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New Limits on WIMP Dark Matter from Annual Modulation Analysis of the CDEX Experiment at the China Jinping Underground Laboratory

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We present results on light weakly interacting massive particle (WIMP) searches [1] with annual modulation (AM) analysis on data from a 1-kg mass p-type point-contact germanium detector of the CDEX-1B experiment at the China Jinping Underground Laboratory. The 90% C.L. allowed regions implied by the DAMA/LIBRA and CoGeNT AM-based analysis are excluded at >99.99% and >98% C.L., respectively. These results correspond to the best sensitivities at $m_\chi < 6$ GeV/c^2 among WIMP AM measurements.

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The Weakly Interacting Massive Particle (WIMP, denoted as χ) is a favored candidate of dark matter (DM). The direct laboratory searches of WIMPs can be probed by WIMP-nucleus (χ-N) elastic scattering. Within the astrophysical dark matter halo model, the χ-N rates have distinctive annual modulation (AM) feature with maximum intensity at June and a period of 1 yr due to the Earth's motion relative to to the galaxy dark matter distribution. AM analysis of χ-N can provide smoking-gun signatures for WIMPs independent of background modeling.

Positive results were concluded at significance of 12.9 σ and 2.2 σ from AM-based analysis of DAMA/LIBRA [2, 3] and CoGeNT [4] experiments, respectively. However, these interpretations were challenged by integrated rate experiments with liquid xenon [5–7], cryogenic bolometer [8–10], ionization germanium [11] detectors and were probed and excluded by AM analysis from XMASS-1 [12] and XENON100 [13, 14] experiments as well.

The CDEX experiments, located in the China Jinping Underground Laboratory (CJPL) with about 2400 m of rock overburden, utilizes p-type point contact germanium detectors (pPCGe) [15] for dark matter direct detection. The low analysis threshold of about 200 eVee implies AM studies with germanium can complement the liquid xenon results. It provides an alternative probe to the allowed parameter space of DAMA/LIBRA and CoGeNT and extends the reach of AM test to lower lower m_χ.

The CDEX-1B experiment is the second phase of the CDEX experiment and has previously given the upper limits for spin-independent (SI) and spin-dependent (SD) cross sections by the χ-N recoil spectral analysis [16]. The pPCGe target of mass 1 kg (fiducial mass of 939 g, after corrections due to a 0.88±0.12 mm surface layer) was shielded with 20 cm of copper, 20 cm of polyethylene and 20 cm of lead, from inside to outside. The whole setup was assembled inside a 6 m(H)×8 m(L)×4 m(W) polyethylene room with wall thickness of 1 m. The target was enclosed by an NaI(Tl) anti-Compton detector from September 27, 2014 to August 2, 2017 (Run-1), and subsequently without NaI(Tl) (replaced by passive copper shielding) from August 4, 2017 till December 2, 2018 (Run-2). The gaps from December 27, 2014 to March 8, 2015 and from March 16, 2016 to June 02, 2016 were due to calibration with neutron gamma-ray sources, respectively. The two runs have 751.3 and 428.1 live days, respectively, and together span a total of 1527 calendar days (~4.2 yr), with the total exposure of 1107.5 kg-day.

The 4.2 yr of CDEX-1B data are separated into 35 subdatasets in different time bins, each with about 1 month of live time. WIMP candidate events in the bulk of the detector are selected via some basic cuts and the bulk or surface (B/S) events discrimination. The B/S correction procedure is done by likelihood fitting of the bulk or surface rise-time distribution probability density functions (PDFs) and has no cut efficiency associated [16].

Stability of χ-N candidate events with time is demonstrated in Fig. 1 with the bulk event count rates after B/S correction at three energy ranges which are most relevant to the sensitivities at $m_\chi = 8$ GeV/c^2.

The only requirement for AM analysis is to have stable background with time. The modeling of their origins and spectral shapes, which are sources of uncertainties in the time-integrated spectral analysis, is not involved. We adopted a scenario of the time-independent background contribution plus an exponentially time-dependent background contribution from the L-shell x-rays from cosmogenic isotopes. The expected time dependence due to the cosmogenic origin background contributions was observed. It dominated the background in energy ranges of 1.0−1.4 keVee.

