New limits on spin-independent and spin-dependent couplings of low-mass WIMP
dark matter with a germanium detector at a threshold of 220 eV

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An energy threshold of (220±10) eV was achieved at an efficiency of 50% with a four-channel ultra-low-energy germanium detector each with an active mass of 5 g. This provides a unique probe to WIMP dark matter with mass below 10 GeV. With a data acquisition live time of 0.338 kg-day at the Kuo-Sheng Laboratory, constraints on WIMPs in the galactic halo were derived. The limits improve over previous results on both spin-independent WIMP-nucleon and spin-dependent WIMP-neutron cross-sections for WIMP mass between 3−6 GeV. Sensitivities for full-scale experiments are projected. This detector technique makes the unexplored sub-keV energy window accessible for new neutrino and dark matter experiments.

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There is compelling evidence from cosmological and astrophysical observations that about one quarter of the energy density of the universe can be attributed to Cold Dark Matter (CDM), whose nature and properties are still unknown.1 Weakly Interacting Massive Particles (WIMP, denoted by \( \chi \)) are the leading candidates for CDM. There are intense experimental efforts2 to look for WIMPs through direct detection of nuclear recoils in \( \chi N \rightarrow \chi N \) elastic scattering or in the studies of the possible products through \( \chi \chi \) annihilations.

Supersymmetric (SU3) particles3 are the leading WIMP candidates. The popular SUSY models prefer WIMP mass \( m_{\chi} \) in the range of ~100 GeV, though light neutralinos remain a possibility.4 Most experimental programs optimize their design in the high-mass region and exhibit diminishing sensitivities for \( m_{\chi} < 10 \) GeV, where an allowed region due to the annual modulation data of the DAMA experiment5,6 − further reinforced by the first DAMA/LIBRA results7 − remains unprobed. Simple extensions of the Standard Model with a singlet scalar favors light WIMPs.8 Detectors with sub-keV threshold are needed for probing this low-mass region and studying WIMPs bound in the solar system, and non-pointlike SUSY candidates like Q-balls.10 This presents a formidable challenge to both detector technology and background control. Only the CRESST-I experiment has set limits11 with sapphire(Al2O3)-based cryogenic detector at a threshold of 600 eV.

The Kuo-Sheng (KS) Laboratory12 is located at 28 m from a 2.9 GW reactor core with an overburden of about 30 meter-water-equivalence. Limits on neutrino magnetic moments \( (\mu_\nu) \)13 with a 1.06-kg germanium detector (HPGe) at a threshold of 5 keV were reported14. These data also allowed the studies of reactor electron neutrinos15 and reactor axions16. A background level of ~1 event kg\(^{-1}\)keV\(^{-1}\)day\(^{-1}\)(cppkd) at 20 keV, comparable with those of underground CDM experiments, was achieved. The current goal is to develop detectors with kg-scale target mass, 100 eV-range threshold and low-background specifications for the studies of WIMPs, \( \mu_\nu \) and neutrino-nucleus coherent scatterings.

Ultra-low-energy germanium detectors (ULEGe) is a matured technique for sub-keV soft X-rays measurements. They typically have modular mass of 5−10 g while detector arrays of up to 30 elements have been constructed. Compared with Al2O3, Ge provides enhancement in \( \chi N \) spin-independent couplings \( (\sigma_{SI}^{\chi N}) \) due to the A\(^2\) dependence1,18, where A is the mass number of the target isotopes. The isotope \( ^{73}\text{Ge} \) (natural isotopic abundance of 7.73%) comprises an unpaired neutron such that it can provide additional probe to the spin-dependent couplings of WIMPs with the neutrons \( (\sigma_{SD}^{\chi N}) \). The nuclear recoils from \( \chi N \) interactions in ULEGe only give rise to ~20% of the observable ionizations compared with electron recoils at the same energy. The suppression ratio is called the quenching factor \( (QF) \).19 For clarity, all ULEGe measurements discussed hereafter in this article are electron-equivalent-energy, unless otherwise stated.

The ULEGe array consists of 4-element each having an active mass of 5 g.20 Standard ultra-low-background specifications were adopted in its construction and choice of materials. It has identical external dimensions as the 1-kg HPGe of Ref.14. Apart from swapping between the two detectors, data taking was performed with
all other hardware components, shieldings configuration, electronics and data acquisition (DAQ) systems kept identical. The schematic diagram of the experimental setup inside the shieldings is depicted in Figure 1.

