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Limits on Low-Mass WIMP Dark Matter with an Ultra-Low-Energy Germanium Detector at 220 eV Threshold (10'+5')

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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[1]. 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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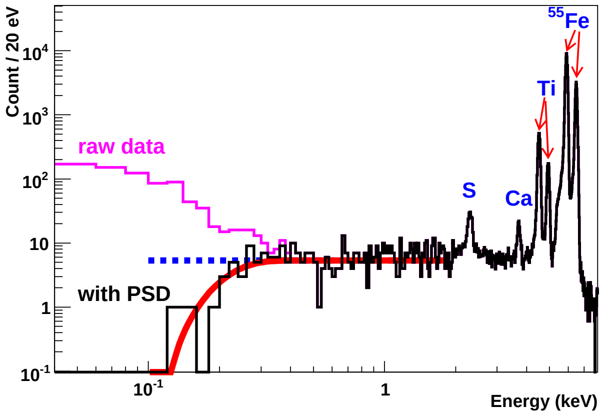

Figure 1: Measured energy spectrum of the ULEGe with ^{55}Fe source together with X-ray from Ti, Ca and S. The black histogram represents events selected by PSD cuts.

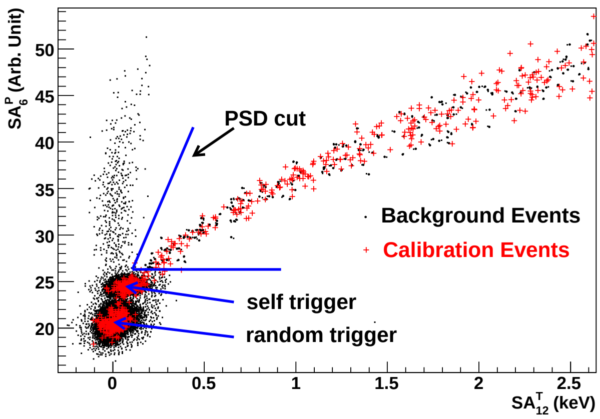

Figure 2: Scattered plots of the SA_6^P versus SA_{12}^T signals, for both calibration and physics events[1]. The PSD selection is shown.

Weakly Interacting Massive Particles (WIMP, denoted by χ) are the leading candidates for Cold Dark Matter (CDM)[2]. There are intense experimental efforts 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 $\chi\bar{\chi}$ annihilation products. Most experimental programs optimize their design in the high WIMP mass (m_χ) region and exhibit diminishing sensitivities for $m_\chi < 10$ GeV, where an allowed region due to the annual modulation data of the DAMA/LIBRA[2] experiment remains unprobed. Detectors with sub-keV threshold are needed for probing this mass range, and present a formidable challenge to both detector technology and background control. We report the first results in an attempt towards such goals[1].

Ultra-low-energy germanium detectors(ULEGe) is a matured technique for sub-keV soft X-rays measurements. Compared with Al_2O_3 which also has set limits[3] at the sub-keV threshold, Ge provides enhancement in χN spin-independent couplings($\sigma_{\chi N}^{SI}$) due to the A^2 dependence[2, 4], where A is the mass number of the target isotopes. In addition, The isotope ^{73}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($\sigma_{\chi n}^{SD}$). The nuclear recoils from χN interactions in ULEGe only give rise to $\sim$20% (the Quenching Factor−QF) of the observable ionizations compared with electron recoils at the same energy.

A low-background ULEGe array consisting of 4-element each having an active mass of 5 g was built. Low background measurement was performed at the Kuo-Sheng(KS) Laboratory with an overburden of about 30 meter-water-equivalence. A background level of $\sim$ 1 event $kg^{-1}keV^{-1}day^{-1}$ (cpkkd) at 20 keV, comparable with those of underground CDM experiments, was achieved in a previous experiment with a 1-kg HPGe detector[5] for the studies of neutrino magnetic moments. Details of the detector and shielding components can be refereed to Ref. [1]. Energy calibration was achieved by the 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) in Figure 1. 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.

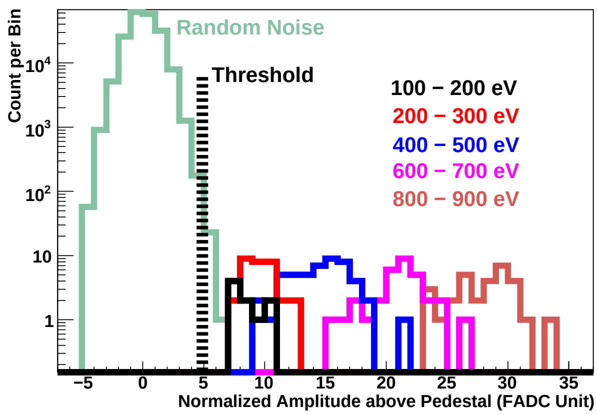

Figure 3: The distributions of noise fluctuation of RT-events as well as of the maximum amplitudes of physics events in various energy bins. The discriminator threshold level is also shown.

