サーチフェーリとハッリアスメントがKamiokandeで検出される場合のニュートラリオン型暗黒物を検出する

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Search for neutralino dark matter heavier than the W boson at Kamiokande

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We have searched for possible high-energy neutrino signals which are expected from massive dark matter captured by the Earth and the Sun by making use of upward-going muon samples collected during 7 years of operation of the Kamiokande detector. No excess of events was found from the Earth or the Sun, thus giving an excluded range of parameters for the neutralino dark matter which is hypothesized to constitute the halo of the Galaxy. The upper bounds extend to a mass range of up to ~ 1 TeV, which was never analyzed in previous indirect searches.
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I. INTRODUCTION

Various observational evidence suggests that most of the matter in the Universe is nonluminous. Also, there are a variety of arguments that this matter (so-called dark matter) is nonbaryonic [1].

Studies of the early Universe and modern particle theories working together have provided a list of candidates for dark matter. Most of them are hypothetical particles and other hypothetical entities: axions, monopoles and so on. A part of these candidates are called weakly interacting massive particles (WIMP's). WIMP's are, if they

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exist, cold dark matter (CDM), since they are nonrelativistic at the time of decoupling.

The motivation for cold dark-matter candidates comes from both astrophysical and cosmological arguments. The former involves a scenario for structure formation in the universe. There is an argument [3] that recent data concerning the cosmic microwave background radiation anisotropy by the Cosmic Background Explorer (COBE) satellite [2] is well explained by \( \Omega_{CDM} h^2 \sim 0.2 \) (\( \Omega = \rho / \rho_{\text{crit}} \) is the density parameter of the Universe, where \( \rho_{\text{crit}} = 1.88 \times 10^{-27} \text{g/cm}^3 \) and \( h \) is the Hubble constant in units of 100 km/s Mpc), independently of the dynamical model of large-scale structure formation. In other words, even if dark matter is made of different components, cold dark matter is a necessary ingredient, if this is the case. The other argument is that their relic abundance after the big bang is on the order of the critical density \( \rho_{\text{crit}} \) in a wide range of parameters characterizing them. This comes from the fact that the annihilation cross section, which determines the relic density, is roughly the same as that of weak interactions.

Experimental searches for cold dark matter have been carried out in two ways. One involves a search for nuclear recoil signals from dark matter-nucleus scattering in detectors [4]. However, because the expected signal is small and limited by background, it is not sufficiently sensitive to obtain meaningful results, except for the case of heavy Dirac neutrinos or cosmions [5]. Another method is to look for neutrinos, \( \gamma \) rays, and antiprotons produced by the annihilation of dark matter within the Earth, the Sun, or the galactic halo [6, 7]. Since massive astrophysical bodies have been accumulating dark matter within their structures for a long time, comparable to the age of the universe, this approach is believed to be promising [8–10]. Several reports [11–15] have already given limits on heavy neutrinos, sneutrinos and neutralinos, if the galactic halo contains them. However, in view of the recent results from the CERN \( e^+ e^- \) collider LEP collider, we should focus on heavier dark-matter candidates.

In this paper we analyze our results concerning upward-going muons observed in the Kamiokande detector in a search for possible signals representing high-energy neutrino events coming from the Sun and/or the Earth of dark-matter origin. We give constraints on the parameters describing the neutralinos within the framework of the minimal supersymmetric standard model. This report extends the analysis given in our previous work [14] for heavier neutralinos than the \( W \)-boson mass, which is far beyond the reach of man-made accelerators existing or to be built in the near future. (See Ref. [16] for our result on a search for massive neutrino dark matter.)

## II. Experiment

The Kamiokande detector (Kamiokande-I and its upgraded phase, Kamiokande-II) is an imaging water Cherenkov detector located 2700 m of water equivalent underground in the Kamioka mine, about 300 km west of Tokyo (36.42°N, 137.31°E). In Kamiokande-I, 2340 tons of purified water in a cylindrical steel tank are viewed by 1000 20-in. photomultiplier tubes (PMT's) covering 20% of the tank surface [17]. In Kamiokande-II, the inner detector is surrounded by an anticounter with a 1.5-m-thick water (on average), viewed by 123 20-in. PMT’s. To construct the bottom anticounter, the volume and number of PMT’s in the inner counter were reduced to 2140 tons and 948, respectively [18].

Data taken during the time period between July 6, 1983, and April 11, 1990 have been analyzed. They correspond to 1479 days of “weekday data,” which are fully efficient for upward-going muons, and 441 days of “holiday data” for which on average about 50% of the upward-going muons are not recorded, because of the on-line selection in Kamiokande-I. The missing upward-going muons in the “holiday data” were those entering at a nearly horizontal direction. Upward-going muon candidates were selected by off-line analysis from a total of \( 2.27 \times 10^8 \) events recorded during this period. The selection efficiency was 97%. After this selection, 120684 events remain, almost all of which are downward-going muons traveling nearly horizontally and/or multiple muons. Upward-going muons are finally chosen by a visual scan, and their directions are reconstructed manually. (See Ref. [19] for details of the analysis.) A total of 252 upward-going muons with zenith angles greater than 90°, path length \( \geq 7 \) m, and within the nominal area of 165 m² (Kamiokande-I) and 150 m² (Kamiokande-II) were selected. Muons which pass through the detector with such a long flight path (\( \geq 7 \) m) and corresponding energies above 1.7 GeV retain their primary direction. The reconstruction error of muon direction was estimated to be 2.1° by a Monte Carlo study [19].

