

Results from a Search for Light-Mass Dark Matter with a P-type Point Contact Germanium Detector

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We report on several features present in the energy spectrum from an ultra low-noise germanium detector operated at 2,100 m.w.e. By implementing a new technique able to reject surface events, a number of cosmogenic peaks can be observed for the first time. We discuss several possible causes for an irreducible excess of bulk-like events below 3 keVee, including a dark matter candidate common to the DAMA/LIBRA annual modulation effect, the hint of a signal in CDMS, and phenomenological predictions. Improved constraints are placed on a cosmological origin for the DAMA/LIBRA effect.

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We have recently presented first dark matter limits [1] from the underground operation of p-type point contact (PPC) germanium detectors. PPCs display an unprecedented combination of target mass and reduced electronic noise, resulting in an enhanced sensitivity to low-energy rare events. Promising applications in astroparticle and neutrino physics are expected from this technology [2].

Sources of detector radiocontamination became evident during operation of a PPC at a depth of 330 m.w.e. [1]. A new 440 g PPC diode was built with attention paid to these. The new crystal is a modification of the BEGe (Broad Energy Germanium) geometry, a commercial quasi-planar PPC design from Canberra Industries. It is operated in the Soudan Underground Laboratory (Minnesota, USA). This improved detector, while still not featuring all possible measures against backgrounds (electroformed cryostat components, etc.), has delivered more than one order-of-magnitude background reduction compared to [1]. The background achieved below ~ 3 keVee (keV electron equivalent, i.e., ionization energy), down to the 0.4 keVee electronic noise threshold, is so far the lowest reported by any dark matter detector. The shielding, electronics and basic pulse-shape discrimination (PSD) are similar to those described in [1], with the addition of data storage of raw preamplifier traces, and removal of two internal active shields. An external muon veto is preserved. Veto-coincident events do not accumulate in excess near threshold: we therefore do not apply veto cuts to present data, to avoid a dead time penalty.

A number of peaks are observed in low-energy spectra

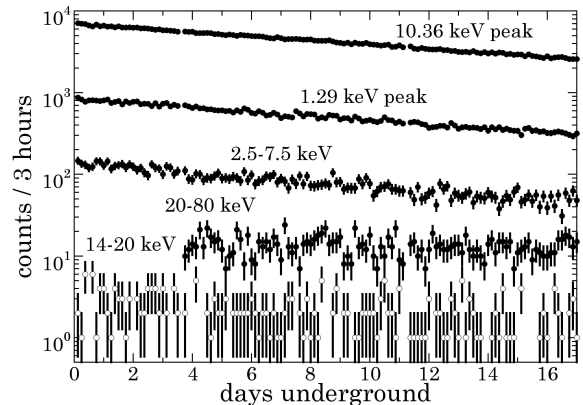


FIG. 1: Decays associated with ^{71}Ge ($T_{1/2} = 11.4\text{d}$) produced via thermal neutron activation of a PPC detector (see text).

from ultra-low background germanium detectors. They originate in activation of the crystal by exposure to cosmogenic neutrons and protons at sea level. Long-lived radioactive products result from their spallation of germanium nuclei. Whenever this progeny decays via electron capture (EC), the deposited energy can be limited to the atomic binding energy of the daughter's captured electron, released as short-ranged X-rays and Auger electrons. Taking place within the crystal, these are detected with $\sim 100\%$ efficiency, giving rise to the observed peaks.

Due to the very short attenuation lengths (few microns) expected from low-energy X-rays in solids and the

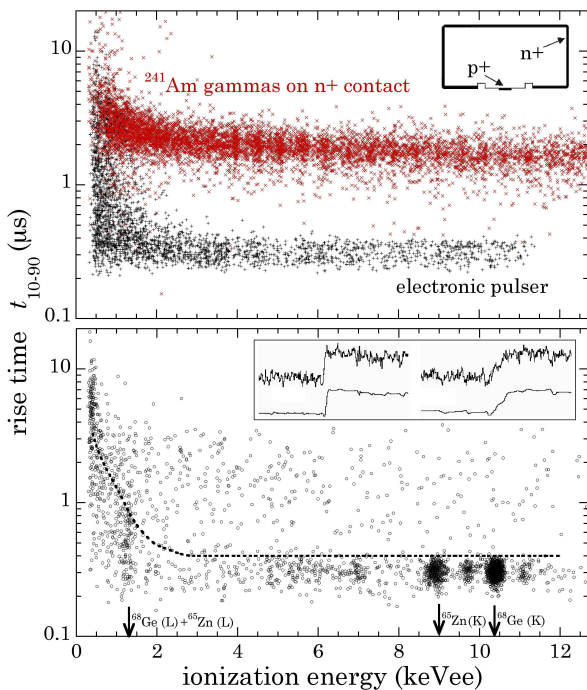


FIG. 2: *Top panel:* Rise time in preamplifier traces from ^{241}Am gammas and a manual scan of reference electronic pulser signals (see text). A change in digitizer range is noticeable above ~ 4 keV. *Bottom panel:* *Idem* for background events collected by the PPC in Soudan. The dotted line represents the 90% signal acceptance contour for bulk events. *Top inset:* Vertical cross section of a BEGe PPC detector, showing the two contacts. *Bottom inset:* Typical preamplifier traces from 1 keVee events, before and after wavelet denoising, for $t_{10-90} = 0.22 \mu\text{s}$ (left) and $t_{10-90} = 1.53 \mu\text{s}$ (right).

