First Results of Tokyo Dark Matter Search with a Lithium Fluoride Bolometer

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Abstract

The First results of the Tokyo dark matter search programme using a 21-g lithium fluoride bolometer are presented. The background spectrum was measured in the surface laboratory. We derive an exclusion plot for the spin-dependently coupled Weakly Interacting Massive Particles (WIMPs) cross section.

Key words: dark matter, bolometer, WIMPs, neutralino, LiF

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1 Introduction

The Weakly Interacting Massive Particles (WIMPs) are promising candidates for the dark matter which might comprise a large fraction of the mass of the Universe. A number of groups are developing low background detectors which have enough sensitivity to detect low energy nuclear recoils caused by the elastic scatterings of the WIMPs off nuclei. Theoretical calculations of the cross sections of the elastic scattering for various detector materials have been worked out by many authors. The cross section is usually separated into two independent parts; spin-independent and spin-dependent part. The spin-independent cross section is essentially proportional to the square of the number of nucleons in the nuclei of the detector material. Therefore, heavier nuclei are suited for the spin-independently interacting WIMPs. On the other hand, the spin-dependent cross section is a function of nuclear spin and the Landé factor of the nucleus used in the detector, where the Landé factor measures the spin factor of an unpaired nucleon in the nucleus. The cross section is also a function of the quark spin contents of the unpaired nucleon. Comparing these factors for various nuclei, one finds $^{19}$F to be the best material to detect the spin-dependently interacting WIMPs[1]. For that reason, we have been working to develop the LiF bolometer[2]. Prior to the planned underground experiments, the preliminary measurements were performed with a 21-g LiF bolometer at the surface laboratory. The results presented here are the first from the Tokyo dark matter search programme.

2 Experimental set-up and measurements

The schematic view of the bolometer is shown in Fig. 1. The bolometer is mounted in a home-made dilution refrigerator placed at the surface laboratory of the University of Tokyo. The 21-g LiF crystal ($20 \times 20 \times 20 \text{mm}^3$) is thermally anchored by two copper ribbons to the mixing chamber of the refrigerator which is cooled down to 10 mK. The temperature of the mixing chamber is monitored by a cerous magnesium nitrate (CMN) magnetic susceptibility thermometer. A home-made high-sensitivity neutron transmutation doped (NTD) germanium thermistor[3] ($1.5 \times 1 \times 1 \text{mm}^3$) is attached to the crystal with GE varnish. The temperature of the crystal is not measured directly, but the zero bias resistance of the thermistor implies that it is a little higher than the temperature of the mixing chamber.

The radioactivity of this crystal was checked by a low-background Ge gamma-ray spectrometer before constructing the bolometer. The concentration of radio-contaminations was less than 0.2 ppb for U, 1 ppb for Th, and 2 ppm for K. The refrigerator is mostly made of low-radioactivity materials, which
were also checked by the Ge gamma-ray spectrometer. The concentration of radio-contaminations of the refrigerator materials were less than 8 ppb for U, 20 ppb for Th, and 10 ppm for K. In particular, the refrigerator materials near the detector crystal were selected carefully. No detectable radioactivity was observed in the radio-assay with the Ge gamma-ray spectrometer. The refrigerator is surrounded by lead shield with a thickness of 10 cm.

A voltage change across the dc-biased NTD Ge thermistor is fed into the source follower placed at the stage with a temperature of 4 K, which includes a low-noise J-FET heated up to 110 K. The signal is then fed into an external low-noise amplifier outside the refrigerator and the pulse shape of the signal is recorded by a digital oscilloscope for off-line analysis.

The detector is calibrated using gamma-ray sources ($^{60}$Co, $^{137}$Cs, and $^{241}$Am) and an alpha-ray source ($^{241}$Am). The $^{241}$Am source was set inside the cryostat in the calibration run previous to the background measurements. In the periodic calibration during the background measurements, the $^{60}$Co and $^{137}$Cs sources are set between the cryostat and the lead shield. Compton edges are used for the calibration by high energy gamma rays which do not make enough photoelectric peak in the low atomic number LiF crystal. An energy resolution for the 60 keV gamma-ray from $^{241}$Am is 4.8 keV (FWHM), which is limited predominantly by the base-line fluctuation. Good linearity is confirmed up to about 5 MeV as shown in Fig.2, where the detector gain for alpha-rays is the same as that for gamma-rays. It implies that the bolometer has no suppression on the collection of the nuclear recoil energy. It must be noted that for the detectors based on ionization such as semiconductor detector and scintillator, the observed energy is generally less than the recoil energy. The detector gain is fairly stable within ±5% against the change of the temperature of the mixing chamber from 9 mK to 13 mK. This feature is desirable for the long term running to search for the WIMPs.