## III. Flux Limit

The expected flux of upward-going muons from atmospheric neutrinos has been calculated to be

\[
\frac{d\Phi_\mu(E_{\text{th}}, \cos \theta_z)}{d \Omega} = \sum_{j=\nu,\bar{\nu}} \int_{E_{\text{th}}}^\infty dE_\nu \frac{d^2\Phi_\nu(E_\nu, \cos \theta_z)}{dE_\nu d\Omega} P_\nu^{\text{obs}}(E_\nu, E_{\text{th}}),
\]

where the last two factors are, respectively, the differential spectrum of the atmospheric neutrinos as a function of the neutrino energy and the zenith angle, and the probability for muon detection in the detector with a detection threshold energy of \( E_{\text{th}} \) when the primary neutrino energy is \( E_\nu \) [20]. \( P_\nu^{\text{obs}} \) is given by

\[
P_\nu^{\text{obs}}(E_\nu, E_{\text{th}}) = N_A \int_{E_{\text{th}}}^{E_\nu} dE_\mu \int_0^\infty dX \int_{E_{\text{th}}}^{E_\nu} dE_\mu' \frac{d\sigma_j(E_\nu, E_\mu')}{dE_\mu'} g(X, E_\mu, E_\mu') ,
\]

where \( \sigma_j \) denotes the cross section for each interaction channel, \( N_A \) is Avogadro’s number, and \( g(X, E_\mu, E_\mu') \) is the detection efficiency.
where \( g(X,E_{\mu},E'_{\mu}) \) is the probability that a muon of initial energy \( E_{\mu}' \) has an energy of between \( E_{\mu} \) and \( E_{\mu} + dE_{\mu} \) after propagating a distance \( X \) in rock; \( N_A \) is Avogadro’s number and \( d\sigma_j/dE_{\nu} \) is the charged-current cross section of the muon production processes \( \nu_{\mu}(\nu_{\mu}) + \text{neucleon} \rightarrow \mu^{-}(\mu^{+}) + X \) and \( \nu_{\tau}(\nu_{\tau}) + \text{neucleon} \rightarrow \tau^{-}(\tau^{+}) + X \); \( \tau^{-}(\tau^{+}) \rightarrow \mu^{-}(\mu^{+}) + \nu_{\mu}(\nu_{\mu}) + \nu_{\tau}(\nu_{\tau}) \).

The function \( g(X,E_{\mu},E'_{\mu}) \) is evaluated as

\[
g(X,E_{\mu},E'_{\mu}) = \delta(R_{\mu}(E_{\mu}) - X - R_{\mu}(E_{\mu})),
\]

where \( R_{\mu}(E) \) is the range of a muon in rock,

\[
R_{\mu}(E) = \int_{E_{\mu}}^{E_{\text{th}}} \frac{dE}{-dE/dX}.
\]

We used the results of Lohman et al. [21] for the energy loss of a muon \( (dE/dX) \). This includes the energy loss by ionization, pair production, bremsstrahlung, and nuclear interaction. We also checked the results by Bezrukov and Bugaev [22]; the agreement was satisfactory. We set the detection threshold energy of muons \( (E_{\text{th}}) \) to be 3.0 GeV as the appropriate average threshold of the Kamiokande data [23].

We calculated [24] \( d\sigma_j/dE_{\nu} \) using the quark distribution function given by Eichten et al. [25], Owens [26], and Botts et al. [27], which includes the QCD evolution effect.

We show \( P_{\nu}^{\text{obs}} \) in Fig. 1. Although muons from \( \tau \) neutrinos are negligible for atmospheric neutrinos, contribution from tau neutrinos for neutrinos from the dark matter annihilation may be significant, since their flux may be comparable to that of muon neutrinos.

In Fig. 2(a) the observed zenith angle distribution of upward-going muons is plotted and compared with the expected flux from atmospheric neutrinos produced in collisions of cosmic rays with the atmosphere [14, 19].

The average flux over the solid angles is \((2.04 \pm 0.13) \times 10^{-13} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \), while the expected value ranges over \((1.92 - 2.45) \times 10^{-13} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \), depending on calculations of the atmospheric neutrino flux [28, 29] and the quark distribution functions. Since the observed flux is consistent with that of atmospheric neutrino events, the upper limits on the flux from dark matter particles have been obtained. [We use an expected flux of \( 1.92 \times 10^{-13} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \) (based on Refs. [25] and [28]) as the standard (hereafter) to set conservative upper limits.] Within the sample, events coming from near the core of the Earth and the Sun are studied as possible high-energy neutrino signals from dark-matter annihilation.