The ULEGe signals were provided by built-in pulsed optical feedback pre-amplifiers, and were distributed to two spectroscopy amplifiers at 6 $\mu$s (SA$_6$) and 12 $\mu$s (SA$_{12}$) shaping times and with different amplification factors. Discriminator output of SA$_6$ defined the trigger conditions for DAQ. The threshold was set to about 4.3$\pm$0.2 times the RMS fluctuations of the SA$_6$ signals above the pedestal. The DAQ rates for the ULEGe were about 5 Hz, due mostly to electronic noise and agreed well with expectations. The SA$_6$, SA$_{12}$, Anti-Compton Veto (ACV) and Cosmic-Ray Veto (CRV) signals were read out by 20 MHz Flash Analog-to-Digital Convertors. Random trigger (RT) events generated at 0.1 Hz and uncorrelated with the rest of the system, as well as various system control parameters, were also recorded.

Energy measurements were given by SA$^T_{12}$ defined in the next paragraph. Figure 2 shows an energy calibration spectrum due to external $^{55}$Fe sources (5.90 and 6.49 keV) together with X-rays from Ti (4.51 and 4.93 keV), Ca (3.69 keV), and S (2.31 keV). Photons with energy lower than 2 keV were completely absorbed by the detector window. The RT-events provided the calibration point at zero-energy. The RMS resolutions for the RT-events and $^{55}$Fe peaks were about 55 eV and 78 eV, respectively. The calibration procedures were performed before and after the DAQ periods. Linearity was checked up to 60 keV with various $\gamma$-sources, and between zero and 2 keV with a precision pulse generator. The energy scale was accurate to $<20$ eV, while deviations from linearity were $<1\%$. The electronic gain drifts, also monitored in situ by the pulse generator, were $<5\%$. A detector hardware “noise-edge” of about 300 eV was achieved.

Pulse shape discrimination (PSD) software was devised to differentiate physics events from those due to electronic noise, exploiting the correlations in both the energy and timing information of the SA$_6$ and SA$_{12}$ signals. Displayed in Figure 2 is a scattered plot of the SA$^P_6$ versus SA$^T_{12}$ signals, for both calibration and physics events. The PSD selection is shown.

Data were taken with the ULEGe at KS with different hardware and software configurations. They provided important input on the background understanding and performance optimizations for future full-scale experiments. The data set with the best background and threshold has a DAQ live time of 0.338 kg-day. The analysis results and the systematic effects at the two energy intervals which defined the sensitivities for $m_\chi$ below and
The ULEGe data were taken in conjunction with a CsI(Tl) scintillator array\textsuperscript{24} for the studies of neutrino-electron scattering. The combined DAQ rate was about 30 Hz. The DAQ dead time and the CRV+ACV selection efficiencies listed in Table I were accurately measured using RT-events\textsuperscript{14}. The maximum amplitude distributions of the RT pedestals and physics events above the noise-edge of 300 eV were measured. The corresponding distributions for events $<$300 eV were evaluated by interpolations to avoid biased sampling. The trigger efficiencies depicted in Figure 3 correspond to the fractions of the distributions above the discriminator threshold level. Events in coincidence with ACV-tags are mostly physics-induced. The fraction of these events surviving the PSD cuts was taken to be the PSD efficiency. This assignment is conservative since the actual efficiency corresponds to the survival fraction of samples after electronic noise events in accidental coincidence were subtracted, and therefore should be higher. Alternatively, under the assumption that the $^{55}$Fe calibration of Figure 1 would give rise to physics events with a flat spectrum down to the lowest energy relevant to this analysis ($<$100 eV), the deviations of the PSD-selected events from a flat distribution provided the second measurement. Consistent

