Limits on spin-independent couplings of WIMP dark matter with a p-type point-contact germanium detector

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We report new limits on spin-independent WIMP-nucleon interaction cross-section using 39.5 kg-days of data taken with a p-type point-contact germanium detector of 840 g fiducial mass at the Kuo-Sheng Reactor Neutrino Laboratory. Crucial to this study is the understanding of the selection procedures and, in particular, the bulk-surface events differentiation at the sub-keV range. The signal-retaining and background-rejecting efficiencies were measured with calibration gamma sources and a novel n-type point-contact germanium detector. Part of the parameter space in cross-section versus WIMP-mass implied by various experiments is probed and excluded.

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About one quarter of the energy density of the universe can be attributed to Cold Dark Matter[1], whose nature and properties are unknown. Weakly Interacting Massive Particles (WIMP, denoted by χ) are its leading candidates. There are intense experimental efforts to study χN→χN elastic scattering via the direct detection of nuclear recoils. Most experimental programs are optimized for mass range at mχ∼10–100 GeV, motivated by popular supersymmetric models. Germanium detectors sensitive to sub-keV recoil energy were identified and demonstrated as possible means to probe the “low-mass” WIMPs with mχ<10 GeV[2]. This inspired development of p-type point-contact germanium detectors (pGe) with modular mass of kg-scale[3].

Our earlier measurements at the Kuo-Sheng Reactor Neutrino Laboratory (KSNL, with a shallow depth of about 30 meter-water-equivalence) using a 4-element array with a total mass of 20 g and analysis threshold of 220 eVee (“eVee” denoting electron-equivalence energy throughout) have placed constraints on mχ>3 GeV[4]. The CoGeNT experiment reported data with a 440 g detector[5], showing an excess of events at the sub-keV range over the background models. A consistent annual modulation signature was observed. Allowed region in the spin-independent χN couplings (σpN) was derived. Intense interest and theoretical speculations in the low-mass WIMP region were generated[6]. The low energy data of the CDMS and XENON experiments[7] have subsequentially excluded the allowed region with different detector techniques, while the original interpretations were defended[8]. It is crucial to have independent experiments which can probe the CoGeNT allowed region and provide further understanding on the detector response and the nature of the sub-keV events in Ge-detectors.

We report new results with a pGe of 840 g fiducial mass (actual crystal mass 926 g) at KSNL. The low-background facilities as well as the hardware, trigger and data acquisition configurations were described in our previous work[4,9]. The detector was enclosed by an NaI(Tl) anti-Compton (AC) detector and copper passive shieldings inside a plastic bag purged by nitrogen gas evaporated from the liquid nitrogen dewar. This set-up was further shielded by, from inside out, 5 cm of copper, 25 cm of boron-loaded polyethylene, 5 cm of steel and 15 cm of lead. This structure was surrounded by cosmic-ray (CR) veto panels made of plastic scintillators read out by photomultipliers. Both AC and CR detectors are crucial, serving both as vetos to reject background and as tags to identify samples for efficiency measurements.

Signals from the point-contact are supplied through a reset preamplifier. The output is distributed to a fast-timing amplifier which keeps the rise-time information, and to amplifiers at both 6 µs and 12 µs shaping time which provide energy information. Signals from the outer surface-electrode are processed with a resistive feedback preamplifier and followed by amplifier at 4 µs shaping...
Background suppression with the PN, AC and CR cuts and the evaluations of their respective \((\epsilon_X, \lambda_X)\) follow the well-studied procedures of earlier experiments\(^4\) \(^9\) \(^1\) Such. The PN cuts are based on pulse shape characteristics and correlations among the fast and shaping signals. They suppress spurious triggers induced by microphonics effects or the tails of pedestal fluctuations. Background induced by the preamplifier reset is identified by the timing correlations with the reset instant. The in situ doubly-tagged AC\(^+\) \(\otimes\) CR\(^+\) events serve as the physics reference samples, with which \(\epsilon_{PN}\) shown in Figure 2 are accurately measured. The majority of the electronics-induced events above noise-edge are identified (\(\lambda_{PN} \approx 1\)). The efficiencies for AC and CR selections are measured by the random events to be, respectively, \(\epsilon_{AC} > 0.99\) and \(\epsilon_{CR} = 0.92\). Measured by reference cosmic samples in which the energy depositions at NaI(Tl) are above 20 MeVee.