The upper limit on upward-going muons from the Earth’s core and from the Sun has already been reported [14, 16].

In 770 m²·yr exposure of Kamiokande toward the Earth’s core (or nadir, zenith angle \( \theta_z \geq 150^\circ \)) we observed 26 muons in the range of zenith angles greater than 150°; the expected number of atmospheric neutrino events is 26.1. The 90% confidence level (C.L.) upper limit was calculated to be \( 4.0 \times 10^{-14} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \).

For a limit on the flux from the Sun, we looked for an excess from the Sun in the distribution of events along the cosine of the angle between the solar direction and the event track. We imposed the condition that the Sun must be below the horizon in order to calculate the live time; the distribution is therefore not flat, as shown by histograms in Fig. 2(b). For this figure we used events that occurred when the zenith angle of the Sun was greater than 115°, since the detection efficiency worsens in the

![FIG. 1. Observation probability of a neutrino as upward-going muons as a function of the neutrino energy. The solid, dot-dashed, dashed, and dotted curves correspond to \( \nu_{\mu}, \nu_{\mu}, \nu_{\tau}, \) and \( \nu_{\tau} \), respectively. The quark distribution used here is given in Ref. [25].](image)

![FIG. 2. (a) Zenith-angle distribution of upward-going muons observed in Kamiokande. (b) The correlation of upward-going muon events with the direction of the Sun. \( \theta_{\text{Sun}} \) is the cosine of the angle between the upward-going muon direction and a radius vector of the Sun. Events which occurred when the zenith angle of the Sun (\( \theta_z^{\text{Sun}} \)) was greater than 115° were taken into account. The histograms show the expected distributions from atmospheric neutrinos calculated assuming the atmospheric neutrino flux given by Ref. [28] and the quark distribution by Ref. [25].](image)
nearly horizontal direction. For a total exposure of 215 m$^2$ yr, we observed 5 muons coming within 25° of the Sun while the expected number is 6.6; we thus obtain 90% C.L. limit of 6.6 \times 10^{-14} \text{ cm}^{-2} \text{ sec}^{-1}.

We used a half angle of between 10° and 30° for the cone from the source (Earth and/or Sun) direction as the angular window for a dark-matter search, depending on the expected angular spread of the signal (discussed later).

IV. THE MODEL

In the minimal supersymmetric standard model (MSSM) [30], there are four neutralino mass eigenstates which can be expressed as linear combinations of superpartners of the hypercharge gauge boson ($B$), of the neutral SU(2) gauge boson ($W_3$), and of the neutral components of Higgs doublets ($H_d^0$, $H_u^0$). The neutralino mass matrix is characterized by four parameters ($M_1, M_2, \mu,$ and $\tan \beta \equiv v_2/v_1$), which, respectively, correspond to the $\tilde{B}$ and $W_3$ (nonphysical) masses, a parameter describing the mixing between the two Higgs superfields in the superpotential, and the ratio of the two vacuum expectation values, $\langle H_d^0 \rangle = v_1$ and $\langle H_u^0 \rangle = v_2$. The lightest neutralino is denoted as the neutralino:

$$\chi = Z_{n1} \tilde{B} + Z_{n2} \tilde{W}_3 + Z_{n3} \tilde{H}_d^0 + Z_{n4} \tilde{H}_u^0.$$  \hspace{1cm} (5)

Grand unification relates $M_1$ to $5/3 M_2 \tan^2 \theta_W$ at the weak scale; its mass ($m_\chi$) is consequently given by three free parameters ($M_2, \mu,$ and $\tan \beta$). Figure 3 gives an example which shows the neutralino composition and mass in the ($\mu, M_2$)-plane for $\tan \beta = 8$. We call neutralino with $Z_{n1}^2 + Z_{n2}^2 < 0.01$ a “Higgsino-like” neutralino, that with $Z_{n1}^2 + Z_{n2}^2 > 0.99$ a “gaugino-like,” and the rest as “mixed.” The MSSM contains three physical neutral particles: two $CP$-even states ($\tilde{H}_d^0$, $\tilde{H}_u^0$) and one $CP$-odd state ($\tilde{H}_3^0$). The relationships among the Higgs boson masses are given by

$$m_{H_{1,2}}^2 = \frac{1}{2} m_{H_d}^2 + m_Z^2 + \epsilon \pm \Delta,$$ \hspace{1cm} (6)

where

$$\Delta = [ (m_{H_d}^2 + m_Z^2 + \epsilon)^2 - 4 m_{H_d}^2 m_Z^2 \cos^2 2\beta ]/2 \epsilon - 4 m_{H_d}^2 \sin^2 \beta - 4 m_Z^2 \cos^2 \beta]^{1/2}$$ \hspace{1cm} (7)

and

$$\epsilon = \frac{3 \alpha_W m_t^4}{2 \pi m_W^2 \sin^2 \beta} \ln \left( 1 + \frac{m_t^2}{m_Z^2} \right).$$ \hspace{1cm} (8)

Here $\epsilon$ is the contribution of the one-loop radiative correction, which was recently recognized to be sizable in relations among the three Higgs particles [31]. $m_Z, m_W$ are the weak-boson masses, $m_t$ is the top quark mass (which we assume to be 150 GeV), $m$ is the mass of the superpartner of the top quark, and $\alpha_W$ is the SU(2) fine structure constant.] The lightest scalar Higgs boson mass ($m_{H_d}$) is also taken as a free parameter. Although the masses of the supersymmetric partners of the quarks and leptons (which we collectively refer to as squarks) are all undetermined, for simplicity we give them all the same mass ($m_q$).