| Energy Bin            | 198–241 eV | 1.39–1.87 keV |
|-----------------------|------------|--------------|
| Raw Background Counts | 105212     | 0            |
| Selection Cuts and Systematic Effects: | | |
| Trigger Efficiency (%) | | 100          |
| DAQ Dead Time (%)     | 11.0 ± 0.1 | 110          |
| PSD – Cumulative Background Survival Fraction (%) | 0.008 | 97 |
| Signal Efficiency (%) | 66 ± 6 | 100 |
| ACV – Cumulative Background Survival Fraction (%) | 0.0 | 2.7 |
| Signal Efficiency (%) | 98.3 ± 0.1 | 0.0 |
| CRV – Cumulative Background Survival Fraction (%) | 0.0 | 91.4 ± 0.1 |
| Signal Efficiency (%) | | |
| After-Cut Background Counts | 0 | 0 |
| After-Cut Normalized Background Rates (kg$^{-1}$keV$^{-1}$day$^{-1}$) | $0 \pm 0.018_0$ (stat) $± 0.003_0$ (sys) | $0 \pm 0.013_0$ (stat) $± 0.0007_0$ (sys) |
| Quenching Factor | 0.200 ± 0.006 | 0.244 ± 0.007 |
| Sampling in $m_\chi$ (GeV) | 5 | 50 |
| $\sigma_{\text{SI}}^N$ ($10^{-39}$ cm$^2$) | | |
| Mean & Errors due to Background & QF Uncertainties | $0 \pm 0.64_0$ (Bkg) $± 0.01(QF)$ | $0 \pm 0.153_0$ (Bkg) $± 0.003(QF)$ |
| Limit at 90% Confidence Level | < 0.81 | < 0.20 |
| $\sigma_{\text{SI}}^{\text{SI}}$ ($10^{-34}$ cm$^2$) | | |
| Mean & Errors due to Background & QF Uncertainties | $0 \pm 1.96_0$ (Bkg) $± 0.03(QF)$ | $0 \pm 0.47_0$ (Bkg) $± 0.01(QF)$ |
| Limit at 90% Confidence Level | < 2.40 | < 0.59 |

FIG. 3: Selection efficiencies of the PSD cut, as derived from the $^{55}$Fe-calibration and in situ data with ACV tags. Also shown are the best-fit 1σ region and the trigger efficiency for physics events recorded by the DAQ system.

Events in coincidence with ACV-tags are mostly physics-induced. The fraction of these events surviving the PSD cuts was taken to be the PSD efficiency. This assignment is conservative since the actual efficiency corresponds to the survival fraction of samples after electronic noise events in accidental coincidence were subtracted, and therefore should be higher. Alternatively, under the assumption that the $^{55}$Fe calibration of Figure 1 would give rise to physics events with a flat spectrum down to the lowest energy relevant to this analysis ($<$100 eV), the deviations of the PSD-selected events from a flat distribution provided the second measurement. Consistent

FIG. 4: The measured spectrum of ULEGe with 0.338 kg-day of data, after CRV, ACV and PSD selections. Background spectra of the CRESST-I experiment\textsuperscript{11} and the HPGe\textsuperscript{14} are overlaid for comparison. The expected nuclear recoil spectra for two cases of ($m_\chi$, $\sigma_{\text{SI}}^{\text{SI}}$) are superimposed onto the spectrum shown in linear scales in the inset.
results were obtained with both approaches, as depicted in Figure 5. The larger uncertainties of the first method are due to the limited statistics from only the in-situ ACV samples. The efficiencies and their uncertainties adopted for analysis were derived from a best-fit on the combined data set. A threshold of (220±10) eV was achieved with a PSD efficiency of 50%.

The ULEGe spectrum normalized in cpkkd unit after the CRV, ACV and PSD selections is displayed in Figure 3, showing comparable background as CRESST-I[11]. Listed in Table I are the normalized background rates, indicating that statistical uncertainties dominate over the systematic effects. The formalisms followed those of Ref. [18] using standard nuclear form factors, a galactic rotational velocity of 230 km s$^{-1}$ and a local WIMP density of 0.3 GeV cm$^{-3}$ with Maxwellian velocity distribution. No subtraction of background profiles was made such that the WIMP signals cannot be larger than the observed event rates. The unbinned optimal interval method as formulated in Ref. [22] and widely used by current CDM experiments was adopted to derive the upper limits for the possible $\chi N$ event rates. By comparing the observed background in different energy intervals with the expected number of events due to $\chi N$ recoils for each $m_\chi$, the optimal intervals producing the most stringent limits to $\sigma_{\chi N}^{SI}$ and $\sigma_{\chi n}^{SD}$ were selected. Corrections due to QF, detector resolution and various efficiency factors were incorporated. The energy dependence of QF in Ge was evaluated with the TRIM software package [25]. The uncertainties were taken to be their difference with the statistical best-fit values of the available data [27] from 254 eV to 200 keV nuclear recoil energy.

