Experimental constraints on a dark matter origin for the DAMA annual modulation effect

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A claim for evidence of dark matter interactions in the DAMA experiment has been recently reinforced. We employ a new type of germanium detector to conclusively rule out a standard isothermal galactic halo of Weakly Interacting Massive Particles (WIMPs) as the explanation for the annual modulation effect leading to the claim. Bounds are similarly imposed on a suggestion that dark pseudoscalars might lead to the effect. We describe the sensitivity to light dark matter particles achievable with our device, in particular to Next-to-Minimal Supersymmetric Model candidates.

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The DAMA and DAMA/LIBRA [1] experiments have accumulated a combined 0.82 ton-years of NaI[Tl] exposure to putative dark matter particles, substantially exceeding that from any other dedicated search. The newer DAMA/LIBRA array features a larger target mass and an improved internal radiopurity. The first DAMA/LIBRA dataset has confirmed the evidence for an annual modulation in the few keV portion of the spectrum [2], an effect previously observed in DAMA. The observed modulation has all the characteristics (amplitude, phase, period) expected [3] from the motion of an Earth-bound laboratory through a standard isothermal halo composed of WIMPs. The statistical significance of the modulation has reached 8.2 sigma. No other explanation has been found yet, prompting the DAMA collaboration to claim the effect is due to dark matter interactions.

Competing dark matter searches have been able to exclude most of the phase space (nuclear scattering cross section vs. WIMP mass) available as an explanation for this time-modulated signal. However, as a result of insufficiently-low energy thresholds in those detectors, it has been proposed [4, 5] that light WIMPs of less than $\sim$10 GeV/c^2 could cause the observed modulation while avoiding existing experimental constraints. This hypothesis has been recently ruled out by COUPP [6], for those cases where WIMP-nucleus scattering is mediated by a spin-dependent coupling [4]. The results presented here exclude the remaining spin-independent phase space [5]. These new limits effectively preclude a standard WIMP halo as a viable explanation for the DAMA observations.

A new type of germanium radiation detector with an unprecedented combination of crystal mass and sensitivity to sub-keV signals has been described in [7]. These detectors provide significant improvements over conventional coaxial designs (Fig. 1). Details on the modifications leading to this performance, as well as a description of the applications for this device, can be found in [7]. We refer to this design as a p-type point contact (PPC) germanium detector (HPGe).

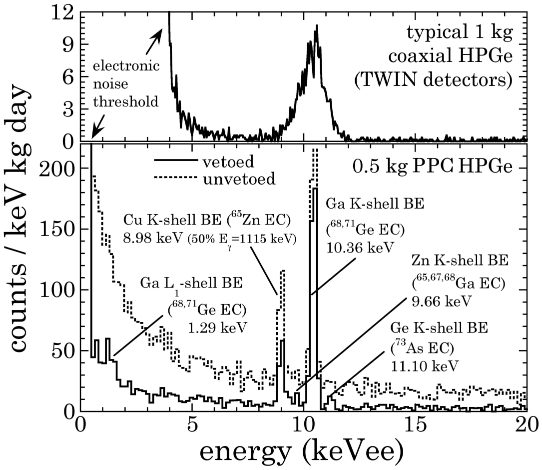

FIG. 1: Improvements in threshold and resolution in a PPC design (bottom), compared to a typical coaxial HPGe [8] (top). Cosmogenic peaks are clearly resolved in the PPC spectrum. BE stands for binding energy, EC for electron capture.