exclusive use of radioclean materials near the crystals, all low-energy peaks observed so far have a cosmogenic origin internal to germanium. For p-type diodes an additional obstacle against external low-energy radiation arises from a quasi-inactive n+ contact, spanning most of the surface of the semiconductor. This contact is created by lithium diffusion down to a depth 0.5-1 mm. Fig. 1 displays the decay of the 10.36 keV K-shell EC peak from ^{71}Ge produced via intense thermal neutron activation of a PPC. A peak at 1.29 keV, originating in L-shell EC, exhibits the same decay (also the region 0.5-1.29 keV, not shown for clarity). So does the 2.5-7.5 keV “plateau”, but not events above 10.36 keV. The ratio of activity in the plateau to that under the 10.36 keV peak matches the estimated fraction of Li-diffused volume, suggesting an origin for most plateau events in partial charge collection from ^{71}Ge decays within the n+ contact.

These partial energy depositions could be an issue, in that they accumulate signals in the region of most interest for dark matter studies, i.e., near threshold. In inspecting preamplifier traces from PPCs we noticed a population of low-energy slow pulses, featuring rise times (t_{10-90}) significantly longer than the typical $t_{10-90} \sim 0.3 \mu\text{s}$. These are mentioned in early germanium detec-

tor literature as originating precisely in the n+ contact. Their cause is the weak electric field intensity next to the lithium-diffused region [3]. We demonstrated the association between partial charge collection and slow rise time by irradiating the “closed end” (side opposite to p+ contact, Fig. 2 inset) of the PPC in [1] with gammas from a ^{241}Am source. Fig. 2 displays the much longer rise times associated with partial energy depositions in the n+ contact from the short-ranged 59.5 keV gamma (attenuation length in Ge ~ 1 mm). Full-energy depositions, taking place deeper in the crystal, produce the expected $t_{10-90} \sim 0.3 \mu\text{s}$. Using a MCNP-PoliMi [4] simulation of the energy-depth profile in this calibration, it is possible to faithfully reconstruct the ^{241}Am energy spectrum when the charge collection efficiency ϵ is described by a best-fit logistic (sigmoid) function of the form $\epsilon = 1/(1 + 43.5 e^{-86(d-0.14)})$, where d is the interaction depth in cm. This implies an outermost “dead” layer of ~ 1 mm, followed by a ~ 1 mm “transition” layer prone to partial charge collection, in good agreement with [3]. Since we intend to reject surface events in our dark matter search by performing data cuts based on t_{10-90} , in what follows we conservatively revise the fiducial mass of our detector to be 330 g (two outer mm discarded).

Based on this discussion, low energy (few keV) radiation can reach the PPC active volume through a single region, the intra-contact passivated surface, at the center of which the 5 mm p+ point-contact is established (Fig. 2, inset). The protective SiO_x passivation layer is just ~ 1500 Angstroms thick. Any events arising from an external low-energy source must originate from materials in the line-of-sight of this surface (diameter 2.2 cm). These are specially-etched virgin PTFE, similarly treated OFHC copper and a needle contact (gold-plated brass, its tip wetted with low-background pure tin).

Fig. 2 (bottom) shows the rise time distribution for low-energy events in the PPC at Soudan. These data correspond to an eight week period starting three months after underground installation, to allow for nearly complete ^{71}Ge decay. The top panel shows the same distribution for a collection of electronic pulser events in this detector. After a small upwards shift in t_{10-90} by $0.1 \mu\text{s}$, these strongly resemble radiation-induced bulk events in this representation. The shift accounts for the additional charge collection time affecting energy depositions in the bulk of the crystal. Simulations of charge collection corroborated the magnitude of the applied shift. The dotted line in the bottom panel represents the 90% boundary for signal acceptance of pulser events. We further confirmed that this signal acceptance also applies to bulk events by observing the preservation of the L-shell EC activity from ^{68}Ge (1.29 keV) and ^{65}Zn (1.1 keV), before and after this rise time cut. While this makes us confident that our signal acceptance for bulk events is understood at least down to 1 keV, the possibility remains of some unrejected surface events closer to threshold. A comparison with the distribution of ^{241}Am surface events (Fig. 2) indicates that any such contamination should be modest.