Exclusion plots on both ($m_\chi$, $\sigma_{\chi N}^{SI}$) and ($m_\chi$, $\sigma_{\chi n}^{SD}$) planes at 90% confidence level for galactically-bound WIMPs were then derived, as depicted in Figures 5 and 6, respectively. The DAMA-allowed regions [5, 6] and the current exclusion boundaries [11, 28] are displayed. The model-independent approach of Refs. [23, 30] were adopted to extract limits on the spin-dependent cross-sections. Consistent results were obtained when different $^{73}$Ge nuclear physics matrix elements [31] were adopted as input. The constraints on the effective axial four-fermion $\chi$-proton and $\chi$-neutron spin-dependent couplings [30] at $m_\chi=5$ GeV are displayed in Figure 6. The parameter space probed by the $^{73}$Ge in ULEGe is complementary to that of the CRESST-I experiment [11] where the $^{27}$Al target is made up of an unpaired proton instead. New limits were set by the KS-ULEGe data in both $\sigma_{\chi N}^{SI}$ and $\sigma_{\chi n}^{SD}$ for $m_\chi$$\sim$3–6 GeV. The remaining DAMA low-$m_\chi$ allowed regions in both interactions were probed and excluded. The observable nuclear recoils at $m_\chi=5$ GeV and $\sigma_{\chi N}^{SI}$$=0.5 \times 10^{-39}$ cm$^2$ (allowed) and $1.5 \times 10^{-39}$ cm$^2$ (excluded) are superimposed with the measured spectrum in the inset of Figure 3 for illustrations. It is expected that recent data from the COUPP [32] experiment can place further constraints in the spin-dependent plots of Figures 6a&b.

This work extends the bounds on WIMPs by making measurements in a new observable window of 100 eV–1 keV in a low-background environment. Understanding and suppression of background at this sub-keV region is crucial for further improvement. Measurements are conducted with the ULEGe at an underground laboratory. There are recent advances in “Point-Contact” Ge detector [33] which offer potentials of scaling-up the detector mass to the kg-range. Preliminary results in dark matter searches were recently reported [34]. The mass-normalized external background will be reduced in massive detectors due to self-attenuation [17]. Further reduction in threshold may be possible with improved junction field-effect-transistors and by correlating signals from both electrodes. The potential reach of full-scale experiments with 1 kg-year of data and a benchmark background level of 1 cpkkd is illustrated in Figures 4 and 6. Such experimental programs are complementary to the many current efforts on CDM direct searches.

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FIG. 6: (a) Left: Exclusion plot of the spin-dependent $\chi$-neutron cross-section versus WIMP-mass. Same conventions as those in Figure 5 are used. (b) Right: Constraints at $m_\chi = 5$ GeV on the effective axial four-fermion $\chi$-proton ($a_p$) and $\chi$-neutron ($a_n$) spin-dependent couplings, in units of $2\sqrt{2}G_F$ following the formulation of Ref. [30]. The parameter space within the bands of the corresponding experiments are allowed. The shaded area at the origin is the combined allowed region.

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Appendix I:

Trigger Efficiency at Threshold — Reply to arXiv:0806.1341v2

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The authors in a recent paper [1] raised questions on our estimates of trigger efficiency in the evaluation of the constraints on WIMP Dark Matter in the low-mass (< 10 GeV) domain with a Ultra-Low Energy Germanium (ULEGe) detector at a threshold of 220 eV [2]. The discrepancy originates from some misleading terminology in Ref. [2]. We address the issue in details in this reply. We show how the trigger efficiencies are derived and demonstrate that the results of Ref. [2] are correct.

I. CONCEPT OF EXPERIMENT

Details of the experimental setup and data analysis, as well as the definitions of notations, can be referred to Ref. [2]. There are two categories of events relevant to the present discussion: physics signals (PHY) and electronic noise (ELE). The PHY events are due to actual energy depositions at the ULEGe by gammas, neutrons, neutrinos, WIMPs and other radiations, while ELE events are induced by the various stages in the readout electronics. The majority of the events above the noise edge of 300 eV are PHY-events. A particularly good method to extract a clean sample of PHY-events below the noise edge for further studies is to require that the ULEGe signals are in coincidence with the Anti-Compton Veto (ACV) tag. However, PHY-events due to neutrinos or dark matter interactions would have to be in anti-coincidence with ACV. A major goal of the experiment is to lower the threshold by suppressing ELE while keeping PHY-events in some substantially large and known fraction.

