



Search for Neutrinos from Annihilation of Captured Low-Mass Dark Matter Particles in the Sun by Super-Kamiokande

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Super-Kamiokande (SK) can search for weakly interacting massive particles (WIMPs) by detecting neutrinos produced from WIMP annihilations occurring inside the Sun. In this analysis, we include neutrino events with interaction vertices in the detector in addition to upward-going muons produced in the surrounding rock. Compared to the previous result, which used the upward-going muons only, the signal acceptances for light (few-GeV/ c^2 -200-GeV/ c^2) WIMPs are significantly increased. We fit 3903 days of SK data to search for the contribution of neutrinos from WIMP annihilation in the Sun. We found no significant excess over expected atmospheric-neutrino background and the result is interpreted in terms of upper limits on WIMP-nucleon elastic scattering cross sections under different assumptions about the annihilation channel. We set the current best limits on the spin-dependent WIMP-proton cross section for WIMP masses below 200 GeV/ c^2 (at 10 GeV/ c^2 , 1.49×10^{-39} cm² for $\chi\chi \rightarrow b\bar{b}$ and 1.31×10^{-40} cm² for $\chi\chi \rightarrow \tau^+\tau^-$ annihilation channels), also ruling out some fraction of WIMP candidates with spin-independent coupling in the few-GeV/ c^2 mass range.

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Weakly interacting massive particles (WIMPs) are favored as particle candidates for nonbaryonic cold dark matter (DM), as their interaction strength can explain the thermal relic abundance of DM [1–3]. A promising way to identify a WIMP DM particle is to search for excess neutrino flux generated by WIMP self-annihilations inside the Sun [4–7] (WIMP neutrinos). As the Sun travels on the Milky Way arm, WIMPs in the DM halo could occasionally become gravitationally bound after losing energy by scattering off nuclei in the Sun. The WIMPs then pair annihilate in the deep solar core, producing neutrinos from decays of the annihilation products which propagate outward through the Sun and may be detected in terrestrial neutrino detectors. An excess of a high-energy neutrinos from the Sun, with energies much greater than the $\sim O$ (10 MeV) solar-fusion neutrinos, observed in neutrino detectors can be interpreted in terms of WIMP annihilation rate. We assume that WIMPs annihilate via a single channel to a pair of fermions or bosons. Also, we assume that the WIMP capture and annihilation rates are in equilibrium, which enables us to remove the WIMP-annihilation cross-section dependence and allows comparison to direct detection results on WIMP-nucleon elastic scattering cross section.

Thanks to the hydrogen-rich composition and large gravity of the Sun, tight limits on the spin-dependent (SD) scattering cross section of WIMPs on protons have been placed by neutrino telescopes such as Super-Kamiokande (SK) [8], IceCube [9], Baksan [10], and ANTARES [11]. Recent event excesses or annual modulation signals reported by direct detection experiments such as DAMA/LIBRA [12], CoGeNT [13], CRESST [14], CDMS II Si [15] and conflicting null results from other direct- and indirect-detection experiments motivate a careful search for light WIMPs below 30 GeV/ c^2 . As typical resulting neutrino energies are roughly one-third to one-half of the WIMP mass [2] or lower, the SK detector's sensitivity to few-GeV neutrinos makes it suitable for this search [16–19].

Super-Kamiokande is a cylindrical water Cherenkov detector located in the Kamioka mine in Japan. The inner detector (ID) of 22.5 kton fiducial volume is instrumented with 11 129 20-in. Hamamatsu photomultiplier tubes (PMTs) and the outer detector (OD) is instrumented with 1885 8-in. PMTs for use as a veto. Information about the experimental setup of the detector and its calibration, data reduction, and event reconstruction can be found elsewhere [20–22].

