First Results from Dark Matter Search Experiment in the Nokogiriyama Underground Cell

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An experiment to search for hypothetical particle dark matter using cryogenic thermal detector, or bolometer is ongoing. The bolometer consists of eight pieces of 21 g LiF absorbers and sensitive NTD germanium thermistors attached to them and is installed in the Nokogiriyama underground cell which is a shallow depth site (∼15 m w.e.). We report on the results from the first running for about ten days using this arrayed bolometer system together with appropriate shieldings and muon veto counters. From the obtained energy spectra the exclusion limits for the cross section of the elastic neutralino-proton scattering are derived under commonly accepted astrophysical assumptions. The sensitivity for the light neutralino with a mass below 5 GeV is improved by this work.

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I. INTRODUCTION

There are a number of observational evidences to believe that a large fraction of the matter in the Universe exists in the form of non-baryonic particle dark matter. Supersymmetric neutralino is one of the most plausible candidates for such exotic particle dark matter. Various experimental efforts are being made aiming at detection of low energy nuclear recoils caused by the elastic scatterings of the neutralinos off nuclei [1].

Conventional detectors like semiconductor detectors or scintillators generally have a quenching factor less than unity. Here the quenching factor is defined as the ratio of the energy detection efficiency for a nuclear recoil to that for an electron. On the other hand, because the bolometer is sensitive to the whole energy deposited in the absorber the quenching factor of the bolometer should be unity in principle. Actually a quenching factor close to unity has been measured by Milan group [2].

We have been developing bolometers with lithium fluoride absorbers [3]. Fluorine is considered to have a large cross section for elastic scattering of the axially-coupled neutralino off the nucleus compared with other nuclei [4]. Recently we have successfully constructed the bolometer array with a total mass of 168 g and installed it in the Nokogiriyama underground cell with a depth of 15 m w.e.

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In this paper we report on the first results from the experiment performed in the Nokogiriyama underground cell using the bolometer array.

II. EXPERIMENTAL SET-UP AND MEASUREMENT

The bolometer array used in this work contains eight 21 g LiF bolometers. The schematic drawing of the bolometer array is shown in Fig. 1. The neutron transmutation doped (NTD) germanium thermistors with the similar temperature dependence of the resistance are attached to the crystals. The thermistor senses a small temperature rise of the absorber crystal caused by the neutralino-nucleus scattering. Each crystal is placed on four copper posts and thermally insulated by the Kapton sheets. Moderate thermal anchoring of the crystal to the copper holder with a temperature of 10 mK is realized by a oxygen free copper (OFC) ribbon. The lithium fluoride crystals are checked by a low-background Ge spectrometer prior to the construction of the bolometer. The concentration of radioactive contaminations is less than 0.2 ppb for U, 1 ppb for Th, and 2 ppm for K. The bolometer array is mounted on a mixing chamber of a dilution refrigerator which is mostly made of low-radioactivity materials radio-assayed in advance by low-background Ge spectrometer.

Each thermistor is biased through a 100 MΩ load resistor. The voltage change across the thermistor is fed into the eight channel source follower circuit placed at the 4 K stage which include a low noise junction field effect transistor (J-FET), Hitachi 2SK163. Since the J-FET does not work at this low temperature, it is connected to a printed circuit board with thin stainless steel tubes and manganin wires to be thermally isolated from the circuit board with a temperature of 4 K and the temperature of the FET is maintained above 100 K by the heat produced by itself.

The signal from the source follower circuit is in turn amplified by an eight channel voltage amplifier placed just above the refrigerator. The output of the voltage amplifier is fed into a double pole low-pass filter with a cut-off frequency of 226 Hz and in turn into the 16-bit waveform digitizer to record the pulse shape of the signal for off-line analysis.

The passive radiation shielding consists of 10 cm-thick oxygen free high conductivity copper layer, 15 cm-thick lead layer, 1 g cm\(^{-2}\)-thick boric acid layer and 20 cm-thick polyethylene layer. The latter two layers act as a neutron shield. In order to avoid muon-induced background we employ a veto system which consists of 2 cm-thick plastic scintillators.

The constructed detector system is installed in the Nokogiriyama underground cell which is located about 100 km south from Tokyo and relatively easy to access. The depth of an overburden of sand is inferred to be about 15 m w.e. In this work six bolometers of the bolometer array are used and energy spectrum are measured for about ten days. Two bolometers have some problems in the cooling procedure.

Since the detector is enclosed in a cryogenic vacuum can during the measurements it is impossible to place the gamma-ray source close to the detector for energy calibration. The energy calibration during the measurements is, therefore, performed by 662 keV gamma-rays from a \(^{137}\)Cs source and 1333 keV and 1173 keV gamma-rays from a \(^{60}\)Co source placed outside a helium dewar of the dilution refrigerator and inside the radiation shieldings. Furthermore, the sharp peak at 4.78 MeV due to the neutron capture reaction of \(^{6}\)Li observed in the background spectrum is also used for the energy calibration. Fig. 2 shows one of the obtained energy calibration plots. Linearities of the six bolometers up to 5 MeV are recognized. It must be noted that linearity down to 60 keV gamma-ray is confirmed prior to this measurement using gamma-ray from \(^{241}\)Am source set inside the cryostat.