In order for PHY-events to be included in the final spectra where physics is extracted, they have to survive three procedures, the efficiency of each of which must be known. These efficiency factors were summarized in Table 1 of Ref. [2]:

1. Trigger efficiency ($\epsilon_{\text{Trig}}$) — that PHY would produce a trigger signal to the data acquisition (DAQ) system. This efficiency depends on the energy of PHY.

2. DAQ efficiency ($\epsilon_{\text{DAQ}}$) — that the trigger signal would actually activate the DAQ system resulting in a complete event recorded in the computer. This efficiency is independent of the energy of PHY.

3. Analysis efficiency ($\epsilon_{\text{Anly}}$) — that offline software procedures would retain PHY and suppress ELE.

Some PHY would be rejected in the process leading to an efficiency factor which is energy-dependent.

Among these three efficiency factors, the derivations of $\epsilon_{\text{DAQ}}$ and $\epsilon_{\text{Anly}}$ were discussed in Ref. [2]. The $\epsilon_{\text{DAQ}}$ was evaluated accurately by “Random Trigger” (RT) events to be 89% — fraction of the RT events actually recorded in the computer. (cited in Table 1 as “DAQ Dead Time” of 11.0%). Same procedures were used in our earlier work on neutrino magnetic moments [3]. The evaluation of $\epsilon_{\text{Anly}}$ by two different approaches was discussed in the text and the results were shown in Figure 3. Further elaborations are made in Ref. [4]. The rest of this reply would focus on $\epsilon_{\text{Trig}}$.

II. DISCREPANCIES AND ORIGINS

Ref. [1] challenged our values of $\epsilon_{\text{DAQ}} \sim 89\%$, stating that the “discriminator threshold of 20 eV” and “RMS resolution of pedestal (that is, RT events) of 55 eV” would imply a DAQ rate ($R$) of $\sim$20kHz, based on a known relation [5]

$$R \sim \frac{1}{4\tau} \exp \left( -\frac{d^2}{2\sigma^2} \right), \quad (1)$$

where $\tau$ is the shaping time (=6 $\mu$s for the trigger signal SA$_6$), $\sigma$ is the RMS of the pedestal noise fluctuations and $d$ is the threshold level above the pedestal. The calculated rate is much higher than the actual DAQ rate of $\sim$5 Hz for the ULEGe in the actual measurement.

This discrepancy originates from the fact that it is incorrect to use these two energy values together in Eq. 1. In the experiment, the “energy” of an event is defined by integrating (the “Q-mode”) the SA$_{12}$ signal within time intervals (-20,51.2) $\mu$s where t=0 denotes the trigger instant. That is, the energy is measured through the summation of 71.2X20=1424 FADC numbers. Under this definition, the pedestal (RT) events have an RMS resolution of 55 eV, after appropriate calibration. However, the triggering was done by comparing the SA$_6$ signal with a pre-set discriminator level. That is, the relevant quantity in this operation is the amplitude of the pulse (the “A-mode”) — and in fact of a different pulse (SA$_6$ instead of SA$_{12}$, but this is a minor point). The RMS-resolution of RT events in Q-mode is not related to the trigger configuration in A-mode and therefore should not be taken as the $\sigma$ of Eq. 1 which describes the trigger rate. It is an experimental optimization frequently used (also discussed in Ref. [3]) — that the energy definitions are based on averaging over long periods, while the triggering schemes make use of the instantaneous response of the signal.
FIG. 1: Typical SA$_6$ pulses due to (a) Top: a random trigger event and (b) Bottom: a physics event at 139 eV in coincidence with anti-Compton signal. The pedestal mean and the discriminator threshold were denoted by dotted and dashed lines, respectively.

III. EVALUATION OF TRIGGER EFFICIENCY

Having identified the source of discrepancy which led to the incorrect conclusions in Ref. [1], we present the evaluation of $\epsilon_{\text{Triq}}$ in what follows. Displayed in Figures 1a&b are typical SA$_6$ signals for RT and PHY events, respectively. The amplitude is presented in FADC unit (2 V is equivalent to 256 FADC unit). The PHY-event was measured to be 139 eV in the Q-mode, and in coincidence with ACV. Superimposed is the discriminator level (38 ± 2 mV in hardware unit, uncertainties mostly from instabilities over time) which is 4.8 FADC unit above the mean value of the pedestal level. It can be seen that the RT event is below threshold while the PHY event is above threshold by $\sim$1.5 FADC unit, thereby provided a trigger to the DAQ system with good margin.