The SK high-energy neutrino data include neutrino events with visible energy > 30 MeV and are divided into three categories: among contained events in which the neutrino interacts inside the ID, fully contained (FC) events have observed Cherenkov light entirely contained in the ID, partially contained (PC) events additionally have an exiting particle that deposits energy in the OD. Upward-going muons (up- μ) are produced by neutrino interactions in the rocks and water surrounding the detector. FC events are distributed in seven sub-GeV (visible energy < 1.33 GeV) and six multi-GeV (visible energy > 1.33 GeV) subcategories, and then further divided based on particle identification (e -like or μ -like), number of reconstructed Cherenkov rings, number of decay electrons, and so on. PC events are classified as “OD stopping” or “OD through-going” based on their energy deposition in the OD. Up μ 's either stop in the detector (stopping) or pass through the detector (through-going). Through-going up- μ events are further divided into “showering” and “nonshowering” categories [23].

A signal from a 10-GeV/ c^2 WIMP will mostly fall in the FC sub-GeV and multi-GeV samples, and heavier WIMP signals will be mainly distributed in the PC and up- μ categories. To increase signal acceptance for light WIMPs, FC and PC events are included in the WIMP search sample. We take into account all neutrino flavors ($\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e, \nu_\tau, \bar{\nu}_\tau$). Compared to the previous analysis [8], which used up- μ events only, the signal acceptance has increased 47 times for the 10-GeV/ c^2 $b\bar{b}$ channel.

The analysis in this Letter uses data accumulated during the SK I–IV run periods. The SK-I (1996–2001), SK-II

(2002–2005, with half PMT coverage), and SK-III (2006–2008) periods correspond to 1489, 799, and 518 days of live time for the FC and PC samples, and 1646, 828, and 636 days of live time for the up- μ sample, respectively. The SK-IV period started in 2008; this analysis uses 1096.7 live days of FC, PC, and up- μ data collected until March 2012.

The Monte Carlo simulation [21,24] originally generated for the primary atmospheric neutrino flux [25] is divided into two independent samples and is used for two purposes: first, to predict atmospheric-neutrino background, and second, to produce the WIMP neutrino signal by reweighting to match the signal flux and spectrum. To predict the atmospheric-neutrino background, a 250-year MC sample per SK run period is normalized to the live time of each SK run period and oscillated with parameters $\sin^2\theta_{13} = 0.025$, $\sin^2\theta_{12} = 0.304$, $\sin^2\theta_{23} = 0.425$, $\Delta m_{21}^2 = 7.66 \times 10^{-5} \text{ eV}^2$, and $\Delta m_{32}^2 = 2.66 \times 10^{-3} \text{ eV}^2$. In the other 250 years of MC sample per run period, events coming approximately from the solar direction are selected and then weighted by the ratio of WIMP neutrino flux to original atmospheric-neutrino flux. To simulate the neutrino flux from WIMP annihilation in the Sun at SK, we used the WIMP MC simulator WIMPSIM 3.01 [26]. Focusing on the light WIMP search, we considered WIMP masses from 4 to 200 GeV/c^2 for $\chi\chi \rightarrow \tau^+\tau^-/b\bar{b}/W^+W^-$ channels. The spectrum of the $b\bar{b}$ channel is “softest” and the $\tau^+\tau^-$ channel produces a “harder” spectrum.

In order to discriminate the large background of atmospheric neutrinos at low energies, which have an $\propto E^{-2.7}$ power-law spectrum, and to take into account the energy-dependent angular correlation for low-energy events, we perform a least-squares fit which makes full use of the

energy, angle, and flavor information. Under the hypothesis that the collected SK data consist of both atmospheric neutrinos and WIMP neutrinos, we compare data to MC calculations. The data and MC calculations in the 18 subcategories are distributed into 480 bins based on reconstructed momentum and $\cos\theta_{\text{sun}}$, where θ_{sun} is the angle between the Sun and the reconstructed event direction. Figure 1 shows an example of data distributions compared to the expected WIMP-induced signal. We fit the data using the least-squares technique based on Poisson statistics to find the amount of signal contribution added to background that best matches the data. For each mass and annihilation channel, the energy spectrum and flavor composition of signal neutrino flux are fixed and the global normalization of the signal flux is allowed to vary freely. The “pull” approach allows us to incorporate systematic uncertainties [27] in the fitting as