V. EXPECTED SIGNAL FROM DARK-MATTER ANNihilation

Since calculations of the event rates from dark-matter annihilation in the Earth and/or Sun are discussed in detail elsewhere [32, 33, 10], we briefly summarize the relevant elements.

The differential neutrino flux ($d\Phi_j/dE_\nu$), with flavor $j$ ($j = \nu_e, \nu_\mu, \nu_\tau, \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$), at a distance of $R$ from the source, is given by

$$\frac{d\Phi_j}{dE_\nu} = \frac{\Gamma_A}{4\pi R^2} \sum_f B_f \frac{dN_{\nu j}}{dE_\nu}.$$ \hspace{1cm} (9)

FIG. 3. Neutralino composition and mass for $\tan \beta = 8$. The dashed curves in the ($\mu, M_2$) plane are contours of constant neutralino mass ($m_\chi$), and the solid curves are contours of constant gaugino fraction, $Z_{n1}^2 + Z_{n2}^2$. (a) $\mu < 0$, (b) $\mu > 0$. 
The quantity $\Gamma_A$ is the rate of dark-matter annihilations in the Earth and/or Sun. Dark-matter particles from the galactic halo are accreted onto the Earth and/or Sun and their number in the Earth and/or Sun is depleted by annihilation. These two processes come to equilibrium if the time scale of annihilation ($\tau_A$) is much shorter than the age, in which case $\Gamma_A = C/2$, where $C$ is the rate for the capture of dark-matter particles from the halo. However, if $\tau_A$ is longer than the age, the annihilation rate is smaller than this,

$$\Gamma_A = \frac{C}{2} \tanh^2(t/\tau_A).$$

Here $t$ is the age of the Earth and/or Sun and $\tau_A$ is given by $(CC_A)^{-1/2}$, where $C_A$ depends on the cross section for neutralino-neutralino annihilation and the distribution of neutralino in the Earth and/or Sun:

$$C_A = \langle \sigma v \rangle_A V_2/V_1^2.$$  \hfill (11)

Here $\langle \sigma v \rangle_A$ is the spin-averaged total annihilation cross section times the relative velocity in the limit of zero relative velocity. It can be evaluated as in Refs. [10, 41]; $V_2$ are the effective volumes for the Earth and/or Sun [34, 32],

$$V_j = V_0 \left[ j \left( \frac{m_\chi}{10 \text{ GeV}} \right) \right]^{3/2},$$

where $V_0 = 2.0 \times 10^{25} (6.5 \times 10^{28}) \text{ cm}^3$ for the Earth (Sun) and $m_\chi$ is the neutralino mass. For a large $t/\tau_A$, $\Gamma_A$ approaches $C/2$, and the neutrino signal is at "full" strength. Although this occurs in almost all cases for neutralinos trapped in the Sun as shown in Ref. [10], those in the Earth rarely reach equilibrium. This is shown in Fig. 4 as contours of the "full signal" fraction for neutralinos trapped in the Earth.

In our calculation of the capture rate by the Earth and/or Sun we followed Gould [32]: the capture rate is expressed by

$$C = c_0 \rho_{DM} \sum_i \frac{F_i(m_\chi)\sigma_{SI}^{\text{SI}} + \sigma_{SD}^{\text{SD}}}{m_\chi m_i} X_i(m_\chi),$$

where $c_0 = 5.7 \times 10^{15} (5.8 \times 10^{24} \text{ sec}^{-1})$ for the Earth (Sun), the sum is taken over element $i$ in a massive object, $\rho_{DM}$ is the dark-matter mass density, $v_{DM}$ is the root mean square velocity, $\sigma_{SI}^{\text{SI}}(\sigma_{SD}^{\text{SD}})$ is the spin-independent (spin-dependent) elastic scattering cross section on nuclei (mass $m_i$) of dark matter particles [8, 10], $F_i$ is the form-factor suppression of spin-independent scattering on nuclei $i$ [32], $f_i$ is the mass fraction of the Earth and/or Sun due to element $i$, and $X_i$ accounts for kinematical effects [32]; $\rho_{DM}$ and $v_{DM}$ are assumed to be those of the halo of our galaxy ($0.3 \text{ GeV/cm}^2$ and $300 \text{ km/s}$). We adopted the elastic scattering cross section of neutralinos with nuclei from Kamionkowski [10], where the European Muon Collaboration (EMC) effect was taken into account with some correction [35], and with a more conservative estimate concerning the contribution of Higgs coupling to the sea of strange quarks present in the nucleon discussed in Ref. [36] (as was done in Ref. [37]) [38]. The kinematical factor was calculated while including a resonant enhancement when the dark-matter mass is near to the masses of the constituent nuclei [32], a suppression factor due to the motion of the Earth and/or Sun [32], a suppression factor due to the lack of coherence in the elastic interaction [32], and a gravitational potential using the density profile given in Ref. [39] for the Earth and in Ref. [40] for the Sun [15]. Figure 5 shows this factor as capture rates of (imaginary) WIMPs with a constant elastic scattering cross section of $10^{-36} \text{ cm}^2$ for several major elements in the Earth and/or Sun, as a function of the WIMP mass. The result for neutralinos is given in Fig. 6 for the Earth as contours in the $(\mu, M_2)$ plane as an example. (See Ref. [10] for the Sun.)