Histograms of large samples of events like those of Figures 1a&b are presented in Figure 2, where the horizontal axis in FADC unit. The RMS is 1.1 FADC unit and represents the noise fluctuation of the SA$_6$ signal. The discriminator threshold level is also shown. Accordingly, one can equate $\tau$=6 µs, $d$=4.8±0.3 and $\sigma$=1.1 in Eq. 1 giving $R \sim 3.1^{+0.6}_{-0.5}$ Hz. The measured rate averaged over the entire DAQ periods of about 17 days and for four channels together is $\sim$5 Hz. This is in good agreement.

The various distributions show the maximum amplitude of PHY-events at various energy ranges measured by the Q-mode. All the events above 100 eV (the relevant range for subsequent analysis) exhibit at least 1 FADC Unit of margin above threshold. The trigger efficiencies were then derived using the maximum amplitude distributions of the RT events at E=0 and the PHY-events between 300 eV to 1000 eV. The mean and RMS for the E=0−300 eV regions were evaluated by interpolation (rather than from actual data) to avoid biased sampling. The results are displayed in Figure 3. We note that the energy range that provides the most severe constraints to the dark matter analysis is that of 200-250 eV, where the trigger efficiency is close to unity.

Using PHY-events as well as data taken with precision test pulser, it can be shown that energy measurements with Q-mode (integration) and A-mode (maximum amplitude) are both valid and equivalent for pulses which are large compared to the noise fluctuations. Moreover, the Q-mode measurements are well-behaved and linear all the way towards the pedestal zero-energy level. On the contrary, the A-mode measurements become inaccurate and the calibration is non-linear as the energy decreases and approaches zero. *Although the threshold is well-defined in amplitude (4.8±0.3 FADC unit), the statement “discriminator threshold at 20 eV” in Ref. [3] has been misleading and too simplistic. It is incorrect to equate the threshold to a single number in Q-mode as its...*
energy scale. That is, the trigger efficiency versus energy curve of Figure 3 is not a step-function. For instance, $\epsilon_{\text{Trig}} = 50 \pm 30\%$ corresponds to an energy range of about 80$\pm$50 eV. This is the root of the misunderstanding and is corrected in the revised text.

IV. COMPARISON OF KS AND Y2L SPECTRA

Another point noted in Ref. [1] is the comparison of spectra in Ref. [2] with those taken at the Y2L underground laboratory in South Korea [6]. Such comparisons would not be appropriate. Different detectors were used even though the specifications are similar. The electronic modules and noise sources (which are affected by many ambient conditions) are not identical. The most important difference is that we did not make an attempt to use pulse shape differentiation (PSD) techniques to suppress ELE-events with Y2L data. The spectra shown with Y2L data are always without PSD cuts, such that the raw “background” – dominated by ELE-events – below the noise edge are extremely high. DAQ rates in both cases are similar, at the range 1-10 Hz. Displayed in Figure 4 are the raw spectra for both KS and Y2L, as well as that after PSD suppression for KS. It can be seen that the raw spectra are comparable. The residual differences are due to ambient electronic noise and radioactive background conditions.

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Additional questions were raised in a recent paper [1] on the experimental concepts and systematic issues of our recent results on WIMP Dark Matter searches in the low-mass (< 10 GeV) domain with a Ultra-Low Energy Germanium (ULEGe) detector at a threshold of 220 eV [2]. We provide clarifications and justifications on these issues, and conclude that there are no flaws in our procedures.

I. COMMENTS AND REPLIES

In a previous version (V2) [3], the authors raised questions on our DAQ dead time, trigger efficiencies and apparent inconsistencies between the Kuo-Sheng Reactor Laboratory (KS) and the Yang-Yang Underground Laboratory (Y2L) data. In an earlier reply [4], these questions were addressed in details. No further comments were made along these lines.

A new version (V3) of the comments [1] was subsequently posted, where questions on the experimental concepts and various systematic issues were raised. We responded on these comments in this article. Section II deals with the basic concepts and performance of the PSD cuts and efficiencies, while Section III elaborates on the reasons behind the various choices made in the experiment. Details of the experimental setup and data analysis, as well as the definitions of notations, can be referred to Ref. [2].

