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Detection of WIMPs Using Low Threshold HPGe Detector

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Abstract An HPGe detector has been constructed for the direct detection of Weakly Interactive Massive Particles(WIMPs). The supersymmetric parameter space for WIMPs detection using this HPGe detector which has 100eV low-energy threshold and 5g mass has been explored based on the so-called Minimal Supersymmetric extension of the Standard Model(MSSM). The result shows that it will be possible to provide the most stringent upper bounds of WIMP-nucleus spin-independent cross-section at the lower WIMPs mass region.

Key words WIMPs, HPGe detector, event rate, form factor, cross-section

1 Introduction

It has been one of the most interesting topics for astrophysics, cosmology and particle physics to directly detect WIMPs[1—4]. In this paper we have discussed the measurement of relic neutrilino that is a kind of most possible WIMPs and have explored the upper bounds of WIMP-nucleus spin-independent cross-sections, using cryogenic low-background HPGe detector. The neutrilino is defined as the linear superposition of four supersymmetric particles[2]:

$$\chi = N_1\tilde{\gamma} + N_2\tilde{Z} + N_3\tilde{H}_1^0 + N_4\tilde{H}_2^0, \qquad (1)$$

Here, the four supersymmetric particles are photino, zino and two neutral higgsinos. The theoretical framework used in this paper for the supersymmetric model is the Minimal Supersymmetric extension of the Standard Model[1—3,5—7]. Generally the typical energy of neutrilino will be in the range of 1 to 1000GeV and according to this estimation, the typical recoiled energies of target nucleons are less than 100keV.

Due to the low energy and low background that is the basic requirement of the detection of dark matter, it will be a big challenge for scientists to design detectors to "find" where WIMPs is. More and more experiments have been planned to explore this problem[8,9]. Different experimental technologies have been tried to decrease the background levels and increase the event rates.

Many materials have been used as the target. High pure germanium has showed dramatically lower radioactive background than others and can also obtain easily lower energy threshold that will benefit the detection of WIMPs. Usually the energy threshold of HPGe detector is about 1keV. In this article, we will discuss the possibility to achieve a much lower threshold by the Pulse Shape Discrimination (PSD) method[10—12] for a 5g-mass HPGe detector and explore the supersymmetric parameter space for WIMPs detection based on the so-called Minimal Supersymmetric extension of the Standard Model(MSSM).

2 HPGe detector

We have chosen 5g-mass HPGe detector to do the feasible researches for WIMPs detection for the first step. The mass of this kind of detector can be easily upgraded to a bigger one. Fig. 1 shows the energy spectrum of calibration using low energy X-ray sources. This spectrum is obtained out of the active and passive shielding system in order to avoid contaminating the low-background shielding environment. One can find that it is clear to see the KX-rays of Ti (4.5keV and 4.9keV) and KX-rays of Mn (5.9keV and 6.5keV). An almost 200eV threshold can be achieved from this spectrum.

The PSD method has also been used to process the

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experimental data. We digitalized the pulses of output current signal of HPGe detector by a 20MHz Flash Analog-to-Digital Converter(FADC). The parameter T-bar($\bar{t}$)[11,12] was used to describe the properties of different pulses and is shown as follows:

$$\bar{t} = Tbar = \frac{\sum_{i} t_i A_i}{\sum_{i} A_i}, \qquad (2)$$

Here, t_i is the time bin of one current shape recorded by FADC; A_i is the current amplitude recorded by FADC at t_i. The scatter plot of T-bar vs. Energy is shown in Fig.2 at the energy range below 1keV. It is very clear from Fig.2 that the signals of the noise of electronics and the signals of electron (or X-ray) can be separated clearly even about 100eV when using PSD cut properly.

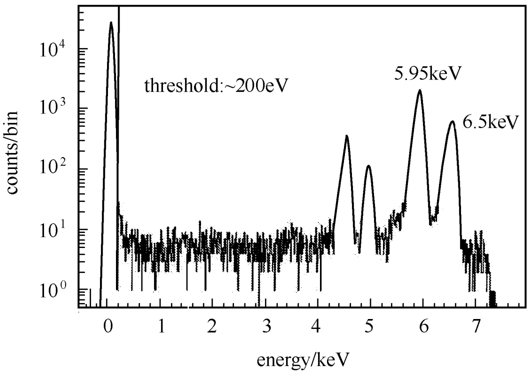

Fig. 1. The energy spectrum of HPGe detector calibrated by X-ray sources.

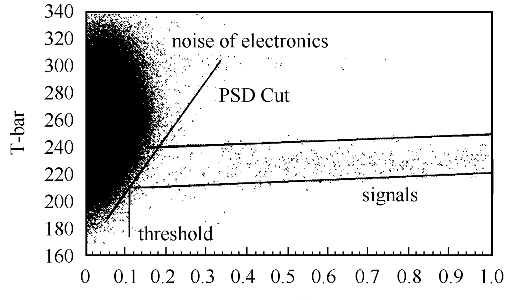

Fig. 2. The scatter plot of T-bar vs. energy for different events.