Several PPCs have been successfully built since the de-

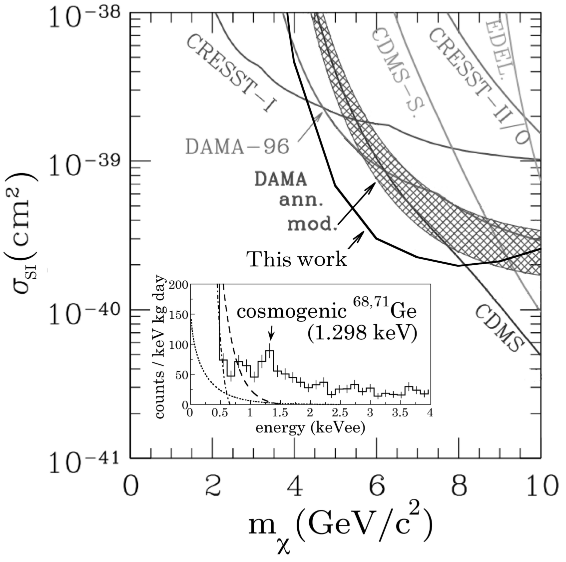

FIG. 2: Parameter space region (cross-hatched) able to explain the DAMA modulation via spin-independent couplings from an isothermal light-WIMP halo [5]. Lines delimit the coupling (σ_{SI}) vs. WIMP mass (m_χ) regions excluded by relevant experiments [5]. All regions are defined at the 90% confidence level. Inset: PPC spectrum used for the extraction of present limits. Lines display the signals expected from some reference WIMP candidates (dotted: m_χ= 8 GeV/c^2, σ_{SI} = 10^{-4}pb. Dashed: m_χ= 6 GeV/c^2, σ_{SI} = 0.002 pb. Dash-dotted: m_χ= 4 GeV/c^2, σ_{SI} = 10^{-2}pb).

scription of the first prototype, most within the MAJORANA collaboration [9]. The dataset utilized here comes from tests of the first prototype in a shallow underground location (330 m.w.e., a pumping station part of the Tunnel And Reservoir Plan of the city of Chicago). While the results obtained already impose constraints on the possible dark matter origins of the DAMA anomaly, it is expected that ongoing cryostat improvements, a longer exposure (8.4 kg-days here) and operation in a deeper laboratory should dramatically improve the dark matter sensitivity of the device. The potential reach of this method is discussed in more detail below.

Listing from the innermost to the outermost components, the shield installed around the detector was: *i*) a 10 cm-thick, low-background NaI[Tl] anti-Compton veto, *ii*) 5 cm of low-background lead, *iii*) 15 cm of standard lead, *iv*) 0.5 cm of borated neutron absorber, *v*) a >99.9% efficient muon veto, *vi*) 30 cm of neutron moderator, and *vii*) a low-efficiency large-area external muon veto. Fig. 1 shows the magnitude of the active background rejection. The rate of random coincidences between PPC and active element events, measured with a pulser, was ~18%. The low-energy dataset used for dark matter limit extraction (inset, Fig. 2) has been corrected to account for these.

The signal from the PPC preamplifier is sent through two shaping amplifiers operating at different integration constants. An anomalous ratio between the amplitudes of these shaped pulses is an efficient tag for microphonic events [10]. These software cuts, applied on the digitized and stored amplifier traces, are trained on datasets consisting of asymptomatic low-energy signals from an electronic pulser. The goal is to obtain the maximum signal acceptance for the best possible microphonic rejection. A correction is also applied to the data, to compensate for the modest signal acceptance losses (few percent) imposed by this method. The energy resolution and calibration were obtained using the cosmogenic activation in ^{71}Ge ($T_{1/2}$=11.4 d), leading to intense peaks at 1.29 keV and 10.36 keV following installation, and a ^{133}Ba source providing five auxiliary lines below 400 keV. An excellent linearity was observed. The energy resolution σ below 10 keV is approximated by $\sigma^2 = \sigma_n^2 + (2.35)^2 E\eta F$, where σ_n=69.7 eV is the intrinsic electronic noise, E is the energy in eV, η= 2.96 eV is the average energy required to create an electron-hole pair in Ge at ~80 K, and F ~0.06 is the measured Fano factor.

The spectrum of energy depositions so obtained can then be compared with expected signals from a standard isothermal galactic WIMP halo. The spectrum of WIMP-induced recoil energies is generated following [11], using a local WIMP density of 0.3 GeV/cm^3, a halo velocity dispersion of 230 km/s, an Earth-halo velocity of 244 km/s and a galactic escape velocity of 650 km/s. The quenching factor (i.e., the fraction of recoil energy measurable as ionization) for sub-keV germanium recoils has been measured with this PPC, using a dedicated 24 keV neutron beam [12]. It was found to be in excellent agreement with expectations [7, 13]. Its effect is included here in generating spectral shapes of WIMP-induced ionization or "electron equivalent" energy (units of "keVee"), like those shown in the inset of Fig. 2. The exceptional energy resolution of this detector has a negligible effect on these spectra. A standard method [6, 14] can then be used to obtain limits on the maximum WIMP signal compatible with the data: employing a non-linear regression algorithm, data are fitted by a model consisting of *i*) a simple exponential to represent the spectral shape of low-energy backgrounds, *ii*) a gaussian peak at 1.29 keV (^{68,71}Ge) with free amplitude and a width (resolution) as described above, and *iii*) for WIMPs of each mass, their spectral shape with a free normalization proportional to the spin-independent WIMP-nucleus coupling. Couplings excluded at the 90% confidence level are plotted in Fig. 2. The last remaining region of phase space available for a standard isothermal WIMP halo to be the source of the DAMA modulation is now ruled out. Other more elaborate halo models might be invoked, but they result in a modest distortion of experimental exclusion lines and DAMA favored phase space, both following a similar displacement within Fig. 2 [5]. Channeling through crystal lattices has been proposed [15, 16, 17, 18] as a mechanism able to recover the compatibility of DAMA and other experiments, even if experimental evidence in the relevant recoil energy regime for NaI[Tl] seems absent