The sum is over all annihilation channels ($F$, e.g.,

\begin{figure}[h]
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\includegraphics[width=\textwidth]{fig4.png}
\caption{Contours of "full signal" fraction for neutralinos trapped in the Earth. Here, $\tan \beta = 1$, $M_{H^0} = 50 \text{ GeV}$, and no radiative correction applied and $m_\chi = \infty$. In the region bounded by the solid lines, the signal is less than 90% of the "full signal" in the region bounded by dotted lines, it is less than 10%. (a) $\mu < 0$; (b) $\mu > 0$.}
\end{figure}
pairs of gauge or Higgs bosons or fermion-antifermion pairs), $B_F$ is the annihilation branch for channel $F$, and $dN_{F_j}/dE_\nu$ is the differential energy spectrum of neutrino type $j$ at the surface of the Earth and/or Sun expected from an injection of the particles in channel $F$ in the core of the Earth and/or Sun. The branching ratio is calculated from the relative magnitude of the annihilation cross section into all possible channels. For the case of neutralinos, we should take account of $\chi\chi \rightarrow f\bar{f}$ ($f$ stands for a fermion), $W^+W^-$, $Z^0Z^0$, $H_1^0H_1^0$, $H_2^0H_2^0$, $Z^0H_1^0$, $ZH_2^0$, and $W^+H^+$ processes as well as subsequent decay of gauge and/or Higgs bosons into fermions \cite{10,41}. The spectrum $dN_{F_j}/dE_\nu$ is a function of the energy of the neutrino as well as energy of the injected particles. A determination of the neutrino spectra is quite complicated, since it involves hadronization of the annihilation products, interaction of the particles in the resulting cascade with the medium in the Earth and/or Sun, and a subsequent interaction of high-energy neutrinos with the medium as they propagate from the core to the surface of the Earth and/or Sun.

We used the same strategy as that of Ritz and Seckel \cite{33} and calculated the neutrino spectra using the Monte Carlo simulation program JETSET (version 7.2) \cite{42}. If the annihilation products are fermion-antifermion pairs, the resulting neutrino spectrum is almost independent of the injection energy, as is discussed in Refs. \cite{33,34}. For gauge bosons ($W^\pm, Z^0$), however, it is dependent on the injection energy, since they may decay nonrelativistically. We calculated neutrino-yield tables from gauge bosons based on the JETSET Monte Carlo simulation of their decays \cite{44}. In this case, the resulting spectra depend on the injection energy; we interpolate the value given in 5 GeV steps to obtain the spectrum of an arbitrary injection energy. Since a Higgs boson decays into fermions and their branching ratios can be calculated as in Ref. \cite{8}, we can use the spectrum from fermions. The final form of the spectrum $dN_{F_j}/dE_\nu$ used in our calculation is given in Appendix A for fermion-antifermion pairs. Figure 7 shows an example of the $\nu_\mu$ spectra from a pair of fragmenting particles.

For particles produced through dark-matter annihilation and injected in the core of the Sun, the energy loss of hadrons in the solar medium and muon-neutrino production from the decay of $\tau$ leptons generated in collisions of $\nu_\mu$'s with the solar medium may be significant in the high-energy region, while they are negligible for the case of the Earth. We take these effects into account, following Refs. \cite{33,10}. For heavy hadrons, their mean energy when they decay would be

$$\langle E \rangle = E_0 e^{E_0/E_\mu} \int_{E_\mu/E_0}^\infty e^{-x} dx$$

where $E_0$ is the injection energy; $E_\mu \sim 250$ GeV for charged hadrons and $E_\mu \sim 470$ GeV for bottom hadrons \cite{33}. Since $\tau$ leptons decay quickly before they interact, no special treatment is necessary. To account for the interactions of the neutrinos with the solar medium, we use the approximation given by Ref. \cite{33} that a neutrino injected with an energy $E$ leaves the Sun with an energy of

$$E_f = \frac{E}{1 + E_\tau}$$

where $\tau_{\nu_\mu} = 1.05 \times 10^{-3}$ GeV$^{-1}$, $\tau_{\nu_e} = 3.8 \times 10^{-4}$ GeV$^{-1}$, $\tau_{\nu_\tau} = 5.3 \times 10^{-3}$ GeV$^{-1}$, and $\tau_{\bar{\nu}_e} = 2.9 \times 10^{-3}$ GeV$^{-1}$, and a probability of

$$P_f = \left(1 + E_\tau\right)^{-\alpha_{\nu}}$$

where $\alpha_{\nu_{\mu}} = 5.1, \alpha_{\nu_e} = 9.0, \alpha_{\nu_\tau} = 1.2$, and $\alpha_{\bar{\nu}_e} = 1.0$.