The BS selection, on the other hand, is a unique feature to pGe. The surface-electrode is a lithium-diffused n\(^+\) layer of mm-scale thickness. Partial charge collection in the surface layer gives rise to reduced measurable energy and slower rise-time (\(\tau\)) in its fast-timing output, as compared to those in the bulk region\(^5\) \(^1\) \(^1\) The thickness of the S layer was derived to be \((1.16 \pm 0.09)\) mm, via the comparison of simulated and observed intensity ratios of \(\gamma\)-peaks from a \(^{133}\)Ba source\(^12\). This gives rise to a fiducial mass of 840 g, or a data size of 39.5 kg-days.

The \(\log_{10}[\tau]\) versus measured energy\((T)\) scatter plot is displayed in Figure 1. The boundary between the bulk and surface layers is not well defined, giving rise to events between the two bands. The observed and actual rates are denoted by \((B', S')\) and \((B, S)\), respectively. Events with \(\tau\) less/larger than \(\tau_0\) are categorized as \(B' \circ S'\) and \(B \circ S\). Typical B'\((S')\) events at \(T \sim 700\) eVee are shown. At \(T > 2.7\) keVee where the \(\tau\)-resolution is better than the separation between the two bands, the assignments \(B = B'\) and \(S = S'\) are justified. At lower energy, \(B' \circ S\) and \(B \circ S\) are related by the coupled equations:

\[
\begin{align*}
\quad B' &= \epsilon_{BS} \cdot B + (1 - \lambda_{BS} \cdot S) \\
S' &= (1 - \epsilon_{BS}) \cdot B + \lambda_{BS} \cdot S
\end{align*}
\]

with an additional unitarity constrain: \(B + S = B' + S'\).

The calibration of \((\epsilon_{BS}, \lambda_{BS})\) involves at least two measurements of \((B', S')\) where \((B, S)\) are independently known. The pulser events are inappropriate since their fast-timing output exhibit different pulse shapes from those of physics events. Instead three complementary data samples, as displayed in Figure 2, were adopted:

\(\text{(I)}\) Surface-rich events with \(\gamma\)-ray sources — Calibrations with both low and high energy \(\gamma\)-sources \((241\)Am at 60 keVee \(\text{and} \ 137\)Cs at 662 keVee, respectively) were performed. As displayed in Figure 2, the measured B'-spectra are compared to the reference B derived from full simulation with surface layer thickness of 1.16 mm as input. The simulated B'-spectra due to external \(\gamma\)-sources over a large range of energy are flat for \(T > 10\) keVee.

\(\text{(II)}\) Bulk-rich events with cosmic-ray induced fast neutrons — A 523 g first-of-its-kind n-type point-contact germanium (nGe) detector was constructed. The components and dimensions are identical to those of pGe.
The surface of nGe is a p⁺ boron implanted electrode of sub-micron thickness. There are no anomalous surface effects. Data were taken under identical shielding configurations at KSNL. The trigger efficiency was 100% above T=500 eVee, and energy calibration was obtained from the standard internal X-ray lines. The AC⁻⊗CR⁺ condition selects cosmic-ray induced fast neutron events without associated γ-activities, which manifest mostly (~85%) as bulk events. Accordingly, the AC⁻⊗CR⁺ spectrum in nGe is taken as the B-reference and compared with those of AC⁻⊗CR⁺⊗B' in pGe.

Using calibration data (I) and (II), (εBS,λBS) are measured by solving the coupled equations in Eq. 2. Standard error propagation formulae are adopted to derive their uncertainties using errors in (B,B',S') as input. As examples, the three allowed bands at threshold and at a high energy band are illustrated in Figure 2. The different orientations of the bands are consequences of the different energy bands. The surface-rich γ-events and the bulk-rich cosmic-ray induced neutron-events play complementary roles in constraining λBS and εBS, respectively. The results are depicted in Figure 3, with εPN overlaid. By comparing the measured in situ Ga-L X-ray peak at 1.3 keVee after BS-selection to that predicted by the corresponding K-peak at 10.37 keVee, a consistent εBS is independently measured.

