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Application of a large-volume NaI scintillator to search for dark matter

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Application of a large-volume NaI scintillator to search for the cold dark matter (DM) in the Universe is discussed. A low-noise ($\sim$5 keV) and low-background ($\sim$5/keV kg day) were achieved even with a large (36.5 kg) NaI scintillator. Light output efficiencies for ^{23}Na and ^{127}I were measured as 0.4$\pm$0.2 and 0.05$\pm$0.02, in the recoil energy range of 5–100 keV and 40–300 keV, respectively. NaI is shown to have merits of a large volume, large scattering cross sections for dark matter, and of 100% abundance of finite-spin nucleus, but to have the demerits of a small form factor due to the finite-size effect of ^{127}I at the presently measured energy region.

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The present Rapid Communication reports the first application of a huge scintillation detector to search for the nonbaryonic dark matter (DM) by investigating directly the elastic scattering of DM by ^{127}I and ^{23}Na nuclei in the NaI detector. Experimentally, DM candidates like heavy neutrino or neutral supersymmetric particles are able to be directly investigated by recoil nuclei scattered off in a detector [1]. The expected density of these candidates near the Earth is as much as 0.3 GeV/cm^3, assuming that they are the major component of DM. As their average velocity relative to the motion of the Earth is as slow as $v/c \sim 10^{-3}$, the expected recoil energy (E_R) of the nucleus which is scattered off by DM is of the order of a few keV to 100 keV, depending on the scattering angle and the DM mass.

The cross section of DM-nucleus scattering, if we assume DM to be neutrinos, is given in terms of the vector (g_V) and the axial vector coupling (g_A) constants, and it is proportional to the square of g_V and/or g_A. g_V and g_A are written as

$$g_V = N_n - (1-4\sin^2\theta_W)N_p \ , \qquad (1)$$

$$g_A = \lambda\sqrt{J(J+1)}\sum_q T_q^3 \Delta q \ , \qquad (2)$$

where N_n and N_p are numbers of the neutrons and protons in the target nucleus, respectively, θ_W is the Weinberg angle, λ is the effective spin parameter of the nucleus, T_q^3 is the third component of weak isospin, and Δq is the fraction of the spin carried by the quark.

In the case of the vector coupling DM such as the Dirac neutrino (ν_D), the scalar neutrino ($\tilde{\nu}$), and so on, since $g_V \gg g_A$ for most target nuclei and $4\sin^2\theta_W \simeq 1$, the cross section is approximately proportional to the square of the number of the neutrons (N_n) in the target (detector) nucleus.

On the other hand, for the axial vector (spin) coupling DM such as the Majorana neutrino (ν_M), and so on, the cross section has only the axial vector term g_A. In this case, the cross section depends only on the valence nucleon carrying the spin of the nucleus. g_A (λ and Δq) is strongly model dependent, but Δq is evaluated [2] by the most recent analysis of the EMC result and the most recent analyses of hyperon decay, and single particle shell model estimates of λ for ^{73}Ge, ^{127}I, and Xe isotopes are shown to be within 15% of the more reliable value for nucleon spin matrix element by using the interacting boson-fermion model [3].

However, the coherency in the sum of the scattering amplitude over all nucleons may be broken in case of large momentum transfer ($q\cdot R > 1$) where R is the radius of the nuclei [2,4–6]. In this case, we cannot treat the nucleus as a point particle and the cross section becomes small. Details of this effect will be mentioned afterward.

Recently, we have succeeded in developing a very low-noise (low-background) NaI detector with a large volume, which has primarily been used as x-ray and γ-ray detectors of ELEGANTS V (Electron Gamma-Ray Neutrino Spectrometer V) [7]. The NaI consists of the 100% odd-N_p ^{23}Na with $J=\frac{3}{2}$ and the 100% odd-N_p ^{127}I with $J=\frac{5}{2}$ and the N_n for ^{127}I is as large as $N_n=74$. Once we have achieved the low-noise requirement in the NaI detector, it is feasible for investigating DM because of the large volume ($\simeq 10-100$ kg) detector and of the large cross section for both the vector coupled and the spin coupled particles in the condition of $qR \ll 1$.