Finally, the flux of upward-going muons from dark matter annihilation is given by

$$N_\mu = \sum_{j=\nu_\mu, \nu_e, \nu_\tau} \int_{E_{th}}^{E_{\mu_{max}}} P^{\mu_b}(E_\mu, E_{th}) \frac{d\Phi_j}{dE_\nu} dE_\nu$$

where $P^{\mu_b}(E_\mu, E_{th})$ is the probability for muon detection in the detector with a detection threshold energy of $E_{th}$ when the primary neutrino energy is $E_\nu$, as defined in Eq. (3) \cite{45}. Here, we include signals from $(\nu_{\mu})$, which

![FIG. 5. Capture rates of WIMPs with a constant elastic scattering cross section of $10^{-36}$ cm$^2$ for several elements, in order to show the effect of the kinematical factor in captures by each element in the Earth and/or Sun [see Eq. (13)]. (a) The case of the Earth: the solid, dashed, dotted and dot-dashed lines show the capture rate by iron, oxygen, silicon, and magnesium. (b) The case of the Sun: the solid, dashed, and dotted lines show the capture rate by iron (multiplied by $10^3$), hydrogen, and helium. Here, since the elastic scattering cross section is assumed to be spin independent, the plots include the form-suppression factor. However, for hydrogen the plot is unchanged, even if it is spin dependent, since the form-suppression factor is small for light nuclei.](image-url)
was negligible in the case of atmospheric neutrinos, but may be significant in this case, since the yield of \( \nu_\mu \) from neutralino annihilation is comparable to, or even larger than, that of \( \bar{\nu}_\mu \). \([P^{\text{obs}}(E_\nu, E_{\text{th}})]\) is defined to be the fraction of muons produced in decays of tau leptons produced in the charged-current interaction.

These signals from the Earth and/or Sun are spread for the following reasons: (1) dark-matter particles orbiting the center of the Earth after being trapped \([32]\); (2) energetic neutrinos generated in the decays of fermions produced in massive DM annihilations; (3) muons produced in collisions of neutrinos with the rock surrounding the detector and scattered from the primary neutrino direction; and (4) multiple Coulomb scattering of muons on route to the detector \([46]\).

For annihilations in the Sun, they should be seen as a point source toward the Sun and processes (2), (3), and (4) are relevant. The window angles used to search for upward-going muons signals are determined by using a Monte Carlo calculation that includes the above processes. Figure 8 shows the calculated limits on window angles for the muons as a function of the dark-matter mass, within which 90% of the neutrino-induced muons are included. Here for neutralinos it is assumed that 80% of the annihilation products are \( bb \), 10% are \( cc \), and 10% are \( \tau \tau \) as typical branching ratios. Since the window-angle distribution does not change much upon varying

![Graphs showing contours in the (\( \mu, M_z \)) plane of the capture rate of neutralinos in the Earth assuming neutralinos are the halo dark matter for \( \tan \beta = 8 \) and \( M_{H^2} = 50 \) GeV. No radiative correction applied and \( M_{\chi} = \infty \). The regions near \( |\mu| \sim M_z \sim (100 - 200) \) GeV surrounded by dot-dashed lines indicate a capture rate of \( 10^{12} \text{ sec}^{-1} \); the spacing between curves are decades, the capture rate decreasing toward higher masses. (a) and (b): \( \tan \beta = 2, M_{H^2} = 40 \) GeV. There is a "valley" near \( \mu M_z \sim 8000 \) GeV in (b). (c) and (d): \( \tan \beta = 8, M_{H^2} = 50 \) GeV. (a) and (b) are the same except \( \mu < 0 \) and \( \mu > 0 \), respectively, so (c) and (d). Plots for \( \tan \beta = 20 \) and \( M_{H^2} = 50 \) GeV are qualitatively similar to (c) and (d).](image-url)
these branching ratios, we use the $10^\circ - 30^\circ$ half-angle cone around the source (Earth and/or Sun) direction as the angular window for a dark-matter search, depending on the neutralino mass. Table I summarizes the window angles used in this report and the experimental limits on the flux of upward-going muons originating from dark-matter annihilation in the Earth and the Sun.

VI. RESULTS AND DISCUSSION

We now compare our experimental upper limits on the extra upward-going muons other than the atmospheric type with the expected flux from dark-matter annihilation in the Earth and/or Sun.