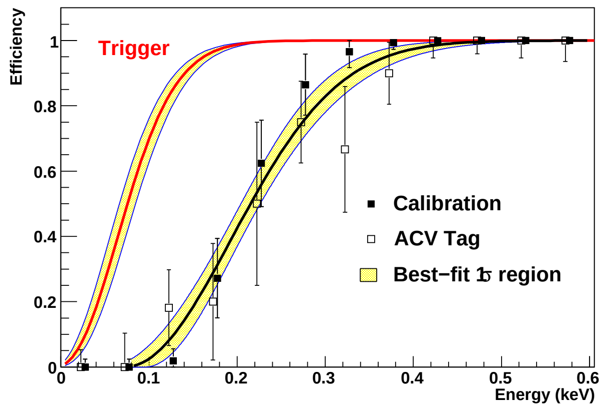

Figure 4: Trigger efficiency for physics events recorded by the DAQ system and the best-fit 1σ region of selection efficiencies of the PSD cut, as derived from the ^{55}Fe-calibration and *in situ* data with ACV tags.

The ULEGe signals were distributed to two spectroscopy amplifiers at 6 μs(SA_6) and 12 μs(SA_{12}) shaping times and with different amplification factors. Pulse shape discrimination (PSD) software[1] 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 in Figure 2. Calibration events and those from physics background were overlaid, indicating uniform response.

Events selected by PSD but with Anti-Compton Veto (ACV) and Cosmic-Ray Veto (CRV) tags were subsequently rejected. The surviving events were ULEGe signals uncorrelated with other detector systems and could be WIMP candidates. The data set adopted for the WIMP analysis has a DAQ live time of 0.338 kg-day. The DAQ dead time is 11%. The CRV and ACV selection efficiencies of, respectively, 91.4% and 98.3% were accurately measured using RT-events[5].

The distributions of noise fluctuations of the RT-events and the maximum amplitude of the physics samples are displayed in Figure 3. All the events above 100 eV exhibit at least 1 FADC Unit of margin above threshold. The trigger efficiencies were derived using the maximum amplitude distributions of the RT events at E=0 and the physics samples 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 trigger efficiencies depicted in Figure 4 correspond to the fractions of the distributions above the discriminator threshold level.

Events in coincidence with ACV-tags are mostly physics-induced. Displayed in Figure 5 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. Under the conservative assumption that all ACV-tagged events in the correct coincidence window are physics-induced [1], f represents the PSD selection efficiency. It can be seen that *only* ULEGe events in correct coincidence with the ACV-tags give a substantial value of f, demonstrating that the PSD-cut was correctly devised and indeed performed its intended functions of suppressing electronic noise events and selecting physics-induced samples.

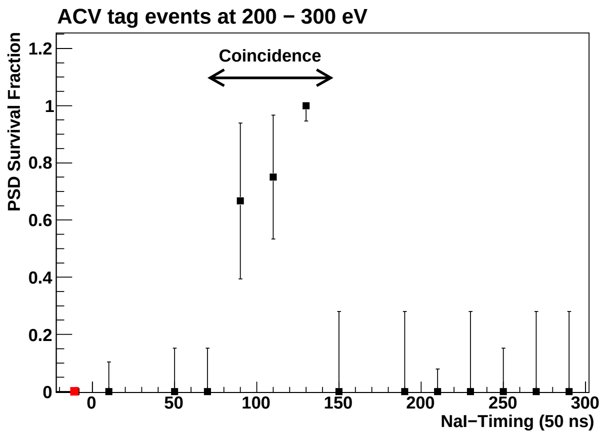

Figure 5: The survival fraction of events at E=200−300 eV with an ACV tag versus the relative timing between the ACV signals and the ULEGe triggers. Overlaid are the actual coincidence time interval between the ACV and the ULEGe systems derived independently from hardware timing. The data point at negative time is due to events without ACV tags, and corresponds to $(1.7 \pm 0.3) \times 10^{-4}$.

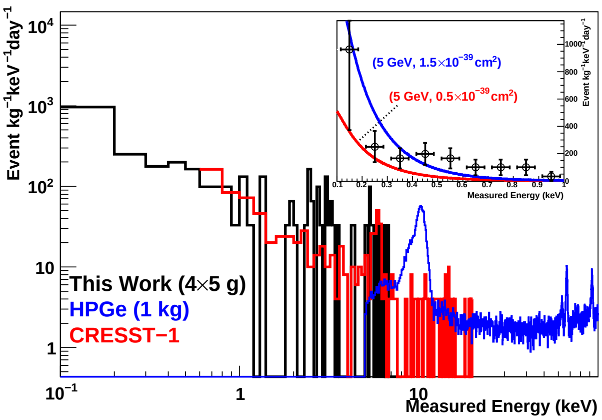

Figure 6: The measured background spectrum of ULEGe with 0.338 kg-day of data, after CRV, ACV and PSD selections. with those from CRESST-I[3] and HPGe[5] overlaid for comparison. The expected nuclear recoil spectra for two cases of $(m_\chi, \sigma^{SI}_{\chi N})$ are superimposed.