The raw spectrum and those of AC⁻⊗CR⁺(⊗B') are depicted in Figure 3. The peaks correspond to known K-shell X-rays from the cosmogenically-activated isotopes. The (εBS,λBS)-corrected spectrum of AC⁻⊗CR⁻⊗B is shown in the large inset. Errors above T~800 eVee are dominated by statistical uncertainties, while those below have additional contributions from the BS calibration errors of Figure 2, which increase as the efficiencies deviate from unity at low energy. The analysis threshold is placed at 500 eVee, where (εBS,λBS)~0.5 and the BS selection is no longer valid. The stability of (εBS,λBS,B',S',B) is studied over changes of τ₀ within the τ-scan range of Figure 1. Measurements of B are stable and independent of τ₀, as indicated by the small variations relative to the uncertainties. On the contrary, (εBS,λBS) exhibit significant shifts in the expected directions. These features indicate that the BS calibration procedures are valid and
The quenching function in Ge is derived with the TRIM \[ 13 \] with conventional as-
cluded) note that an excess remains in the sub-keV region not
achieved. Part of the published DAMA, CRESST-II and
magnitude improvement over our previous results \[ 4 \] is
face background subtraction \[ 6 \] is included. An order of
vored region from the CoGeNT data with additional sur-
mark experiments are superimposed \[ 5, 7, 15 \]. The fa-
is displayed in Figure 4. Bounds from other bench-
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the L-shell X-ray lines predicted by the higher energy K-
y-rays from ambient radioactivity produce
flat electron-recoil background at low energy, as verified
robust. The systematic errors due to parameter choices
are of minor effects to the total uncertainties.

High energy γ-rays from ambient radioactivity produce
flat electron-recoil background at low energy, as verified
by the \(^{241}\)Am and \(^{137}\)Cs spectra of Figure 2, and by the \textit{in situ} AC\(^{+}\)⊙CR\(^{-}\)⊙B spectra. This, together with the L-shell X-ray lines predicted by the higher energy K-peaks, are subtracted from AC\(^{-}\)⊙CR\(^{-}\)⊙B. At a given \(m_\chi\), the flat background is measured at an energy range of at least 1.7 keVee and beyond the tail (<1%) of the \(\chi N\) recoil spectra. The residual spectrum corresponds to \(\chi N\) candidate events and is depicted in the small in-
set of Figure 3. Constraints on \(\sigma_{SI}^N\) are derived via the “binned Poisson” method \[ 13 \] with conventional astrophysical models \[ 1 \] (local density of 0.3 GeV/cc and Maxwellian velocity distribution with \(v_0=220\) km/s and \(v_{\text{esc}}=544\) km/s). The event rates of \(\chi N\) spin-independent interaction cannot be larger than the residual spectrum. The quenching function in Ge is derived with the TRIM software which matches well with existing data \[ 14 \]. As illustration, \(\chi N\) recoil spectrum due to an allowed (excluded) \(\sigma_{SI}^N\) at \(m_\chi=7\) GeV is shown in Figure 3. Ex-
clusion plot of \(\sigma_{SI}^N\) versus \(m_\chi\) at 90% confidence level is displayed in Figure 4. Bounds from other bench-
mark experiments are superimposed \[ 5, 7, 14 \]. The fa-
vored region from the CoGeNT data with additional sur-
face background subtraction \[ 6 \] is included. An order of magnitude improvement over our previous results \[ 4 \] is
achieved. Part of the published DAMA, CRESST-II and
CoGeNT allowed regions are probed and excluded. We
note that an excess remains in the sub-keV region not
yet accounted for in this analysis, the understanding of
which is the theme of our on-going investigations.

Studies continue on \(p Ge\) and \(n Ge\) at KSNL. Projects on
improvement of electronics and sub-noise-edge analysis \[ 11 \] are being pursued. Dedicated dark matter
experiment CDEX with sub-keV germanium detectors
are taking data at the new China Jinping Underground
Laboratory \[ 16 \]. This facility provides the attractive fea-
tures such as a rock overburden exceeding 2400 m and
horizontal drive-in access.

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