3 Energy spectrum of recoiled nuclei

For direct detection of neutrilino based on ionization, scintillation or cryogenic phonon techniques, the differential energy spectrum of nuclear recoils can be the typical form[13]:

$$\frac{\mathrm{d}R}{\mathrm{d}E_{\mathrm{R}}} = \frac{R_0}{E_0 r} \mathrm{e}^{-E_{\mathrm{R}}/E_0 r}, \qquad (3)$$

Here E_R is the recoil energy. R_0 is the total event rate (1 count/day·kg). E_0 is the most probable incident energy of a dark matter particle of mass m_χ. $r = 4 m_\chi m_N/(m_\chi + m_N)^2$ is a kinematical factor. R is the event rate (1/keV·day·kg). This means that the event rate of recoiled nucleus will exponentially increase with the decrease of its energy. So lower energy threshold will benefit the detection of WIMPs. This formula should do some corrections when it is used experimentally. Several corrections have to consider the following:

(a) The detector is located on the Earth moving through the dark matter sea around it. So it is necessary to do the correction of the velocity distribution of WIMPs relative to the detector.

(b) Due to the measurement of recoiled energy of heavy nucleus, it should consider the quenching effect of recoiled nucleus. More usually, the heavy ion will have less 'visible' energy in one detector than gamma or electron at the same energy. The ratio f_{n} of these two numbers is defined as the quenching factor of recoiled nucleus.

(c) It is different for the spin-independent and spin-dependent interaction between the WIMPs and the target nucleus of the detector. Here we just consider the spin-independent interaction because this interaction is more sensitive than the spin-dependent interaction.

(d) For spin-independent interaction, it is necessary to do the from factor correction that is due to the finite size of the nucleus.

Usually the differential event rate for elastic neutrilino-nucleus scattering is described as follows taking account of all of these corrections[14]:

$$\frac{\mathrm{d}R}{\mathrm{d}E_{\mathrm{R}}} = N_{\mathrm{T}} \frac{\rho_\chi}{m_\chi} \int_{\nu_{\min}}^{\nu_{\max}} \mathrm{d}\nu \cdot f(\nu) \cdot \nu \frac{\mathrm{d}\sigma}{\mathrm{d}E_{\mathrm{R}}}, \qquad (4)$$

Where, N_{T} is the number of the detector target nucleus, $\rho_\chi = 0.3\mathrm{GeV} \cdot c^{-2} \cdot \mathrm{cm}^{-3}$ is the local density of WIMPs in the galactic halo, m_χ is the mass of WIMPs. ν and $f(\nu)$ are the WIMPs velocity and velocity distribution function in the Earth frame respectively and $f(\nu)$ is assumed as Maxwell-Boltzmann distribution in our galaxy rest frame with a velocity dispersion of $\nu_{\mathrm{rms}} = 270 \pm 24\mathrm{km} \cdot \mathrm{s}^{-1}$ and an escape velocity of $\nu_{\mathrm{esc}} = 650 \pm 240\mathrm{km} \cdot \mathrm{s}^{-1}$. $\mathrm{d}\sigma/\mathrm{d}E_{\mathrm{R}}$ is the WIMPs-nucleus differential cross-section.

The nuclear recoil energy is given by $E_{\mathrm{R}} = m_{\mathrm{red}}^2 \nu^2 (1 -$

$\cos\theta)/m_N$, where θ is the scattering angle in the WIMPs-nucleus center-of-mass frame, m_N is the mass of nucleus and m_{red} is the reduced mass of WIMPs-nucleus. $\nu_{max} = \nu_{esc}$ is the maximum possible velocity of WIMPs in the galactic frame and equal to its escape velocity. ν_{min} is the minimal velocity which can be obtained from the minimal recoiled energy E_{th} where E_{th} is the energy threshold of the detector and can be described as:

$$\nu_{min} = \left(\frac{m_N E_{th}}{2m_{red}^2}\right)^{1/2}. \qquad (5)$$

The differential WIMPs-nucleus cross-section can be factorized as $d\sigma/dE_R \propto \sigma_C^0 F^2(E_R)$, here σ_C^0 is the point-like WIMPs-nucleus cross-section and $F^2(E_R)$ denotes the nuclear form factor defined as Fourier transform of the nuclear matter distribution. For the purpose of the comparison between different kinds of target nuclei, it is convenient to convert σ_C^0 to $\sigma_{scalar}^{nucleon}$ which is the WIMPs-nucleus scalar cross-section and the relation of these two parameters can be shown as follows[13]:

$$\sigma_{scalar}^{nucleon} = \frac{1 + m_\chi^2/m_N^2\sigma_C^0}{1 + m_\chi^2/m_p^2A^2}. \qquad (6)$$

Where, m_p is the proton mass and we use the same value for χ-neutron and χ-proton coupling. The quenching effect of recoil nucleus should also be considered and f_n is defined as $f_n = E_R/E_v$, and it is called the quenching factor of recoiled nucleus, where E_v is the "visible" energy or measured energy of recoil nucleus by the detector.