Figure 9 shows exclusion plots in the $(\mu, M_\nu)$ plane at the 90%-confidence-level obtained from these upper limits. We take two extreme cases of the squark mass: (A) $m_{\tilde{q}} = \infty$ and no radiative correction is applied; (B)

$$m_{\tilde{q}} = \begin{cases} 2.5 m_X & (2.5 m_X > m_{\tilde{q},\text{min}}) \\ m_{\tilde{q},\text{min}} & (2.5 m_X \leq m_{\tilde{q},\text{min}}) \end{cases}$$


\begin{table}[h]
\begin{center}
\caption{Upper limits on upward-going muon flux from the Earth and the Sun based on the Kamiokande data.}
\begin{tabular}{cccc}
\hline
Source & Window angle & Observed events & Expected events & Flux limit (cm$^{-2}$sec$^{-1}$) \\
\hline
Earth & $30^\circ$ & 26 & 26.1 & $4.0 \times 10^{-14}$ \\
 & $25^\circ$ & 22 & 18.2 & $4.8 \times 10^{-14}$ \\
 & $20^\circ$ & 13 & 11.7 & $3.4 \times 10^{-14}$ \\
 & $15^\circ$ & 9 & 6.6 & $3.3 \times 10^{-14}$ \\
 & $10^\circ$ & 7 & 2.9 & $3.7 \times 10^{-14}$ \\
 & $5^\circ$ & 1 & 0.73 & $1.4 \times 10^{-14}$ \\
Sun & $30^\circ$ & 8 & 9.6 & $7.9 \times 10^{-14}$ \\
 & $25^\circ$ & 5 & 6.6 & $6.6 \times 10^{-14}$ \\
 & $20^\circ$ & 3 & 4.2 & $5.8 \times 10^{-14}$ \\
 & $15^\circ$ & 2 & 2.4 & $5.5 \times 10^{-14}$ \\
 & $10^\circ$ & 1 & 1.0 & $4.8 \times 10^{-14}$ \\
 & $5^\circ$ & 0 & 0.26 & $3.4 \times 10^{-14}$ \\
\hline
\end{tabular}
\end{center}
\end{table}

\begin{figure}[h]
\includegraphics[width=\textwidth]{fig7}
\caption{Examples of the neutrino spectra from a particle-antiparticle pair injected at an energy of $(E_{\text{inj}} + E_{\text{inj}})$. The abscissa is the scaled energy $Z_\nu = E_\nu / E_{\text{inj}}$. (a) Spectra for $E_{\text{inj}} = 200$ GeV. The solid, dot-dashed, dashed, and dotted curves are muon-neutrino yields from a $\bar{c}c$, $bb$, $tt$, and $\tau\tau$ pair, respectively. These are almost energy-independent. The solid (dashed) histogram shows the same from a $W^+W^-$ ($Z^0Z^0$) pair, which depends on the injection energy. (b) Spectra from $W$ and $Z$ boson decays. The solid and dot-dashed histograms are muon-neutrino yields from a $W^+W^-$ pair of $E_{\text{inj}} = 95, 150$ GeV, respectively. The dashed and dotted histograms are those from a $Z^0Z^0$ pair of $E_{\text{inj}} = 95, 150$ GeV, respectively.}
\end{figure}

\begin{figure}[h]
\includegraphics[width=\textwidth]{fig8}
\caption{Window angles which contain more than 90% of the signal expected from neutralino annihilation in (a) the Earth and (b) the Sun. The solid lines represent the window angles for $\nu_\mu$-induced muons; the dashed lines are for $\bar{\nu}_\mu$-induced muons. Also indicated by dotted lines are the window angles used to search for extra upward-going muons from the data.}
\end{figure}

\begin{figure}[h]
\includegraphics[width=\textwidth]{fig9}
\caption{Exclusion plots in the $(\mu, M_\nu)$ plane at 90%-confidence-level from the Kamiokande data. The solid line represents the expected signal from neutralino annihilation for $m_{\tilde{q}} = \infty$ and no radiative correction is applied. The dot-dashed line represents the expected signal for $m_{\tilde{q}} = 2.5 m_X$. The upper limits are shown by the solid curves for the Earth and the dotted curves for the Sun.}
\end{figure}
FIG. 9. Regions where the neutralino is excluded at the 90% confidence level as the primary component of the galactic halo by limits on the upward-going muons observed in Kamiokande. (a)–(d) and (i)–(k): the Earth; (e)–(h), (l) and (m): the Sun. (a)–(h): $\tan \beta = 8$; (i): $\tan \beta = 2$; (j)–(m): $\tan \beta = 20$. (a), (b), (e), (f), (i)–(m): $m_q = \infty$, no radiative correction (RC); (c), (d), (g) and (h): $m_q = \max(2.5m_x, m_{q\text{min}})$, RC, where $m_{q\text{min}} = 126$ GeV. (a)–(h): solid (dashed) lines surround the excluded region when the mass of the lightest Higgs particle ($M_{H_2}$) is 50 (70) GeV. (i): $M_{H_2} = 40$ GeV. (j)–(m): solid (dashed, dotted) lines for $M_{H_2} = 50$ (70, 90) GeV. (a) and (b) are the same except $\mu < 0$ and $\mu > 0$, respectively, so (c) and (d), and so on, but for (i) no excluded region exists for $\mu < 0$. There is no excluded region for the Sun corresponding to the same parameters used in (i).
FIG. 9. (Continued).
where $m_{\tilde{q}}_{\text{min}} = 126$ GeV is taken as the limit from the Collider Detector at Fermilab (CDF) result [47], and a radiative correction is applied [$m = m_{\tilde{q}}$ in Eq. (8)] [48]. Figures 9 (c), (d), (g), and (h) are for case (B), and the others are for case (A). Several contours are shown, respectively, varying the lightest Higgs boson mass ($m_{H_2}$). The excluded areas become smaller as $m_{H_2}$ grows, since the main part of the elastic-scattering cross section changes as $m_{H_2}^4$. We can see that the excluded areas are for mainly “mixed” neutralino composition. They extend along the isomass contours for the case of the Earth, due to a resonance enhancement during captures. For the case of the Sun, they extend to a heavier neutralino region than that of the Earth, but are less sensitive to Higgsino-like or gaugino-like neutralinos. The effects of the finite squark mass and radiative correction are mixed for case (B) plots. Although the excluded areas become narrower for smaller $\mu$ and $M_2$, the effects are small for larger $\mu$ and $M_2$. The excluded areas become larger as $\tan \beta$ becomes large.