In the present experiment, the detector system was made of nine NaI modules out of 20 ones used for ELEGANTS V, each with dimensions of 102 mm $\times$ 102 mm$\times$1024 mm. They are assembled as shown in Fig. 1. The central NaI module acts as the DM detector and the surrounding 8 NaI modules act as passive and active shields. The NaI detector is viewed at both ends by low-background photomultipliers (PMT) with the K-free window. A 102 mm quartz light guide is inserted between the NaI and PMT to absorb γ rays from radioac-

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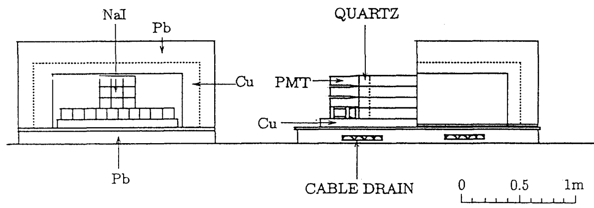

FIG. 1. Schematic drawings of the NaI detector arrangement in ELEGANTS V.

tive contamination in the PMT's. The NaI material has been purified to the level below 0.3 ppm for potassium, and the low-background aluminum metal has been used for the detector case. The detector array is shielded by the 10 cm OFHC (oxygen free high conductive copper) and 15 cm lead bricks, the inside of which is filled by the N_2 gas evaporated from the liquid N_2 to replace the air containing natural Rn gas. In order to avoid cosmic-ray backgrounds, the whole system is set at the Kamioka underground laboratory with 2700 mwe. Details of the detector array are given elsewhere [7].

The pulse-height spectrum of the central NaI detector in anticoincidence with all pulses from the surrounding 8 NaI detectors were observed and the typical low energy part of the observed spectrum is shown in Fig. 2 for a live time of 6.0 days (220 kg day). The energy scale is calibrated by using the 59.5 and 17.5 keV γ ray and x ray from the ^{241}Am source, 14.4 and 122 keV γ rays from the ^{57}Co source, and 28 keV x ray from ^{127}I in the NaI detector itself. The bump at the 46.5 keV is due to an extremely small amount ($\sim 2.6\times10^{-3}$ Bq/kg) of ^{210}Pb radioactive contamination inside the NaI crystal [8]. The contribution of β rays from ^{210}Pb decay in the low-energy region (~ 10 keV) spectrum was evaluated by the observed peak yield of the 46.5 keV γ ray from ^{210}Pb. The noise threshold is around 4 keV and the unknown background rate at 5 keV is around 5.1/keV day kg as shown in Fig. 2, which are remarkably low levels for this type of large NaI detector.

The velocity of the recoil nucleus scattered off by DM is as slow as $v_R \sim 10^{-3}c$. Thus the ionization (pulse

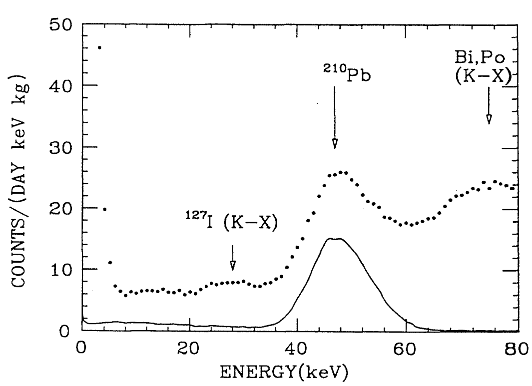

FIG. 2 Observed spectrum at the energy region of the present interest. Solid line shows the component of ^{210}Pb contamination.

height) of the recoil nucleus is much reduced in comparison with that of the electron with $v_e \simeq c$ [9]. The observed energy (pulse height) E_0 is, for simplicity, given as

$$E_0 = fE_R , \tag{3}$$

where E_R is the recoil energy and f is the conversion (reduction) factor of the pulse height for the recoiling nucleus with respect to the electron.