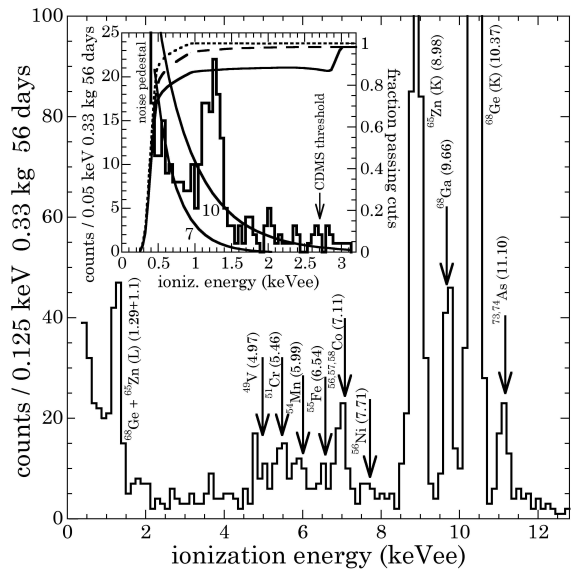


FIG. 3: Low-energy spectrum after all cuts, prior to efficiency corrections. Arrows indicate expected energies for all viable cosmogenic peaks (see text). *Inset*: Expanded threshold region, showing the ^{65}Zn and ^{68}Ge L-shell EC peaks. Overlapped on the spectrum are the sigmoids for triggering efficiency (dotted), trigger + microphonic PSD cuts (dashed) and trigger + PSD + rise time cuts (solid), obtained via high-statistics electronic pulser calibrations. Also shown are reference signals (exponentials) from 7 GeV/c^2 and 10 GeV/c^2 WIMPs with spin-independent coupling $\sigma_{SI} = 10^{-4}$ pb.

Fig. 3 displays Soudan spectra following the rise time cut, which generates a factor 2-3 reduction in background (Fig. 2). Modest PSD cuts applied against microphonics are as described in [1]. This residual spectrum is dominated by events in the bulk of the crystal, like those from neutron scattering, cosmogenic activation, or dark matter particle interactions. Several cosmogenic peaks are noticed, many for the first time. All cosmogenic products capable of producing a monochromatic signature are indicated. Observable activities are incipient for all.

We employ methods identical to those in [1] to obtain Weakly Interacting Massive Particle (WIMP) and Axion-Like Particle (ALP) dark matter limits from these spectra. The energy region employed to extract WIMP limits is 0.4-3.2 keVee (from threshold to full range of the highest-gain digitization channel). A correction is applied to compensate for signal acceptance loss from cumulative data cuts (solid sigmoid in Fig. 3, inset). In addition to a calculated response function for each WIMP mass [1], we adopt a free exponential plus a constant as a background model to fit the data, with two Gaussians to account for ^{65}Zn and ^{68}Ge L-shell EC. The energy resolution is as in [1], with parameters $\sigma_n = 69.4$ eV and $F = 0.29$. The assumption of an irreducible monotonically-decreasing background is justified, given the mentioned possibility of a minor contamination from residual surface events and the rising concentration

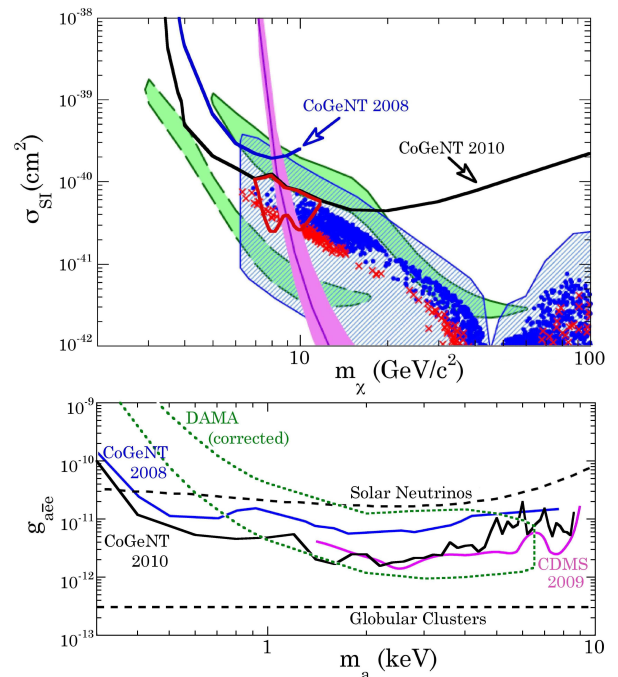


FIG. 4: *Top panel*: 90% C.L. WIMP exclusion limits from CoGeNT overlaid on Fig. 1 from [6]: green shaded patches denote the phase space favoring the DAMA/LIBRA annual modulation (the dashed contour includes ion channeling). Their exact position has been subject to revisions [7]. The violet band is the region supporting the two CDMS candidate events. The scatter plot and the blue hatched region represent the supersymmetric models in [8] and their uncertainties, respectively. Models including WIMPs with $m_\chi \sim 7-11$ GeV/c^2 provide a good fit to CoGeNT data (red contour, see text). The relevance of XENON10 constraints in this low-mass region has been questioned [14]. *Bottom panel*: Limits on axio-electric coupling $g_{a\bar{e}e}$ for pseudoscalars of mass m_a composing a dark isothermal galactic halo (see text).