II. SELECTION CUTS AND EFFICIENCIES

A. General Comments

The objectives of applying selection criteria (“cuts”) on experimental data is to reject undesirable “background” events and increase the fraction of “signal” events in the data sample. The events surviving the cuts need not be all signals, only that usually, the signal-to-background ratios are enhanced by the selection.

There are much freedom in the choice of these cuts. There may be effective or ineffective cuts, but in general, all cuts are valid. The variables (“figure of merits” FoM) on which the cuts are applied are defined to optimize the performance. The FoMs can be mathematical constructions and need not correspond to, or be linear to, certain physical variables. Once the events are selected by the cuts, the physical parameters (like energy) can be derived for these events with different algorithms which are themselves constructed to give the best resolutions for these quantities.

When a set of cuts are applied to experimental data, the corresponding “selection efficiencies” must be evaluated. These are the probabilities that potential signal events that will survive these cuts. The goals of applying cuts are to suppress background events as much as possible while keeping the selection efficiencies as large as possible.

B. Specific: This Analysis

In this particular analysis [2], the ACV and CRV cuts are straightforward. They are signals from detector components other than the ULEGe target, and their efficiencies were evaluated by random trigger (RT) events. Their performance are summarized in Table 1 of Ref. [2].

It is the PSD-cut which was questioned by Ref. [1]. This cut was applied to the variables “SA6” and “SA12”, as displayed again in Figure 1. Among them, SA12 also provides an energy measurement, while SA6 is a mathematical construction to optimize the performance of signal-vs-background differentiation. In this case, “background” corresponds to electronic noise events below the hardware noise edge.

Motivations for the choice of SA6: The two pulses SA6 and SA12 are correlated for physics signals. The correlations are different and less strong for noise-events. The conceptual idea behind the PSD cut is that, given the energy of an event is known through measurements by SA12, positive fluctuations of the SA6-pulses in physics-induced events at a particular time interval and amplitude ranges can be expected. This is probed by the

![Figure 1: Scattered plots of the SA6 versus SA12 signals, for both calibration and physics events before ACV and CRV cuts. The PSD selection is shown.](image-url)
PSD cut. The selected time interval is optimized for energies near threshold (<300 eV), such that this interval no longer corresponds to the amplitude-peaks of SA₀ for events at higher energy. Therefore, SA₀ being non-linear with energy does not jeopardize the validity of the cut. The reasons behind the non-linear behaviour is well-understood — and in fact intentional.

Is the PSD cut arbitrary? NO. The application of the PSD cut is based on genuine understanding on the behaviour of the detector hardware. Such PSD techniques — correlations of two signals at two shaping times and, alternatively, of the full and partial integrations of the signals — are well-established ones at higher energy in the case of α/γ separation in many detector systems.

Displayed in Figure 2 are the survival fraction \( f \) of events at E=200–300 eV with an ACV (Anti-Compton) tag versus the relative timing between the ACV signals and the ULEGe triggers. Overlaid are the actual coincidence time interval between the ACV and the ULEGe systems determined independently from hardware timing. The coincidence window is about 3 µs. This is defined by (a) the 6 µs shaping time output SA₀ from ULEGe which provided the trigger timing; and (b) the increased time-jitters at low energy. The ACV and ULEGe signals outside this range are accidentals and uncorrelated.

It can be seen that ONLY ULEGe events in correct coincidence with the ACV-tags give a substantial value of \( f \). The survival fraction for events without ACV-tags (denoted by the data point at negative time in Figure 2) — predominantly due to electronic noise at this energy — is \((1.7±0.3)×10^{-4}\). This proves that the PSD cut is successfully devised and is performing its intended functions of “suppressing electronic noise events and selecting the physics-induced events”.

Selection Efficiencies: The PSD-efficiency for physics-induced events \( \epsilon_{\text{PSD}} \) is related to the measured survival fraction \( f \) by

\[
f = \frac{(\epsilon_{\text{PSD}} \times P + f_N \times N)}{P + N},
\]

where \( P \) and \( N \) are, respectively, the numbers of physics-induced and noise events in correct coincidence with ACV, while \( f_N \) is the survival fraction for events triggered by electronic noise. In this experiment, \( f \) and \( P + N \) are measured quantities, \( f_N \sim 10^{-4} \) at 200–300 eV and even less at lower energy, while the average \( N \) can be evaluated from the non-coincidence samples where \( P = 0 \). It can be seen that, in general, \( \epsilon_{\text{PSD}} > f \) so long as there are finite fraction of noise events in the ACV-tagged sample.