The factors f for Na and I were obtained by measuring the pulse-height spectrum of recoil nuclei produced by inelastic and elastic scattering of fast neutrons from the ^{252}Cf source with a small (2.5 cm $\phi\times0.5$ cm) NaI detector. In order to absorb γ rays from the ^{252}Cf source, a 2 cm thick lead plate and a 1.5 cm thick copper plate were set in front of the detector. Multiple scattering effects of neutron are negligibly small in the detector because of its small size. The linearity in the light output was examined by using ^{57}Co (6.4 keV, 14.4 keV), ^{133}Ba (31 keV), ^{210}Pb (46.5 keV), ^{241}Am (59.5 keV), and ^{128}I (4 keV) sources. ^{128}I ($T_{1/2}=24.99$ min) was produced inside the detector by the neutron capture. The nonlinearity in the light output was negligibly small in the range of 4–60 keV. A relatively wide gate of 2 μsec of the charge analog-to-digital convertor (LeCroy 2249W) was used to avoid effects of the difference of time delays in the light-emission process.

The observed peak at the energy of 56.7 keV (^{127}I*), which is shown in Fig. 3(a), is due to the inelastic scattering of ^{127}I$(n,n')^{127}$I*. The peak shows a tail at higher energy side due to the additional recoil energy of ^{127}I. The peak was simulated by the sum energy spectrum of $E_{\rm total}$ ($=56.7$ keV$+f_IE_R$) with the measured energy resolution of 8.0 keV (FWHM) using the Monte Carlo method, where the recoil energy (E_R) of ^{127}I* is calculated by the kinematics of ^{127}I$(n,n')^{127}$I*(56.7 keV) reaction. The typical peak shape and the energy resolution were examined by using the ^{241}Am (59.5 keV) source. The energy spectrum of neutrons from the ^{252}Cf source was assumed to be a Maxwellian distribution with the mean energy of 2.35 MeV. The peak was well reproduced with the factor $f_I=0.05\pm0.02$ as shown in Fig. 3(a).

A low energy spectrum only due to neutron elastic scattering is also shown in Fig. 3(b). Here the component of other background due to the irradiation of neutron was carefully subtracted by measuring the spectrum before and after neutron irradiation. The spectra of recoil energy of neutron elastic scattering from ^{252}Cf neutron source are expressed by the function

$$g(E_R)=\alpha\exp(a_1E_R^3+a_2E_R^2+a_3E_R+a_4) , \tag{4}$$

where α is the normalization constant. The measured energy spectrum of Fig. 3(b) was fitted by the function

$$Y(E_0)=\alpha_{\rm Na}g_{\rm Na}\left[\frac{E_0}{f_{\rm Na}}\right]+\alpha_{\rm I}g_{\rm I}\left[\frac{E_0}{f_{\rm I}}\right]+\beta(E_0) , \tag{5}$$

where $\beta(E_0)$ is the energy function of unknown background. From the fit we obtained the values $f_{\rm Na}=0.4\pm0.2$, $f_{\rm I}=0.05\pm0.02$, and $\beta(E)\approx0$ in the energy region of $E_0=2$–40 keV as shown in Fig. 3(b). Here the quoted errors of factors f's are mainly due to the sys-