$$\chi^2 = \min_{\{\epsilon_j\}} \left[2 \sum_{i=1}^N \{N_i^{\text{exp}} - N_i^{\text{data}} + N_i^{\text{data}} \ln(N_i^{\text{data}}/N_i^{\text{exp}})\} + \sum_{j=1}^J \left(\frac{\epsilon_j}{\sigma_j} \right)^2 \right],$$

where

$$N_i^{\text{exp}} = N_i^{\text{BG}} \left(1 + \sum_{j=1}^J f_j^i \epsilon_j \right) + \beta N_i^{\text{Z}} \left(1 + \sum_{j=1}^J g_j^i \epsilon_j \right),$$

and i is the index of the bins, N_i^{data} is the number of events observed in each bin, N_i^{BG} is the background expectation in

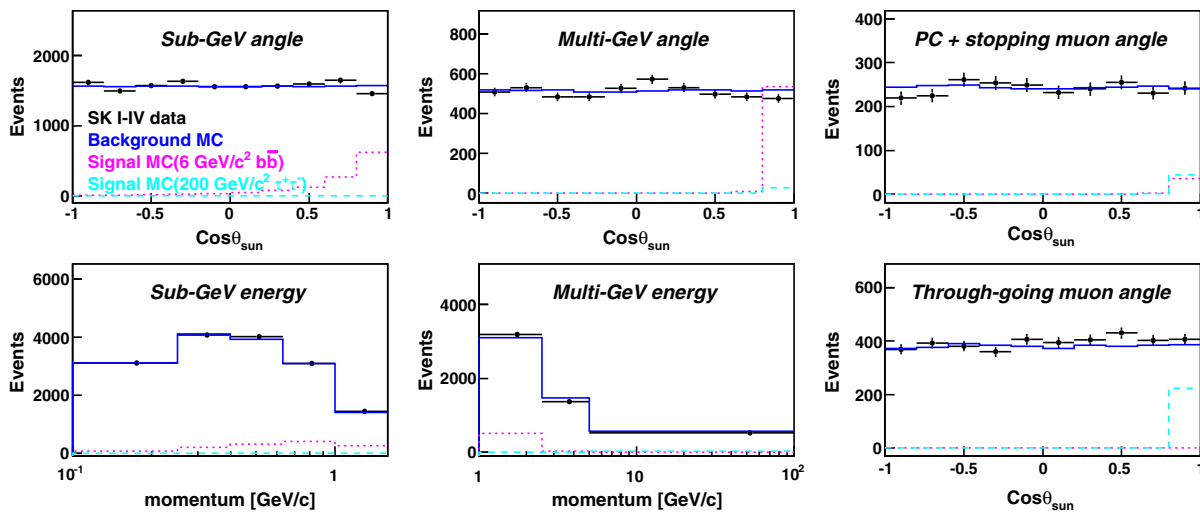


FIG. 1 (color online). Angular and reconstructed momentum [GeV/c] distributions of SK I–IV data (black crosses), atmospheric-neutrino background MC events (normalized to data live time, blue solid line), WIMP neutrino signal MC events for the $6\text{-GeV}/c^2$ $b\bar{b}$ channel (magenta dotted line) and the $200\text{-GeV}/c^2$ $\tau^+\tau^-$ channel (cyan dashed line) at 90% upper limit, magnified 30 times for visibility. Among seven sub-GeV samples, the single-ring e -like 0-decay-electron and μ -like 0,1-decay-electron samples are combined and shown in the left-hand column. In the middle column, six multi-GeV samples are combined and shown. PC and up- μ samples are shown in the right-hand column.