According to Equation (4), if we have measured the event rate spectrum for elastic neutrilino-nucleus scattering, the parameter $\sigma_{scalar}^{nucleon}$ can be given just as the function of parameter m_χ and that can be plotted as a two-dimension exclusive curve at the WIMPs-nucleus cross-section vs. WIMPs mass m_χ parameter space. This result allows the comparison between different target elements and the theoretical predictions.

4 Result estimation of our experiment

Here we give the estimation of WIMPs-nucleus cross-section limits as a function of the WIMPs mass for spin-independent interaction for our experiments (thin lines). The detector of our experiments is an HPGe detector with 100eV low-energy threshold and 5g mass. As usually[8,13], we take the value of quenching factor of Ge nucleus as $f_n = 0.25$. For Ge detector, the lowest event rate that has been obtained by the 2.758kg Ge detector from Heidelberg-Moscow experiment is about 0.05cpd(count/keV·kg·day) in the underground laboratory. One experiment that has been finished by our collaboration shows that the event rate can be about 1 cpd for 1kg Ge detector which is run in the passive and active shielding on the ground[15]. So it will be safe for us to assume the event rate of our HPGe detector as 0.1cpd because our detector will also be run in one 700m-depth underground laboratory. Therefore we can obtain estimation of this experiment shown in Fig. 3. At the same time we give the other two estimations using different event rates (0.01cpd) and different detector mass (100g) in Fig. 3. Several experimental results from different teams: DAMA[4], CDMS[5], EDELWEISS[6] and CRESST[7] have been shown in Fig. 3, too. These collaborations have obtained the most stringent upper limits up to now.

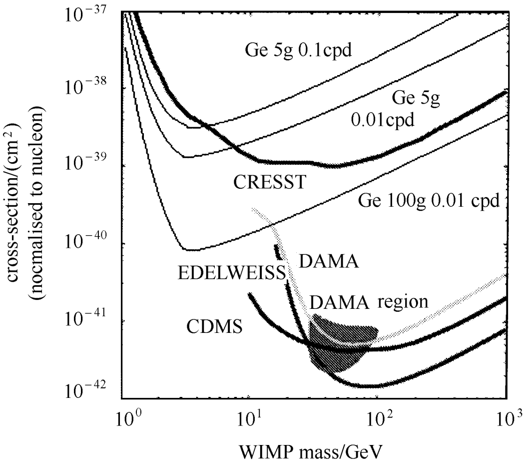

Fig. 3. The WIMPs-nucleus cross section limits of our experimental projection and results from other experiments.

5 Discussion

We have described a low-threshold HPGe detector that will be used to detect WIMP. Some discussions have been done for the theoretical estimation of WIMP-nucleus cross-section limit as a function of the WIMP mass for spin-independent interaction. The results are shown as follows:

(1) An HPGe detector with 5g mass has obtained a low energy threshold of 100eV by using the PSD method. This is very promising for using it to detect WIMP, especially for low-energy WIMP.

(2) According to the MSSM theory, the estimated WIMPs-nucleus cross-section is given for this detector with

0.1cpd background level(Fig.3).The result shows that it is a bit better than the newest result of CRESST Collaboration at the lower energy range.This projected result will be the most stringent upper limit for the spin-independent WIMP-nucleus cross-section at the lower energy range (< 7GeV)of WIMPs mass.

(3) If much lower background level (0.01cpd) can be achieved, it will show a more competitive result. Furthermore, an increase of detector mass is also beneficial for obtaining a better result. In Fig.3, we show the projected results for 5g-mass and 100g-mass detector with 0.01cpd background level respectively. The results show that it will be an impressive experimental projection.

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低能量阈 HPGe 探测器测量 WIMPs

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摘要 建立了一套用于暗物质 WIMPs 粒子直接探测研究的低本底、低能量阈高纯锗探测器,探测器质量为 5g,能量阈可以达到 100eV.基于标准模型的最小超对称性扩展理论(MSSM),讨论了该探测器可能研究的超对称参数空间.研究结果表明,在 WIMPs 较小质量区域,这一实验可能给出 WIMPs 与锗核相互作用截面的最低上限.

关键词 WIMPs 高纯锗探测器 事例率 形状因子 截面

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