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 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 dark matter particles, substantially exceeding that from any other search. The newer DAMA-LIBRA array features a larger target mass and an improved radiopurity. The first DAMA-LIBRA data set has confirmed the evidence for an annual modulation in the first few keV portion of the spectrum [2], an effect previously observed in DAMA. The observations have all the characteristics (amplitude, phase, period) expected [3] from the motion of an Earth-bound laboratory through a standard isothermal halo composed of weakly interacting massive particles (WIMPs). The statistical significance of the effect is 8.2 sigma. No other explanation has been found yet, prompting a claim for evidence of dark matter interactions [2].

Competing dark matter searches have excluded most of the phase space (nuclear scattering cross section vs WIMP mass) available as an explanation for this modulation. However, as a result of insufficiently low energy thresholds in those detectors, it has been proposed [4,5] that light WIMPs of less than $\sim 10\ \mathrm{GeV}/c^2$ could cause the observed modulation while avoiding existing experimental constraints. This hypothesis has now been ruled out [6] for spin-dependent WIMP-nucleus couplings [4]. Our present results exclude the remaining spin-independent phase space [5]. These new limits effectively preclude a standard WIMP halo as the reason for the DAMA observations.

A new type of germanium 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 designs (Fig. 1). Details on the modifications leading to this performance and a discussion of detector applications can

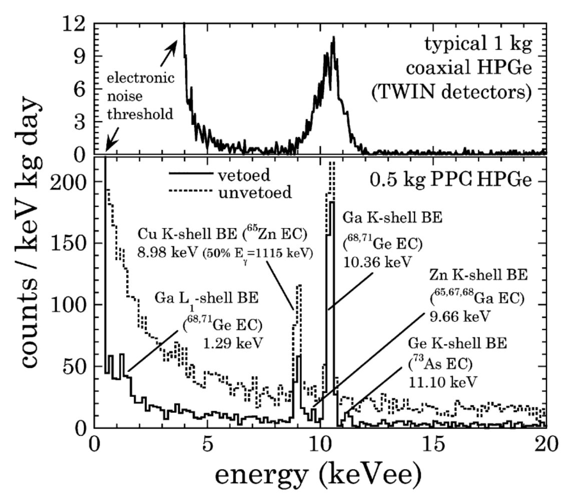

FIG. 1. Improvements in threshold and resolution in a PPC design (bottom), compared to a typical coaxial HPGe [34] (top). Cosmogenic peaks are clearly resolved in the PPC spectrum. BE stands for binding energy, EC for electron capture.

be found in [7]. We refer to this design as a p-type point contact (PPC) germanium detector (HPGe).

Several PPCs have since been built, most within MAJORANA [8]. The data set utilized here comes from tests of this first prototype (0.475 kg active mass) in a shallow underground location (330 mwe, part of Chicago's Tunnel And Reservoir Plan). While the results obtained already impose constraints on the dark matter origins of the DAMA anomaly, it is expected that ongoing detector improvements, a longer exposure (presently 8.4 kg-days) and deeper operation should dramatically improve our dark matter sensitivity. The potential reach of this method is discussed below.

Listing from innermost to outermost components, the shielding around the detector was: (i) a 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 polyethylene, and (vii) a low-efficiency large-area external muon veto. Figure 1 shows the active background rejection. The fraction of random coincidences between PPC and active vetoes, measured with a pulser, was ∼18%. The low-energy data set used for analysis (inset, Fig. 2) is corrected to account for these.