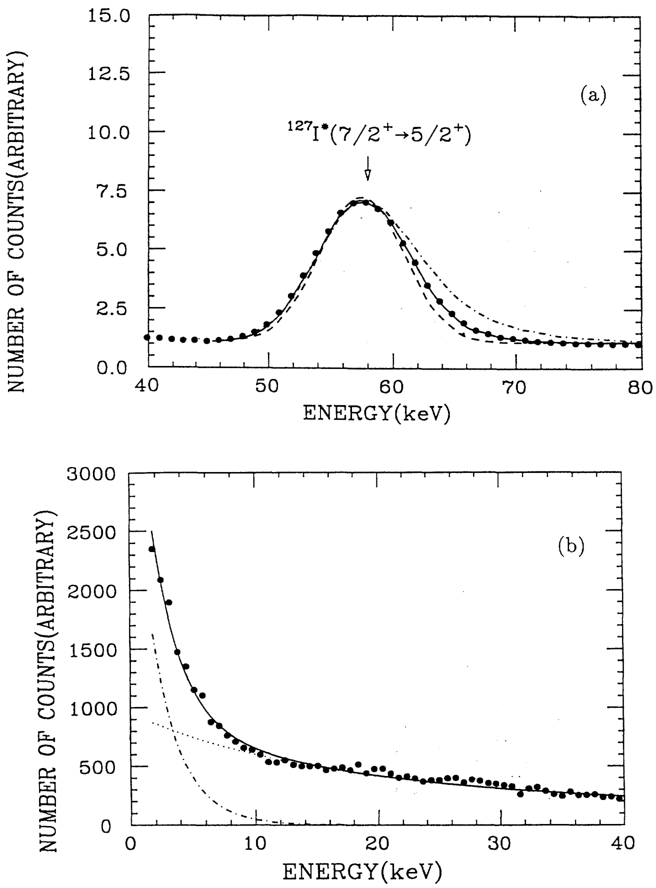

FIG. 3. (a) A part of the observed energy spectrum at the 50–60 keV region for neutrons fom ^{252}Cf. The peak corresponds to the 56.7 keV γ ray from the first excited state in ^{127}I by inelastic scattering of the neutrons. The tail at the high energy side indicates the contribution from the recoil of ^{127}I. The dots show the experimental result. The solid line shows the estimated spectrum by the Monte Carlo simulation with the conversion factor $f=0.05$. Dashed and dotted lines indicate those with $f=0$ and $f=0.1$, respectively, for comparison. (b) The observed energy spectrum at the 0–40 keV region for elastic scattering of the ^{252}Cf neutron. The dotted and dash-dotted lines indicate the component of ^{127}I and ^{23}Na recoil, respectively.

tematic errors in the fitting procedure. Statistical errors are negligibly small. The systematic errors (σ_f) are estimated by using the relationship of $\sigma_f^2=2/(\partial^2\chi^2/\partial f^2)$ in the curve fitting procedure, where χ^2 is known in the least-squares method. The measured factors $f_{\rm Na}$ and $f_{\rm I}$ are effective only in the energy regions $E_R=5-100$ keV ($E_0=2-40$ keV), and $E_R=40-300$ keV ($E_0=2-20$ keV), respectively. Angular distributions of neutron elastic scattering in the Monte Carlo simulations are taken from the experimental data [10,11]. The measured factor $f_{\rm Na}$ is consistent with the recent precise measurement by the Saclay group [13].

Evaluating the limit on the maximum halo density of the DM's, the observed spectrum, shown in Fig. 2, was analyzed in terms of the recoil spectra of ^{23}Na and ^{127}I with the measured conversion factors. The small value of the conversion factor ($f_{\rm I}$) affects the lowest measurable energy of ^{127}I recoil. The threshold energy of $E_0=5$ keV corresponds to $E_R=100$ keV, and the condition of $qR \ll 1$ is broken. We must consider the finite-size effect of the nucleus in the DM-nucleus cross section. The finite-size effect of the cross section is written in terms of a form factor $F(q)$ as

$$\frac{d\sigma}{d\Omega}=\left[\frac{d\sigma}{d\Omega}\right]_{\rm point}|F(q)|^2 , \quad (6)$$

where $(d\sigma/d\Omega)_{\rm point}$ is the cross section of the DM-nucleus elastic scattering by using g_V and g_A in Eqs. (1) and (2), which are calculated assuming that the target nucleus is a point particle.