The largest uncertainty in our result comes from the estimate of the Higgs boson coupling to the sea of strange quarks in nucleons, which is implied from a measurement

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**TABLE II.** Fitting coefficients for the neutrino spectra from fermion-antifermion annihilations.

<table>
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<tr>
<th>Coefficients</th>
<th>$c \bar{c}$</th>
<th>$b \bar{b}$</th>
<th>$t \bar{t}$</th>
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</tbody>
</table>
FIG. 10. Regions in the $(\mu, M_2)$ plane in which the neutralino is not a good dark-matter candidate. Areas where $\Omega_\chi h^2 > 1$ and $< 0.02$ are shown as solid (dotted) boundaries. (a)–(d): $\tan \beta = 8$, $M_{H_u} = 50$ GeV; (e) and (f): $\tan \beta = 2$, $M_{H_u} = 40$ GeV; (g) and (h): $\tan \beta = 20$, $M_{H_u} = 50$ GeV. (a), (b), (e)–(h): $m_\chi = \infty$, no radiative correction (RC); (c) and (d): $m_\chi = 2.5 m_\chi$, RC. (a) and (b) are the same except $\mu < 0$ and $\mu > 0$, respectively, so (c) and (d) and so on.
of the pion-nucleon $\sigma$ term. This plays a major role in spin-independent elastic scattering [8]; if we adopt the estimate by Ref. [49] instead of that by Ref. [36] used here, the expected dark-matter signal becomes about three times larger [37], thus leading to larger excluded areas. Finally, we mention that these exclusion plots change little if we take into account the uncertainties in the velocity ($200 < \sqrt{2/3}$ $v_{\text{DM}} < 400$ km/s [50]) and the halo density ($0.2 < \rho_{\text{DM}} < 0.43$ GeV/cm$^3$ [50]), though the expected signal may be reduced to 63% or enhanced to 180% of the value used here.

So far, the mass density of neutralinos in our galaxy has been fixed at 0.3 GeV/cm$^3$, that of the halo of our galaxy. However, if the relic density of neutralinos after the big bang is too small, they could not be the major component of the halo. Several authors [7, 8, 37] have assumed that the mass density of neutralinos after the big bang is too small, they could not be the major component of the halo. Several authors [7, 8, 37] have assumed that the mass density of neutralinos after the big bang is too small, they could not be the major component of the halo. Several authors [7, 8, 37] have assumed that the mass density of neutralinos after the big bang is too small, they could not be the major component of the halo. Several authors [7, 8, 37] have assumed that the mass density of neutralinos after the big bang is too small, they could not be the major component of the halo. 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[35] We correct the squark exchange terms in Ref. [10] as follows: (1) the relative sign of Z and squark exchange terms in Eq. (A2) of Ref. [10] is positive; (2) the factor in Eqs. (A7) and (A10) of Ref. [10] is replaced by –1/2.


[38] The factors 1.12 and 6.5 in Eq. (A10) of Ref. [10] are replaced by 1.57 and 3.05, respectively.


[43] For spectra from t̄ pairs, we use the fit for the (200+200) GeV case and a slight dependence on energy is ignored. This introduces a slight underestimate of the expected signal.

[44] An analytical estimate of the expected signal from W and Z boson decay is found in Ref. [10].

[45] Here we use the quark distribution given by Ref. [25], which gives the smallest value, to obtain a conservative estimate of the signal.


[51] For Higgsino-like neutralinos, the coannihilation effect of the lightest neutralino and the second-lightest neutralino is effective and lowers the relic density of them. (See Ref. [41] and S. Mizuta and M. Yamaguchi, Phys. Lett. B298, 120 (1993).) However, this effect is not important in our excluded regions and we ignored here.