Alternatively, the deviations of the PSD-selected events from a flat distribution in the low energy portion of ^{55}Fe calibration spectrum of Figure 1 provided the second efficiency measurement. Consistent results were obtained with both approaches, as depicted in Figure 4. 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 6, showing comparable background as CRESST-I[3]. The formalisms followed those of Ref. [4] using standard nuclear form factors, a galactic rotational velocity of 230 $\mathrm{km\,s^{-1}}$ and a local WIMP density of 0.3 $\mathrm{GeV\,cm^{-3}}$ with Maxwellian velocity distribution. The unbinned optimal interval method as formulated in Ref. [6] and widely used by current CDM experiments was adopted to derive the upper limits for the possible χN event rates. 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[7].

Exclusion plots on both $(m_\chi, \sigma^{SI}_{\chi N})$ and $(m_\chi, \sigma^{SD}_{\chi n})$ planes at 90% confidence level for galactically-bound WIMPs were then derived, as depicted in Figures 7 and 8, respectively. The DAMA-allowed regions and the current exclusion boundaries[2] are displayed. The $\sigma^{SD}_{\chi n}$ parameter space probed by the ^{73}Ge in ULEGe is complementary to that of the CRESST-I experiment[3] where the ^{27}Al target is made up of an unpaired proton instead. New limits were set by the KS-ULEGe data in both $\sigma^{SI}_{\chi N}$ and $\sigma^{SD}_{\chi n}$ for $m_\chi \sim 3-6$ GeV. The remaining DAMA low-m_χ allowed regions in both interactions were probed and excluded. The observable nuclear recoils at m_χ=5 GeV and $\sigma^{SI}_{\chi N}$=0.5×10^{-39} cm^2(allowed) and 1.5×10^{-39} cm^2(excluded) are superimposed with the measured spectrum in the inset of Figure 6 for illustrations.

This work extends the bounds on WIMPs by making measurements in a new observable win-

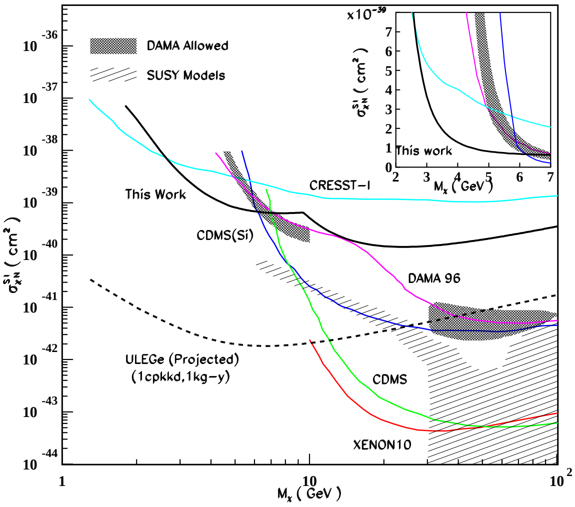

Figure 7: Exclusion plot of the spin-independent χN cross-section versus WIMP-mass. Projected sensitivities of full-scale experiments are indicated as dotted lines.

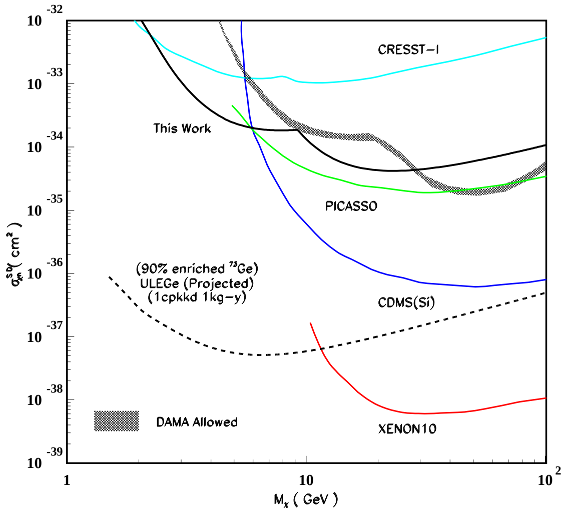

Figure 8: Exclusion plot of the spin-dependent χ-neutron cross-section versus WIMP-mass.

dow 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. There are recent advances in "Point-Contact" Ge detector[8] which offer potentials of scaling-up the detector mass to the kg-range. The mass-normalized external background will be reduced in massive detectors due to self-attenuation. 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 7 and 8. Such experimental programs are complementary to the many current efforts on CDM direct searches.

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