III. ENERGY SPECTRA AND DARK MATTER LIMITS

Fig. 3 shows the energy spectra obtained by the six bolometers during ten days. The bump in the low energy region is considered to be due to microphonics caused by a helium liquefier which recondenses evaporated helium gas from the dewar. While the similar spectra are obtained for four bolometers (D3, D5, D6, and D8), the spectra for the other two bolometers
(D1 and D4) are affected by microphonics below 30 to 40 keV because of their low detector gains.

Comparing the measured energy spectrum with the expected recoil spectrum, the exclusion limits for the cross section for elastic neutralino scattering off the nucleus can be extracted. The calculation is performed in the same manner used in Ref. [9]. The theoretical recoil spectrum 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 halo density of the neutralino to be 0.3 GeV/cm$^3$. The spin factors calculated assuming an odd group model as a nuclear shell model are 0.75 for $^{19}$F and 0.417 for $^7$Li [4]. Since the detector responses for the six bolometers are not the same, the upper limit of the cross section is evaluated independently from the spectrum of each detector. For a given neutralino mass the lowest value of the cross section is taken as a combined limit from the results of the six detectors.

The calculated exclusion limits in case of the spin-dependent interaction are given in Fig. 4. For comparison the exclusion limits derived from the data in the other experiments at deep underground sites [6–10] and the scatter plots predicted in the minimal supersymmetric theories are also shown. Although the other experiments except for Osaka experiment are performed at deep underground laboratories, our experiment gives comparable limits for the light neutralino. This owes to the large cross section for the spin-dependent interaction of $^{19}$F and the low energy threshold of the bolometer. The sensitivity for neutralinos with a mass below 5 GeV is improved by this work.

### IV. PROSPECTS

Compton scattered gamma-rays from the aperture of the shielding and gamma-rays produced through the interaction of cosmic ray muon within the shielding materials are considered major background sources. In order to reduce the muon-correlated background, the veto efficiency must be improved. The present incompleteness of the veto is due to the penetrations for vacuum tubes and the tube of the helium liquefier. Increasing of the coverage of the plastic scintillator will improve the veto efficiency up to 98%. Against the Compton scattered gamma-ray background, internal lead shielding with a thickness of 20 mm surrounding the lithium fluoride bolometer array will be installed. The shielding is made of over 200 year old low-activity lead with a concentration of $^{210}$Pb of less than 0.05 pCi/g. The Compton scattered gamma-rays can be reduced by two orders of magnitude by this internal shielding. Since lead fluorescence X-rays are produced mainly by the muon interaction, their contribution can be ignored if muons are sufficiently vetoed. If these improvements are realized, the sensitivity of this experiment will be improved by more than an order of magnitude even at this shallow depth.

The detector system will be installed in a underground facility with a sufficient depth where cosmic muon induced background is expected to be negligible. The long-term measurements in a deep underground site will bring the sensitivity to the spin-dependent interaction below the level predicted by the supersymmetric theory.

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[1] E. W. Kolb and M. S. Turner, *The Early Universe* (Addison-Wesley, Redwood City, 1989); P. F. Smith and J. D. Lewin, *Phys. Rep.* **187**(1990)203; R. Bernabei, *Riv. Nuovo Cimento* 18(1995), No.5.

[2] A. Alessandrello et al., *Phys. Lett.* B **408**(1997)465.

[3] M. Minowa et al., *Nucl. Instrum. Methods* A **327**(1993)612; W. Ootani et al., *Astrop. Phys.* **9**(1998)325; W. Ootani, doctoral thesis, University of Tokyo, 1998.

[4] J. Ellis and R. A. Flores, *Phys. Lett.* B **263**(1991)259; J. Ellis and R. A. Flores, *Phys. Lett.* B **300**(1993)175.

[5] W. Ootani et al., *Nucl. Instrum. Methods* A **372**(1996)534.

[6] A. de Bellefon et al., *Astrop. Phys.* **6**(1996)35.

[7] C. Bacci et al., *Astrop. Phys.* **2**(1994)117.

[8] R. Bernabei et al., *Astrop. Phys.* **7**(1997)73; R. Bernabei et al., *Phys. Lett.* B **389**(1996)73.

[9] P. F. Smith et al., *Phys. Lett.* B **379**(1996)299.

[10] R. Hazama, doctoral thesis, Osaka University, 1998.
FIG. 1. Schematic drawing of the lithium fluoride bolometer array.
FIG. 2. Linearity obtained for one of six bolometers.
FIG. 3. Energy spectra obtained by six LiF bolometers.
FIG. 4. Exclusion limit obtained from this experiment for spin-dependent interaction as a function of neutralino mass.
Thermistor

OFC holder (10 mK)

LiF (21g)

Contact pad

Li^+ → t + α
Q = 4.78 MeV

Energy (keV)

Pulseheight

60Co

137Cs