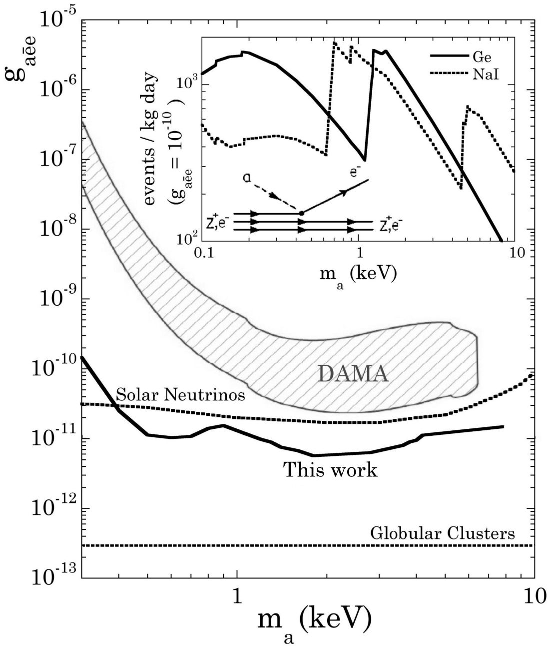

FIG. 3: Hatched region: viable parameter space in an interpretation of the DAMA modulation involving an axio-electric coupling $g_{a\bar{e}e}$ from pseudoscalars composing a dark isothermal halo, according to [21]. The validity of this interpretation is now challenged [23] (see text). The solid line indicates present limits, dashed lines recent astrophysical bounds [24]. Inset: expected pseudoscalar interaction rates in Ge and NaI, for a fixed value of $g_{a\bar{e}e}$, as a function of pseudoscalar mass m_a.

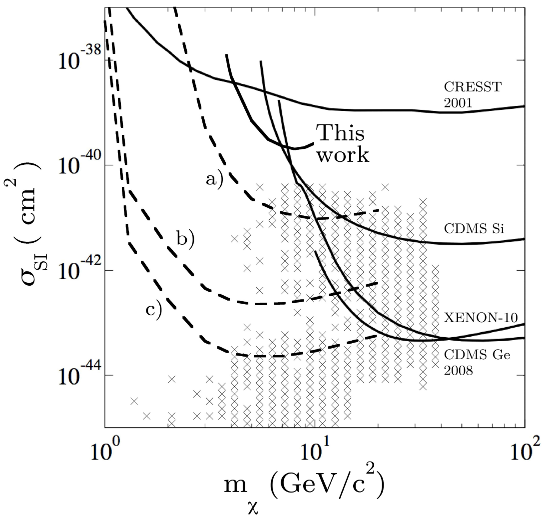

FIG. 4: Solid lines: spin-independent sensitivity from leading experiments in the WIMP low-mass region. A theoretically-favored NMSSM phase space is denoted by crosses. Dashed lines: predicted sensitivity for PPC HPGe in a number of scenarios [7]: a) expected reduction in background from cryostat upgrade, b) background reduction to best achieved in HPGe [25] plus an improvement to 100 eV threshold, c) very conservative limiting sensitivity imposed by ∼15 d of cosmogenic ^{3}H production at sea level for the MAJORANA demonstrator array (a best estimate represents a ×10 further improvement).

[19]. HPGe should also be subject to this presumptive effect [17], leading again to an expected analogous drift of DAMA region and PPC exclusions in Fig. 2. Reference [15] does not include a calculation of channeling for HPGe. In addition, it seems unlikely that compatibility could be recovered in these more *ad hoc* scenarios.