TABLE I. χ^2_{\min} , $\Delta\chi^2$ at $\beta = 0$, $\Delta\chi^2_{90}$ ($\Delta\chi^2$ for 90% Bayesian upper limit), 90% upper limit on the muon-neutrino flux from WIMP annihilations in the Sun at SK and SD, SI, and IVDM scattering cross section limits for each WIMP mass and annihilation channel.

m_χ (GeV/ c^2)	Annihilation channel	χ^2_{\min}	$\Delta\chi^2$ at $\beta = 0$	$\Delta\chi^2_{90}$ (Bayesian)	ν_μ ($\times 10^{12}$ km $^{-2}$ y $^{-1}$)	$\sigma_{SD,p}$ ($\times 10^{-40}$ cm 2)	$\sigma_{SI,p}$ ($f_n/f_p = 1$) ($\times 10^{-43}$ cm 2)	($f_n/f_p = -0.7$) ($\times 10^{-41}$ cm 2)
4	$\tau^+\tau^-$	508.1	0.87	4.4	150	2.22	87.3	24.5
6	$b\bar{b}$	507.8	1.24	4.9	294	17.2	456	128
	$\tau^+\tau^-$	507.8	1.25	4.9	70.8	1.63	44.5	12.2
10	$b\bar{b}$	507.4	1.65	5.4	140	14.9	240	67.5
	$\tau^+\tau^-$	507.6	1.40	5.1	31.0	1.31	21.2	5.95
20	$b\bar{b}$	507.4	1.65	5.4	53.1	14.3	120	44.8
	$\tau^+\tau^-$	509.0	0.06	2.4	13.2	1.42	11.9	4.47
50	$b\bar{b}$	509.0	0.04	3.0	19.8	23.4	89.9	39.0
	$\tau^+\tau^-$	508.9	0.14	2.3	2.67	1.28	4.92	2.14
80.3	W^+W^-	508.8	0.17	2.3	1.09	3.13	8.26	3.73
100	$b\bar{b}$	509.0	0.06	2.4	7.54	31.9	71.3	32.7
	W^+W^-	508.9	0.14	2.3	0.63	2.80	6.26	2.87
	$\tau^+\tau^-$	508.9	0.16	2.3	0.70	1.24	2.76	1.26
200	$b\bar{b}$	508.9	0.12	2.3	2.81	44.9	63.4	30.4
	W^+W^-	508.9	0.07	2.4	0.17	3.00	4.23	2.03
	$\tau^+\tau^-$	508.9	0.08	2.4	0.19	1.33	1.88	0.90

the bin, N_i^χ is the number of events of signal MC in the bin, where β , the global normalization parameter for signal, stands for the allowed fraction of signal, σ_j is the 1σ value of the j th systematic uncertainty, e_j is its pull, and f_j^i/σ_j (g_j^i/σ_j) is the predicted fractional change of the number of background (signal) events in the i th bin due to a 1σ change of the j th systematic uncertainty. In the pull approach, χ^2 is estimated by solving $\delta\chi^2/\delta e_j = 0$ for all e_j 's [27].

For background (signal), 66 (48) sources of systematic uncertainties are considered. A total of 16 systematic uncertainties related to neutrino interaction in SK are considered in common for both background and signal. Another 14 uncertainty sources related to event reduction and 11 sources related to event reconstruction and selection are calculated for SK I, II, III, and IV independently and considered for both signal and background. For background MC events, a total of 25 uncertainties related to the prediction of atmospheric-neutrino flux, including 1σ uncertainties on oscillation parameters, are considered. All the uncertainties in neutrino interaction, event reduction, reconstruction, selection, and background atmospheric-neutrino flux are similar to those described in Ref. [28] except the ones related to zenith angle distributions. These uncertainties are listed elsewhere (for example, Tables VI, VII, and VIII in Ref. [28]). For signal MC events, seven uncertainties related to the oscillation of WIMP neutrinos during propagation through the Sun, vacuum, and Earth are considered. The full systematic uncertainty has up to a 10% effect on the WIMP sensitivity, where the largest contributions come from neutrino interaction and atmospheric-neutrino flux uncertainties.

The best-fit value of β , β_{\min} is defined as the value at which χ^2 is minimized with respect to β . For all tested WIMP hypotheses, we found the resulting β_{\min} values are

all consistent with the hypothesis of no WIMP neutrino contribution, and we set 90% upper limits assuming that the obtained χ^2 values approximately follow a normal distribution. To set a physically meaningful confidence limit, we follow a Bayesian approach [29] and renormalize the β distribution in the physically allowed region ($\beta > 0$). The fitted χ^2 values at minimum (χ^2_{\min} ; DOF is 479), the $\Delta\chi^2$ value at $\beta = 0$ from the minimum, and the $\Delta\chi^2$ values for 90% upper limit ($\Delta\chi^2_{90}$) calculated with the Bayesian approach are shown in Table I for the tested WIMP mass and annihilation channels.