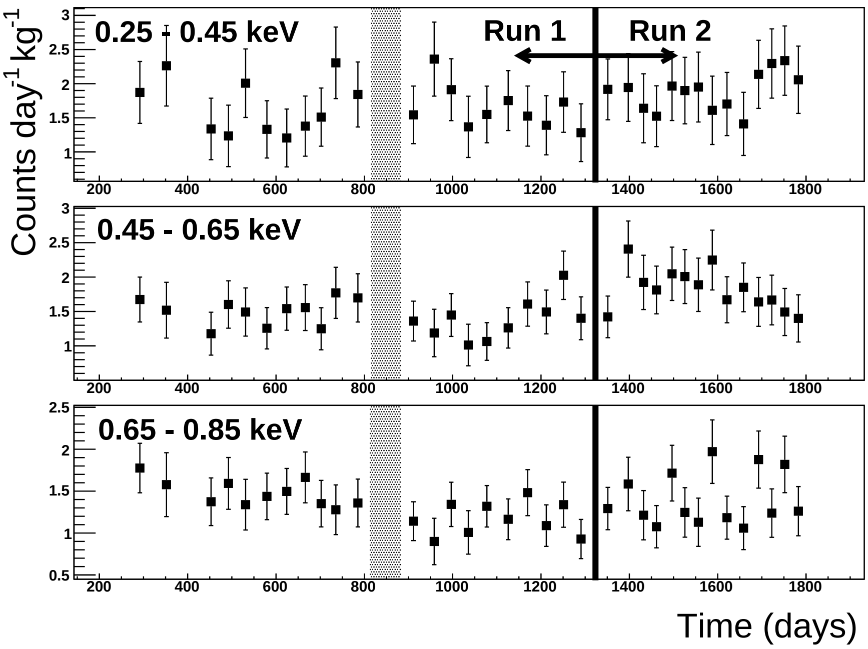

Figure 1: The B/S corrected bulk event counts versus time at three energy ranges, where the shaded area denotes the period of gamma source calibration. A bin size of 200 eVee is used in this plot, while different bin size is adopted in the analysis.

The time-independent background levels of every energy bin were taken as free parameters and were uncorrelated between Run-1 and Run-2 due to the different shielding configurations. The unmodulated χ-N rates were treated as a component of the constant background in AM analysis.

Data at 0.25−5.8 keVee were analyzed, below the region of internal K-shell X-rays. The selected energy-bin-sizes are 50 eVee, 100 eVee and 200 eVee for measured energy at <0.8 keVee, 0.8−1.6 keVee and >1.8 keVee, respectively, according to the requirements of statistical accuracy in B/S correction.

For each of ith energy bin, a minimum χ^2 analysis was performed simultaneously, with

$$\chi_i^2 = \sum_{k\in \mathrm{Run}}^{2} \sum_{j\in \mathrm{Time}}^{N} \frac{(n_{ijk} - P_{ijk} - B_{ik} - A_i cos(\frac{2\pi(t_j-\phi)}{T_{yr}}))^2}{\Delta_{ijk}^2}, \tag{1}$$

where ϕ (fixed at 152.5 days) and T_{yr} (fixed at 1 year) are, respectively, the modulation phase and period. The corrected counts of bulk events are denoted by n_{ijk} corresponding to the respective bin with i, j, k=(energy, time, run). P_{ijk} is the time-varying background contributions of the L-shell X-rays from long-lived isotopes such as ^{68}Ge, ^{68}Ga and ^{65}Zn, with intensities fixed by the measured K-shell X-rays at 8.5−10.8 keV, B_{ik} is the background level, in which we adopted a time-independent background scenario, and ${\Delta_{ijk}}^2$ are the combined statistical and systematic errors dominated by the B/S correction [16]. There are in total 40 energy bins, with 35 time bins divided into 2 runs.

The data are first studied with a model-independent analysis without invoking astrophysical models and parameters. The modulation amplitude A_i of individual energy bins are treated inde-

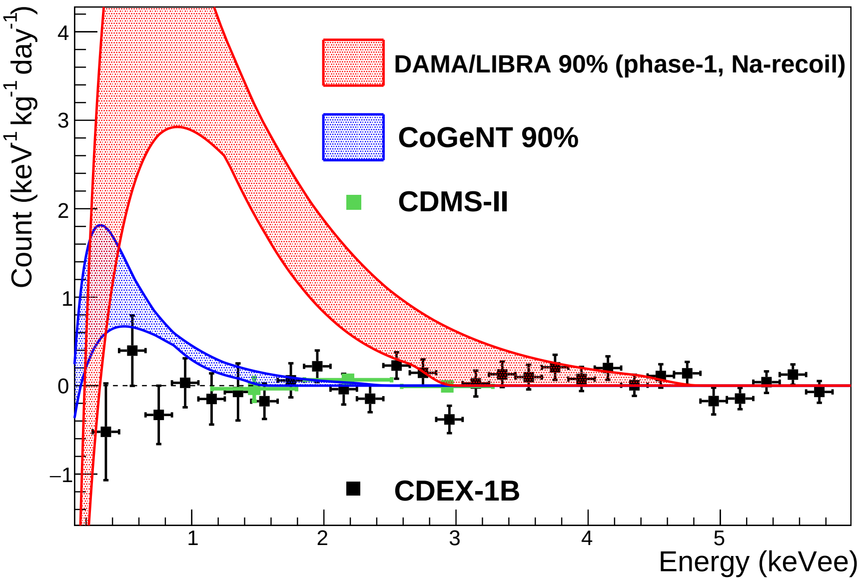

Figure 2: Best-fit solutions of modulation amplitude A_i. The distributions show consistency with null results, i.e., no significant modulation signatures. For illustration purpose, we adopted 200 eVee bin-size for all energy ranges. Derived modulation signals from 90% C.L. allowed region of CoGeNT [4, 17], DAMA/LIBRA (Na-recoil) [18] and best-fit modulation amplitudes of CDMS-II distributed results [19] are superimposed. A bin size of 200 eVee is used in this plot, while different bin size is adopted in the analysis.

pendently, from which the best-fit results $\chi^2/\text{d.o.f} = \sum \chi_i^2/\text{d.o.f} = 1280.47/1280$ are shown in Fig. 2. The distribution of A_i is consistent with null results, showing no evidence of modulation behavior. The null hypothesis test gave a $\chi^2/\text{d.o.f} = 1330.27/1320$. The difference in χ^2 between null hypothesis and independent-amplitude analysis is within χ^2 distribution at p value = 0.14.