While the WIMP hypothesis may at this point seem an unlikely explanation to the DAMA modulation, the DAMA collaboration has reminded us that dark matter candidates are numerous [2, 20, 21]. Of these, axion-like dark pseudoscalars are arguably comparable to WIMPs in their naturalness, being the subject of many dedicated searches. It has been claimed [21] that such a pseudoscalar, coupling to electrons via the axio-electric effect, might be responsible for the observed modulation. Following the prescriptions in [11] and the proportionality between axio-electric and photo-electric couplings described in [22], it would be possible to arrive at a compact expression for the axio-electric interaction rate from pseudoscalars forming a standard dark halo with the properties listed above, acting on a target of mass number A. However, the cross section in [22] tacitly assumes relativistic particle speeds, not the case here. The correct expression for the relevant interaction rate is derived in [23]: $R\ [\mathrm{kg}^{-1}\mathrm{d}^{-1}] = 1.2 \times 10^{19} A^{-1}\ g_{a\bar{e}e}^2\ m_a\ \sigma_{pe}$, where $g_{a\bar{e}e}$ is the dimensionless strength of the coupling, m_a is the pseudoscalar rest mass in keV and σ_{pe} is the photo-electric cross section in barns/atom. These rates are shown for both NaI and Ge in the inset of Fig. 3. Due to the non-relativistic nature of galaxy-bound dark matter, the spectral observable from such interactions would be a peak at an energy corresponding to m_a. DAMA actually observes the bulk of the modulation being centered around such a peak at ∼3 keV [2], albeit hindered by another one from a known source of radioactive contamination (^{40}K). Using a non-linear fitting algorithm and exponential background model as above, it is possible to place 90% C.L. limits on the maximum amplitude of a gaussian peak of width defined by the energy resolution of the detector, buried anywhere in the 0.3-8 keV PPC spectral region. The rate under this peak is then correlated to an excluded value of $g_{a\bar{e}e}$ via the expression above. These constraints are displayed in Fig. 3 together with the values of $g_{a\bar{e}e}$ and m_a claimed to be compatible with the DAMA effect in [21]. While the cosmological relevance of pseudoscalar, scalar and vector dark matter in the keV mass region is emphasized in [23], it is also shown there that the DAMA modulation is too large to be caused by these possibilities. We therefore caution the reader about the relevance of the DAMA region in Fig. 3 and of the conclusions in [21]. More specifically, adopting the rates and reasoning in [23], a pseudoscalar origin for the modulation cannot be justified, but DAMA should still have a competitive sensitivity to such candidates.

An effort is in progress to further reduce the electronic noise in PPCs [7]: improvements to FET (Field Effect Transistor, the first amplification stage) configuration and packaging, preamplifier design, etc., are under active investigation. Detectors like these, with a capacitance of ∼1 pF, should be capable in principle of ionization energy thresholds below 100 eV. The MAJORANA collaboration plans to experiment with a ∼40 kg target mass of PPCs as part of a 60 kg demonstrator array, to profit from their enhanced gamma background rejection [7]. It is natural to wonder about the possible reach of MAJORANA PPCs as dark matter detectors, and specifically about particle phenomenologies where all other existing detector designs would be unable to contribute to the exploration, due to their higher thresholds.

Several scenarios have been proposed where naturally light ($<$10 GeV/c^2) WIMPs appear [23, 26, 27, 28]. Q-balls can similarly lead to modest ionization signals [29]. The lightest neutralino, an electrically neutral particle present in supersymmetric extensions of the Standard Model (SM), is a well motivated candidate for WIMP dark matter [30]. Its properties have been studied mostly within the Minimal Supersymmetric Standard Model (MSSM) [31], where very light neutralinos with large detection cross sections were found to be possible [32]. The Next-to-Minimal Supersymmetric Standard Model (NMSSM) is a well-justified extension of the MSSM which elegantly generates a Higgsino mass parameter of electroweak scale through the introduction of a new chiral singlet superfield. This has interesting implications for neutralino dark matter [33], and new regions of the parameter space exist which lead to light neutralinos with the correct dark matter relic density [34]. In order to illustrate these properties various scans of the NMSSM parameter space have been performed with the code NMHDECAY [35]. The choice of input parameters is beyond the scope of this letter and will be given in [36]. The favored space is shown by crosses in Fig. 4. A conservative projected sensitivity for MAJORANA PPCs is also displayed. A clear complementarity to other detection schemes is observed.

In conclusion, by virtue of their sensitivity to very small energy depositions, large mass and excellent energy resolution, PPC detectors are ideally suited for confirming or definitively disproving DAMA's claim of dark matter discovery. Clearly, technologies able to explore the many possible phenomenological faces of the dark matter problem should be encouraged and developed. The unresolved mystery of the DAMA annual modulation is a reminder of how often surprises arise in particle physics, where and when they are least expected.

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