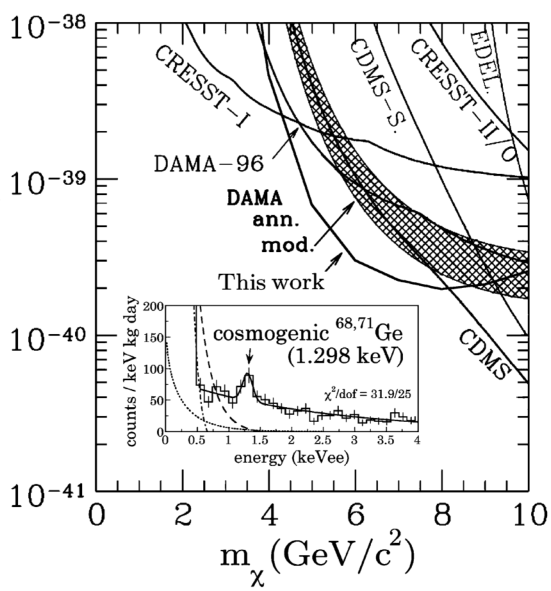

FIG. 2. Parameter space region (crosshatched) able to explain the DAMA modulation via spin-independent couplings from an isothermal light-WIMP halo [5]. Lines delimit the coupling ($\sigma_{\rm SI}$) vs WIMP mass (m_χ) regions excluded by relevant experiments [5]. All regions are defined at the 90% confidence level. Inset: PPC spectral region (0.47–3.94 keV) used for the extraction of present limits. The solid line is the best fit (null hypothesis) to the data. Other lines display the signals expected from some reference WIMP candidates (Dotted line: $m_\chi = 8$ GeV/c^2, $\sigma_{\rm SI} = 10^{-4}$ pb. Dashed line: $m_\chi = 6$ GeV/c^2, $\sigma_{\rm SI} = 0.002$ pb. Dash-dotted line: $m_\chi = 4$ GeV/c^2, $\sigma_{\rm SI} = 10^{-2}$ pb). The modest maximum recoil energy imparted by these light WIMPs imposes a requirement for the lowest possible detector threshold.

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 [9]. These software cuts, applied on the stored amplifier traces, are trained on data sets 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 immediately following installation, and a ^{133}Ba source (five lines below 400 keV). An excellent linearity was observed. The energy resolution σ below 10 keV is given by $\sigma^2 = \sigma_n^2 + (2.35)^2 E\eta F$, where $\sigma_n = 69.7$ eV is the intrinsic electronic noise measured with a pulser, E is the energy in eV, $\eta = 2.96$ eV is the average energy required to create an electron-hole pair in Ge at ∼80 K, and $F \sim 0.06$ is the measured Fano factor.

The spectrum of energy depositions obtained can be compared with expected signals from a standard isothermal galactic WIMP halo. The spectrum of WIMP-induced recoil energies is generated as in [10], 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 (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 [11]. It was found to be in excellent agreement with expectations [7,12]. Its effect is included here in generating spectral shapes of WIMP-induced ionization or "electron equivalent" energy (units of "keVee"), as in the inset of Fig. 2. The exceptional energy resolution of this detector has a negligible effect on these spectra. A standard method [6,13] is used to obtain limits on the maximum WIMP signal compatible with the data: employing a nonlinear regression algorithm, data above the electronic noise pedestal (0.47–3.94 keV) are fitted by a model consisting of (i) a single exponential to represent low-energy backgrounds, (ii) a gaussian peak at 1.29 keV (^{68,71}Ge) with free amplitude and a resolution (width) as 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 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 (masses above 8 GeV/c^2 are eliminated by the CDMS experiment). 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

[14–17] 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 [18]. HPGe should also be subject to this presumptive effect [16], leading again to an expected analogous drift of DAMA region and PPC exclusions in Fig. 2 (Ref. [14] does not include 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 [2,19,20]. Of these, axionlike dark pseudoscalars are arguably comparable to WIMPs in their naturalness, being the subject of many dedicated searches. It has been claimed [20] that such a pseudoscalar, coupling to electrons via the axio-electric effect, might induce the modulation. Following the prescriptions in [10] and the proportionality between axio-electric and photo-electric couplings described in [21], it is possible to arrive at a compact expression for the axio-electric interaction rate from pseudoscalars forming a dark halo with the properties listed above, acting on a target of mass number A. However, the cross section in [21] tacitly assumes relativistic particle speeds, not the case here. The corrected magnitude for the interaction rate is derived in [22]: $R[\mathrm{kg}^{-1}\,\mathrm{d}^{-1}] = 1.2 \times 10^{19} A^{-1} g_{a\bar{e}e}^2 m_a \sigma_{pe}$, 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 illustrated in the inset of Fig. 3. Because of the nonrelativistic nature of galactic dark matter, the spectral observable from such interactions is a peak at an energy equal to m_a. DAMA actually observes the bulk of the modulation being centered around such a peak at $\sim$3 keV [2], albeit hindered by another from a known source (^{40}K). Using a nonlinear 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, corresponding to $0.3 < m_a < 8.0$ keV, with a width defined by the resolution of the detector. The fitting region is restricted to 0.47–8.07 keV. 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 in [20] to be compatible with the DAMA effect. While the cosmological relevance of pseudoscalar, scalar and vector dark matter in the keV mass region is emphasized in [22], it is also shown there that the DAMA modulation seems too large to be caused by these possibilities. We therefore caution the reader about the relevance of the DAMA region in Fig. 3. Adopting the reasoning in [22], 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]. With a capacitance of $\sim$1 pF, PPCs should be capable of ionization energy thresholds below 100 eV. The MAJORANA collaboration plans to use a $\sim$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 for which all other experiments would be unable to contribute to the exploration, due to higher thresholds.