Figure 2 shows the derived 90% upper limit on the muon-neutrino flux from WIMP annihilations in the Sun at SK. The limit shown here for ν_μ is an example; limits on other flavors or antineutrinos are determined by appropriate flavor scaling for the given WIMP annihilation channel assumption. The sensitivity study was done by substituting SK data with 500 sets of toy MC data generated for the hypothesis of no WIMP-annihilation contribution and the result is shown together in Fig. 2 as a band representing a 1σ range of results.

Using DARKSUSY 5.0.6 [30], we convert the upper limit on the neutrino flux to upper limits on WIMP-nucleon cross sections. We assume that WIMPs have only a single type of interaction with a nucleus, either an axial vector interaction in which WIMPs couple to the nuclear spin (SD) or a scalar interaction in which WIMPs couple to the nucleus mass [spin independent (SI)]. The SI coupling can have different couplings to neutrons (f_n) and protons (f_p). We consider two representative examples: the commonly assumed isospin-invariant case ($f_n/f_p = 1$) and the case of isospin-violating dark matter (IVDM) [31] with destructive interference $f_n/f_p = -0.7$ [32–35]. The latter is calculated based on Ref. [36]. Also assumed are a standard DM halo

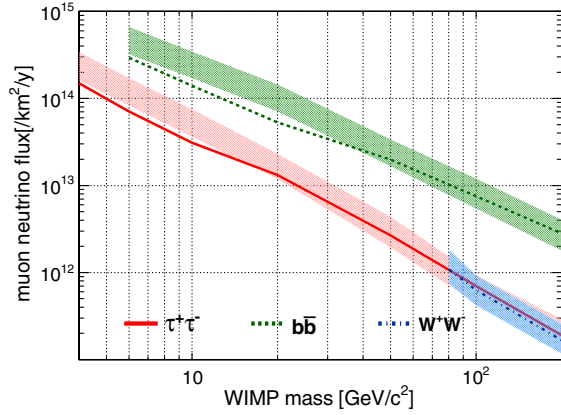


FIG. 2 (color online). The 90% upper limit on total integrated muon-neutrino flux from WIMP annihilations in the Sun at SK for the $\tau^+\tau^-$ channel in red solid line, $b\bar{b}$ in green dashed line, W^+W^- in blue dot-dashed line. The shadowed regions show 1σ bands of the sensitivity study results (color scheme is the same as for data).

with local density 0.3 GeV/cm^3 [37,38], a Maxwellian velocity distribution with a rms velocity of 270 km/s, and a solar rotation speed of 220 km/s. The results are listed in Table I. They are also plotted together with other experimental results in Fig. 3 for SD coupling and Fig. 4 for SI coupling for the isospin-invariant case. For IVDM, we note that for the result given in the Table I, the entire CDMS II Si [15] 90% C.L. signal region will be in tension with our $\tau^+\tau^-$ channel result.