towards threshold that rejected events exhibit. A second source of possibly unaccounted for low-energy background are the L-shell EC activities from observed cosmogenics lighter than ^{65}Zn . These are expected to contribute $< 15\%$ of the counting rate in the 0.5-0.9 keVee region (their L-shell/K-shell EC ratio is $\sim 1/8$ [5]). A third possibility, quantitatively discussed below, consists of recoils from unvetted muon-induced neutrons.

Fig. 4 (top) displays the extracted sensitivity in spin-independent coupling (σ_{SI}) vs. WIMP mass (m_χ). For m_χ in the range $\sim 7-11$ GeV/c^2 the WIMP contribution to the model acquires a finite value with a 90% confidence interval incompatible with zero. The boundaries of this interval define the red contour in Fig. 4. However, the null hypothesis (no WIMP component in the model) fits the data with a similar reduced chi-square $\chi^2/dof = 20.4/20$ (for example, the best fit for $m_\chi = 9$ GeV/c^2 provides $\chi^2/dof = 20.1/18$ at $\sigma_{SI} = 6.7 \times 10^{-41}$ cm^2). It has been recently emphasized [6] that light WIMP models [1, 8, 9] provide a common ex-

planation to the DAMA/LIBRA annual modulation effect [10] and the modest excess of signal-like events in CDMS [11]. These WIMP candidates are also compatible with CoGeNT data (Fig. 4). When interpreted as WIMP interactions, the low energy (3.3 and 4.2 keVee) of the CDMS recoil-like events is suggestive of a light WIMP. However, the 2.7 keVee CDMS threshold (Fig. 3, inset) does not allow for a ready identification of such candidates.

Fig. 4 (bottom) shows limits on axioelectric dark matter couplings, extracted as in [1] from the region 0.5-8.5 keVee. Sensitivity to this coupling should improve with additional exposure. A discussion on the relevance of the DAMA/LIBRA-favored region in this phase space is provided in [12]. Lastly, we refer to [1] for a criticism of ion channeling (Fig. 4) as part of the DAMA/LIBRA effect. In light of our improved sensitivity, a fair treatment of this possibility (i.e., including channeling also for germanium crystals) should render it highly constrained.

Enticing as it is to contemplate cosmological implications from low-energy spectral features, our focus must remain on finding explanations based on natural radioactivity. One evident possibility is a contribution from recoils caused by environmental or muon-induced neutrons. MCNP-PoliMi transport of the environmental neutron flux at Soudan [13] through our shielding geometry generates a prediction short of the observed rise by two orders of magnitude. This prediction matches other studies performed at the same underground depth [15]. The muon-induced contribution prior to vetoing is simulated following [15, 16], and is found to yield just 7% of the rate at threshold (the observed muon veto coincidences limit this process to $< 15\%$). Partial energy depositions from high energy gammas are not expected to accumulate in this region [17]. Other possibilities, including alpha-recoils from radon deposition on the SiO_x passivated surface, degraded beta emissions from ^{40}K in PTFE, excess ^{210}Po [18] on the specially-selected pure tin wetting the central contact, etc., have been studied and found lacking. The hypothesis that the rise might be due to unrejected electronic noise would involve a dramatic deviation from its expected behavior near threshold [19]. Individual inspection of pulses comprising the rise reveals them as asymptomatic (Fig. 2, inset). One conjecture that merits serious investigation is the effect of a surface channel on the intra-contact surface [20], possibly leading to a population of degraded energy events that might nevertheless escape rise time cuts.

In conclusion, we presently lack a satisfactory explanation for the observed low-energy rise in a PPC spectrum devoid of most surface events. In view of its apparent agreement with existing WIMP models, a claim and a glimmer of dark matter detection in two other experiments, it is tempting to consider a cosmological origin. Prudence and past experience prompt us to continue work to exhaust less exotic possibilities. We extend an invitation to other researchers in this field to proceed

with the same caution. If this feature were to originate in dark matter interactions, a PPC-based 60 kg MAJORANA Demonstrator [21] would unequivocally detect an annual modulation effect in both rate and average energy deposited. Indirect searches should soon probe the relevant WIMP phase space region [7].

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