaI [4].

We showed the advantages of the annual modulation for the WIMPs search. Especially, a huge NaI scintillator whose mass is near by 1000kg has the great advantage in searching for the annual modulation of WIMPs. However, as is already shown in the present work, the large ambiguity of the concentration of the ^{222}Rn in the vicinity of the detector reduce the detector sensitivity. The future measurement will be carried out at Oto Cosmo Laboratory in Nara prefecture in Japan. The laboratory is placed in a railway tunnel so that the effect of the ^{222}Rn is negligible. Moreover the concentration of the ^{222}Rn will be continuously monitored. Thus the detector sensitivity will be much better than the present work.

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