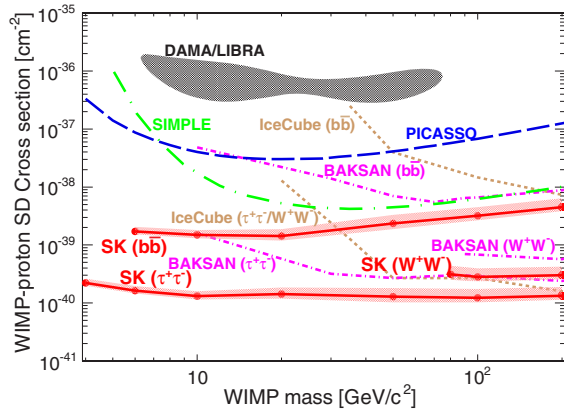


FIG. 3 (color online). 90% C.L. upper limits on SD WIMP-proton cross section calculated at DARKSUSY [30] default are shown in red solid line with uncertainty bands to take account of uncertainties in the capture rate for the $b\bar{b}$, W^+W^- , and $\tau^+\tau^-$ channels from top to the bottom. Also shown are limits from other experiments. IceCube [9] in brown dashed line: $b\bar{b}$ (top) / W^+W^- or $\tau^+\tau^-$ (bottom); BAKSAN [10] in pink dot-dashed line: $b\bar{b}$ (top), W^+W^- (middle), $\tau^+\tau^-$ (bottom); PICASSO [39] (blue long-dashed line); SIMPLE [40] (green long dot-dashed line). The black shaded region is the 3σ C.L. signal claimed by DAMA/LIBRA [12,41].

There are several sources of uncertainties related to the WIMP capture process. Uncertainty in the composition of the Sun is considered by comparing the DARKSUSY default choice BS2005-OP model with the BS2005-AGS,OP model [47] with lower heavy element abundances. For the uncertainty in the nuclear form factor, we compared the Helm-Gould form factor [7] used in DARKSUSY to the choices in Refs. [48,49]. These effects are predicted to be small in the SD-coupling case and up to 25%, 45% respectively in the SI-coupling case where heavier elements than hydrogen contribute to the capture. The effect of uncertainties in the velocity distribution of WIMPs is determined in Ref. [50] to be up to 40% (25)% for SD (SI) couplings. The effects of the planets on the capture rate is determined to be negligible [51,52]. Solar evaporation is expected to have no impact above a WIMP mass of $4 \text{ GeV}/c^2$ [16,53–55]. These uncertainties are added in quadrature and indicated by the shadowed regions in Figs. 3 and Fig. 4. Uncertainty in the local WIMP density will make a similar vertical shift of the limits for all direct and indirect detection experiments, and so is not indicated.

In conclusion, the result of the first WIMP search using contained events in SK is presented. No significant signal excess was found for $4\text{--}200 \text{ GeV}/c^2$ WIMP hypotheses. The derived upper limit on the SD WIMP-proton cross section places the most stringent constraint to date for WIMP masses below $200 \text{ GeV}/c^2$ even for the softest ($b\bar{b}$) channel, assuming the equilibrium condition between

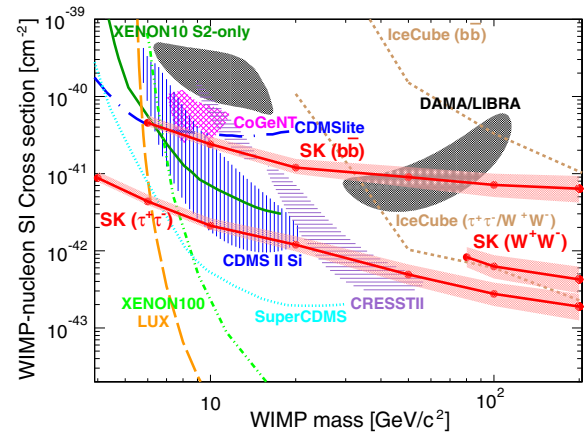


FIG. 4 (color online). 90% C.L. upper limits on the SI WIMP-nucleon cross section (plotting scheme is the same as Fig. 3). Also shown are event excesses or annual modulation signals reported by other experiments: DAMA/LIBRA (black shaded regions, 3σ C.L.); CoGeNT [13] (magenta diagonally cross-hatched region, 90% C.L.); CRESSTII [14] (violet horizontally shaded regions, 2σ C.L.); CDMS II Si [15] (blue vertically shaded region, 90% C.L.); and limits: IceCube [9] in brown dashed line: $b\bar{b}$ (top), W^+W^- or $\tau^+\tau^-$ (bottom); SuperCDMS [42] (cyan dotted line); CDMSlite [43] (blue long dot-dashed line); XENON10 S2-only [44] (dark green dash triple dotted line); XENON100 [45] (green dash double dotted line); LUX [46] (orange long-dashed line).

capture and annihilation rates. For the SI-coupling case with 100% annihilation to $\tau^+\tau^-$, we exclude new regions for WIMP masses below $6 \text{ GeV}/c^2$.

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