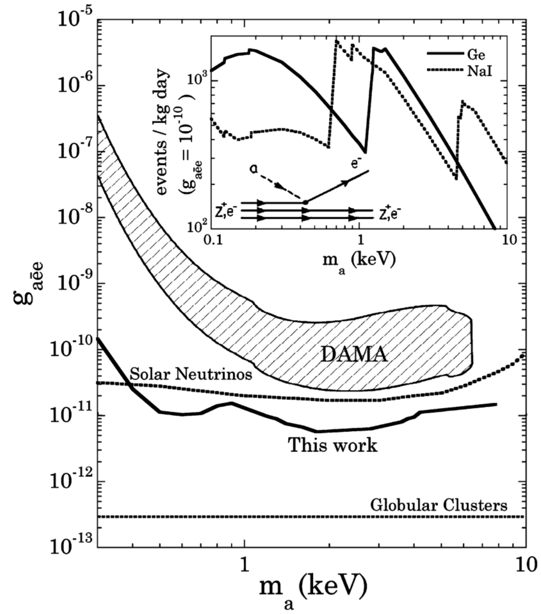

FIG. 3. Hatched region: viable parameter space in an interpretation of the DAMA modulation involving an axio-electric coupling $g_{a\bar{e}e}$ from pseudoscalars composing a dark isothermal halo, according to [20]. The validity of this interpretation is now challenged [22] (see text). The solid line indicates present limits, dotted lines recent astrophysical bounds [35]. 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.

Several scenarios have been proposed where naturally light ($<$10 GeV$/c^2$) WIMPs appear [22–25]. Q-balls can similarly lead to modest ionization signals [26]. The lightest neutralino, a particle present in supersymmetric extensions of the standard model (SM), is a well motivated WIMP candidate [27]. Its properties have been studied mostly within the minimal supersymmetric standard model (MSSM) [28], where very light neutralinos with large detection cross sections were found to be possible [29]. 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 [30]: regions of the parameter space exist which lead to light neutralinos with the correct dark matter relic density [31]. To illustrate these properties, we performed various scans of the NMSSM parameter space with the code NMHDECAY [32]. The choice of input parame-

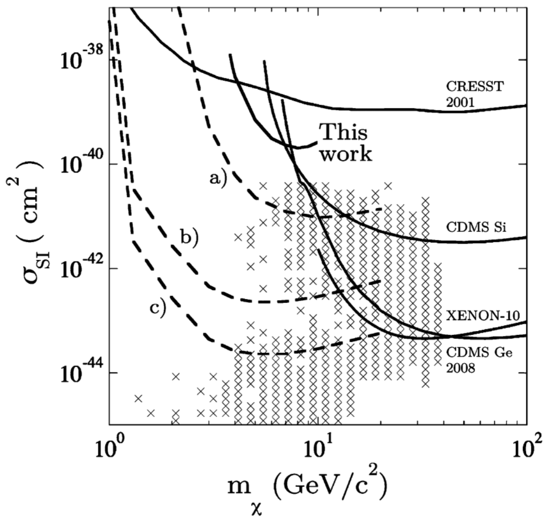

FIG. 4. Solid lines: spin-independent sensitivity from leading experiments in the WIMP low-mass region. A theoretically favored NMSSM phase space is denoted by crosses. Dashed lines: predicted sensitivity for PPC HPGe in a number of scenarios [7]: (a) expected reduction in background from cryostat upgrade, (b) background reduction to best achieved in HPGe [36] 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).

ters is beyond the scope of this Letter and will be given in [33]. The favored space is shown by crosses in Fig. 4. A conservative projected sensitivity for MAJORANA PPCs is overlapped. A clear discovery potential and complementarity to other detection schemes is observed.

In conclusion, by virtue of their sensitivity to 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 all possible dark matter phenomenologies 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 least expected.

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