Statistics are limited in the present analysis since only in situ data were used. The number of noise events in the coincidence ACV-tagged sample is finite but has large uncertainties. Accordingly, the more appropriate approach is to take zero noise-background \((N = 0)\), giving rise to the assignment of \( \epsilon_{\text{PSD}} = f \). The subsequent upper limits derived would therefore be conservative and less constraining ones. The variations of \( \epsilon_{\text{PSD}} \) with energy under this assignment are displayed in Figure 3 of Ref. [2].

![ACV tag events at 200 – 300 eV](image)

**III. EXPERIMENT’S CHOICES**

Inevitably, an experiment has to choose various tools from the available pool in the course of its analysis. We explain why such choices were made for the cases raised in Ref. [1], and illustrate the sensitivities to the physics results if alternative schemes would had been selected instead.

**A. \(^{55}\text{Fe}\) spectrum for Selection Efficiency**

It was explicitly stated in Ref. [2] that the flat \(^{55}\text{Fe}\) spectrum at low energy is an assumption. Under this assumption, the PSD selection efficiencies were derived. The results agree well with those obtained by the more rigorous approach with ACV-tagged events. The good agreement suggests validity of the assumption at the present level of accuracy. Accordingly, it is justified to add these results to further constrain (to reduce uncertainties of) our knowledge of \( \epsilon_{\text{PSD}} \). This is the approach adopted in Ref. [2].

If the data from the \(^{55}\text{Fe}\) spectrum would be ignored altogether and the PSD efficiencies would be derived exclusively from the ACV-tagged events, \( \epsilon_{\text{PSD}} \) at E=200–300 eV would move from \((0.65±0.06)\) to \((0.61±0.08)\). The 50% efficiency line would correspond to 224 eV instead of 216 eV, while the \( \sigma_{\text{SI}} \) limits (in units
FIG. 3: A compilation of all quenching factor (QF) measurements on germanium, with calculations from the TRIM software [6] as well as by the Lindhard model [7] under two parametrizations (k=0.20 and 0.15) overlaid.

of $10^{-39}$ cm$^2$ throughout in this Section) at $m_\chi = 5$ GeV would increase (become less constraining) from 0.81 to 0.88.

B. Quenching Factor

A compilation of all quenching factor (QF) measurements on germanium is given in Figure 3. Overlaid are calculations from the TRIM software [6] as well as by the Lindhard model [7] under two parametrizations (k=0.20 and 0.157). Both schemes have been adopted in various CDM experiments. It can be seen that the TRIM results explain well the QF measurements at both low and high energy. Accordingly, we chose to use this scheme in our analysis. The QF values are less than those evaluated with the Lindhard (k=0.20) model, and hence would give rise to more conservative results.

If Lindhard (k=0.20) would be used, the QF at 1 keV recoil energy will be increased from 0.20 to 0.21. The QF uncertainty estimations of 0.006 in Ref. [2] can account for this deviation. This alternative choice will only have minor effects on the exclusion limits, decreasing it (becoming more constraining) from 0.81 to 0.80 at $m_\chi = 5$ GeV.

C. Constructing Exclusion Plots

The unbinned “optimal interval method” as formulated in Ref. [8] was adopted to derive the exclusion limits. The unbinned formalism allows the use of all available information in the background spectra and was used in other CDM experiments like CDMS and XENON. No background profile was assumed or subtracted, which is also a conservative approach. The sensitivities at low $m_\chi$ under this scheme are driven by the absence of counts between 198 eV and 241 eV.

An alternative method would be to place the background events in different energy bins and follow the formalism of Ref. [9]. For instance, choosing 50-eV bins for $E>$100 eV (thereby deliberately filling the hole at 200−250 eV), the $\sigma_{SI}$ limit at $m_\chi = 5$ GeV would increase (become less constraining) from 0.81 to 1.20. This reduction in sensitivities is expected since data binning involves loss of information.

We conclude that our choices in these three aspects of the experiment are justified. The sensitivities of the physics results (exclusion upper limits) are dominated by the statistical uncertainties of the background spectra. The potential effects on them are minor if alternative schemes would have been chosen instead.

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