3 Results and discussions

With this 21-g LiF bolometer, we made a test running at the surface laboratory at the Hongo campus of the University of Tokyo. Fig. 3 shows the background spectrum corresponding to an exposure of 21 g × 1.19 days. Relatively flat continuum down to 14 keV is observed and the counting rate increases steeply below 14 keV. This increase is mainly due to pick-up noise. The energy spectrum above 14 keV, therefore, is used in our analysis. The counting rate itself is still too high because of the background radiation in the surface laboratory and incompleteness of the radiation shield.

We evaluate an exclusion plot for the spin-dependently interacting WIMP
cross section from the background data obtained by this short test running. The lower limit of the WIMP-nucleus cross section, $\sigma_{\text{WIMP}-N}$, at 95% CL for a fixed WIMP mass can be derived by comparing the obtained background spectrum with the theoretical one. This comparison is done in each energy bin above 14 keV and the lowest value of the cross-section is adopted. The theoretical recoil spectrum for a given WIMP mass is calculated assuming a Maxwellian dark matter velocity distribution with rms velocity of 230 km/s, and then folded with the measured energy resolution and the nuclear form factor. We also assume the local density of the WIMP to be 0.3 GeV/cm$^3$.

It is customary to convert thus obtained $\sigma_{\text{WIMP}-N}$ into a point-like cross section incident on a single proton, $\sigma_{\text{WIMP}-p}$, in order to compare the results of various experiments with different nuclei with one another. We follow the formula (6.6) in Ref. [4] with the spin factor for the fluorine of the odd group model given in Ref. [1]. In Fig. 4, our 95% CL exclusion limits on $\sigma_{\text{WIMP}-p}$ are plotted against the WIMP mass.

We also calculated the exclusion limits for the results of BPRS collaboration[5], UKDMC[6], and EDELWEISS collaboration[7] in the same manner as used in our analysis. They are shown in the same figure for comparison. These three experiments were performed in deep underground laboratories over a long term. Our short-term and small-size experiment in the surface laboratory enabled us to place the exclusion limit which is only a factor of three and ten behind that of EDELWEISS and BPRS group respectively at the WIMP mass of 20 GeV. It demonstrates the advantages of the use of $^{19}$F and the low energy threshold of the bolometer for nuclear recoil.

4 Prospects

We have already constructed a multiple array of eight pieces of 21-g LiF bolometers for the underground experiments and confirmed that each detector has similar performance to that of the single 21-g LiF bolometer used in this work. Installation of the arrayed bolometer in the Nokogiri-yama underground laboratory of the Institute for Cosmic Ray Research, University of Tokyo is in progress. The laboratory is 180 m w.e. deep and located about 60 km to the south of Tokyo. We are going to make engineering runs to make experiences to operate the cryogenic detectors at an underground laboratory. The arrayed bolometer will be shielded with 10 cm-thick oxygen-free copper, 15 cm-thick lead, 1 g/cm$^2$-thick boric acid, and 20 cm-thick polyethylene. Furthermore, a muon veto system with 2 cm-thick plastic scintillator will be employed in order to reduce the background produced by the cosmic ray muon. One of the primary background sources in an underground WIMPs search is fast neutron which produces the nuclear recoil. The ambient fast neutron flux at the
Nokogiri-yama underground laboratory is $2.3 \times 10^{-4} n/cm^2/s$ which is 1/50 of that at the surface laboratory of the University of Tokyo and expected to be reduced with polyethylene shield by a factor of five. The measurements in the Nokogiri-yama underground laboratory is expected to bring the exclusion limit on $\sigma_{\text{WIMP} \rightarrow p}$ below the limit of UKDMC. The measurements in a still deeper underground site will enable us to reach the sensitivity of $\sigma_{\text{WIMP} \rightarrow p} \sim 0.01$ pb, which is comparable to the predicted SUSY WIMP (neutralino) cross section.

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Fig. 1. Schematic drawing of the LiF bolometer.

Fig. 2. Measured linearity of the bolometer. The solid line is the best fit to the data.

Fig. 3. Background spectrum obtained with the LiF bolometer. An exposure is 21 g×1.19 days.

Fig. 4. Exclusion plot derived from the background spectrum shown in Fig. 3 for spin-dependent interacting WIMPs as a function of the WIMP mass. For comparison, exclusion plots derived from the data in Ref. [5–7] and scatter plot predicted in MSSM (10 GeV ≤ M2 ≤ 1 TeV, 10 GeV ≤ |μ| ≤ 1 TeV, tan β = 2, 8) are also given.
Tokyo (LiF) surface
EDELWEISS (sapphire) 4800 m.w.e.
BPRS (CaF2(Eu)) 3500 m.w.e.
UKDMC (NaI(Tl)) 3600 m.w.e.

WIMP-p cross section [pb]
WIMP Mass [GeV]

MSSM