For the model-dependent analysis, the individual A_i are correlated with a known function of m_χ, σ_{SI}, E and bin-size, while the function is related to the applied astrophysics models. Data are then analyzed under the standard spherical isothermal galactic halo model, with a most probable speed of $\upsilon_0 = 220$ km/s, a galactic escape velocity of $\upsilon_{esc} = 544$ km/s, an Earth's velocity related to dark matter of υ_E={232 + 15$cos(2\pi(t-\phi)/T_{yr})$} km/s and local dark matter density of 0.3 GeV/(c^{2}cm^3). Quenching factor of Ge is derived by the TRIM software package [20] with a 10% systematic error adopted for the analysis. Best-fit values of unconstrained σ_{SI} are then valuated by minimizing $\sum \chi_i^2$ of Eq. (1), The Unified Approach [21] is then used to place the upper bounds of positive definite σ_{SI} at different m_χ.

The best-fit solution at m_χ=7.9 GeV/c^2 is $\sigma_{SI} = (-0.37\pm1.43)\times10^{-41}$ cm^2 ($\chi^2 = 1330.20/1319$), or equivalently, $\sigma_{SI} < 1.99\times10^{-41}$ cm^2 at 90% C.L. The upper limits at 90% C.L. on σ_{SI} are derived and shown in Fig. 3. The results refute the 90% C.L. allowed regions inferred from AM-based analysis of DAMA/LIBRA-phase 1 low-m_χ (Na-recoil) [2, 3, 18] and CoGeNT [4] experiments, providing an exclusion at >99.99% and >98% C.L., respectively. The DAMA/LIBRA high-m_χ region (I-recoil) is not probed in this analysis.

The B/S discrimination contributes less than 8% deviation of σ_{SI}, and the uncertainty of K/L ratios is also incorporated in the systematic uncertainty budget.

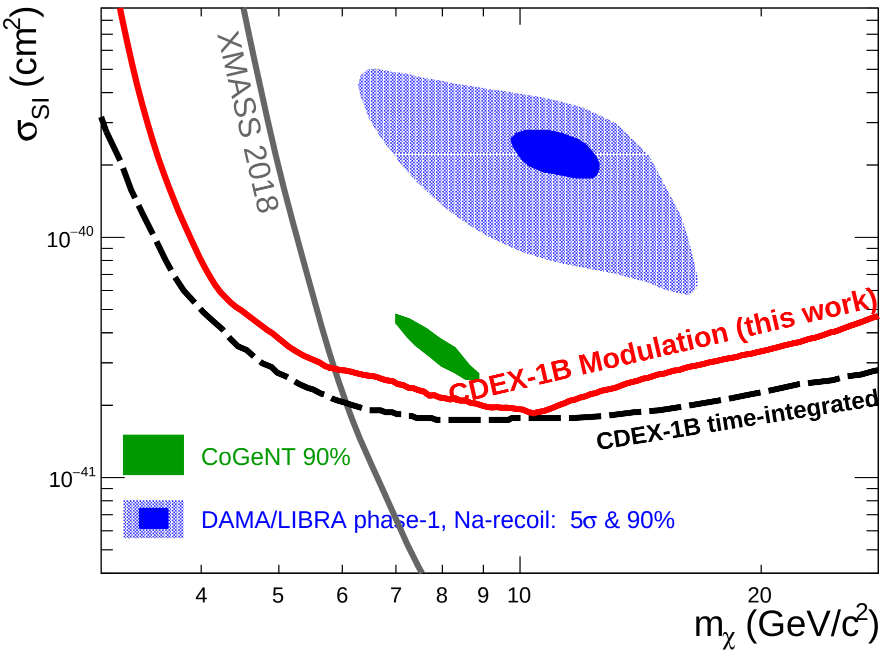

Figure 3: Limits at 90% C.L. from CDEX-1B AM-analysis (red) on spin-independent WIMP-nucleon cross section. Also shown are other AM-based results: 90% C.L. upper limits of XMASS-1 (dark-gray) [12], allowed regions of DAMA/LIBRA (Na-recoil, pale blue: 5 σ, blue: 90% C.L.) [2, 3, 18] and CoGeNT (green: 90% C.L.) [4]. Constraints from the CDEX-1B time-integrated spectral analysis [16] are displayed (black dotted line) as comparison.

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