In the case of ^{127}I, since the threshold energy of $E_0=5$ keV ($E_R=100$ keV) corresponds to the momentum transfer $q\sim 0.8$ fm^{-1}, the form factor $|F(q)|^2$ $[=|\int\rho(r)\exp(-iqr)d^3r|^2]$ is about 0.02, where $\rho(r)$ is the nucleon density in the nucleus. Thus the limit on DM is weaker by a factor $\frac{1}{50}$ than that assuming the point target nucleus.

The evaluated maximum halo density limits on ν_D and ν_M are shown as solid lines in Fig. 4. The limit evaluated by the point target nucleus approximation is also shown by dotted lines. The bends in the lines in the mass region lower than 30 GeV are due to the effect of ^{23}Na. Since ^{23}Na is $\frac{1}{4}$ as massive as ^{127}I, the event rate per keV of the mass range below 30 GeV by ^{23}Na recoil is larger than that by ^{127}I recoil.

Since ^{127}I has much more neutrons than ^{23}Na, it gives more stringent limits on the density of ν_D than ^{23}Na although the form factor of ^{127}I is much smaller. On the other hand, ^{23}Na with the form factor $|F(q)|^2$ $[=|\int|\psi_{nl}(r)|^2\exp(iqr)d^3r|^2)\simeq 1]$ gives more stringent limits on the density of ν_M than ^{127}I, where $\psi_{nl}(r)$ is the

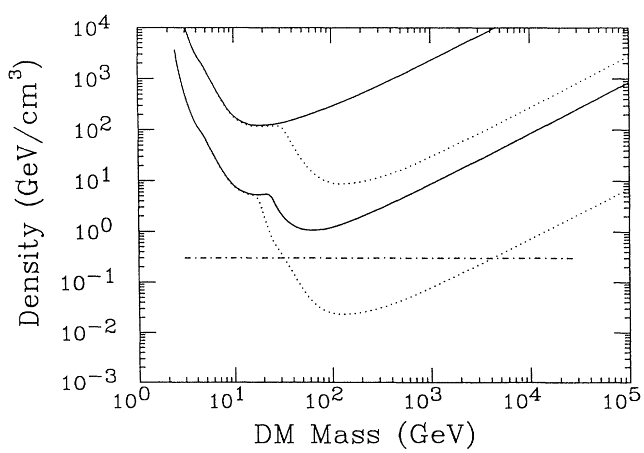

FIG. 4. The evaluated maximum halo density limits on ν_D (lower) and ν_M (upper). Upper regions from the lines are excluded. The effects by the form factor $|F(q)|^2$ of ^{23}Na and ^{127}I are included in the analysis (solid lines). Dotted lines show the result of point particle approximation. The dash-dotted line indicates the crucial density of 0.3 GeV/cm^3.

wave function of the valence nucleon carrying the spin fraction Δq. These limits are weaker than the Ge experiment [12] by a factor of 5 for ν_M and a factor of 100 for ν_D.

In conclusion, we have applied a large-volume NaI scintillator to search for DM and achieved a low-noise ($\simeq 5$ keV) and low-background [$\simeq 5$ counts/(keV kg day)] measurement. The ionization efficiency, which is indispensable for DM search and other related subjects, has been successfully measured by neutron scattering, resulting in $f_{\mathrm{I}} = 0.05 \pm 0.02$ and $f_{\mathrm{Na}} = 0.4 \pm 0.2$. Because of the small conversion factor (f_{I}), there is large finite-size effect of ^{127}I in the presently measured energy region. It is very important to reduce the noise level to measure the lower momentum transfer region. This experiment made sure that the scintillation detector can be used for the direct detection of DM. The present method can be applied to more promising scintillators such as CaF_2 [large g_A, large f, and $|F(q)|^2 \simeq 1$].

Note added in proof. After the submission of this Rapid Communication, two articles concerning the application of the NaI scintillator were brought to our attention [14]. Our detector is about 47 times heavier than theirs, but the noise and background levels and the DM limits in the present work are comparable to their result.

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