Dark Matter Detection with Polarized Detectors

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We consider the prospects to use polarized dark-matter detectors to discriminate between various dark-matter models. If WIMPs are fermions and participate in parity-violating interactions with ordinary matter, then the recoil-direction and recoil-energy distributions of nuclei in detectors will depend on the orientation of the initial nuclear spin with respect to the velocity of the detector through the Galactic halo. If, however, WIMPS are scalars, the only possible polarization-dependent interactions are extremely velocity-suppressed and, therefore, unobservable. Since the amplitude of this polarization modulation is fixed by the detector speed through the halo, in units of the speed of light, exposures several times larger than those of current experiments will be required to be probe this effect.

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Although dark matter has been known for several decades to dominate the mass budget of galaxies, its particle nature is still mysterious. The coincidence between the interaction strength required for an early-Universe relic to have the right cosmological density and the electroweak interaction strength motivates the idea that dark matter is composed of some weakly-interacting massive particle (WIMP) [1–4]. However, WIMPs constitute a broad class of dark-matter candidates, including heavy fourth-generation neutrinos, various supersymmetric particles, particles in models with universal extra dimensions [5], etc.; they may be scalar particles or fermions, and if fermions, Majorana or Dirac particles. The precise nature of the couplings of dark matter to ordinary particles varies considerably among the models.

An array of searches for WIMPs is now underway, but terrestrial direct-detection experiments, designed to detect nuclear recoils from collisions with dark-matter particles in the Galactic halo, provide likely our best hope to detect dark matter [6]. These detectors measure the energy of the nuclear recoils; the spectrum of such recoil energies can then be used to discriminate a WIMP signal from background, and in case of detection, to constrain WIMP parameters and discriminate between different WIMP candidates. It has also been suggested [7–9] that the *direction* of the nuclear recoil can additionally be used to distinguish backgrounds and to constrain dark-matter parameters, and this approach is now being implemented experimentally [10].

However, there is yet another handle these experiments can exploit: the spin polarization of the detector nuclei. If WIMPs are scalar particles, then their interaction rate is essentially independent of the orientation of the nuclear spins. In scalar-nucleus scattering, the leading nuclear-polarization dependent terms arise from dimension 5 operators and are generically proportional to $|\vec{q}\,|^2(\vec{q}\cdot\vec{s}\,) \sim m_N^3 v^3(\hat{q}\cdot\vec{s}\,)$ where $\vec{q}$ is the momentum transfer, m_N is the nuclear mass, v is the dark matter speed, and $\vec{s}$ is the nuclear polarization. Since this contribution to the total rate is $\mathcal{O}(v^3) \sim 10^{-9}$, its effects are negligible in direct detection. However, if dark-matter particles are fermions and if these particles have a parity-violating interaction with ordinary matter, then the total detection rate as well as the recoil and energy/direction distribution can depend non-trivially on the polarization of the target nuclei. Thus, measuring the polarization dependence of these distributions may help discriminate between backgrounds and shed light on the WIMP's particle nature in case of detection.

To illustrate, consider a toy model with a dark-matter particle χ of mass m_χ that interacts with a spin 1/2 nucleus N of mass m_N via the four-Fermi operator,

$$G\bar{\chi}\gamma^\mu(a+b\gamma_5)\chi\bar{N}\gamma_\mu(c+d\gamma_5)N \quad , \tag{1}$$

where G is a dimension -2 coupling constant, and a, b, c, and d are real parameters. For simplicity and without loss of generality we treat the nucleus as a point particle; the effects of all form factors and nuclear matrix elements are assumed to be contained in the coefficients of our effective interaction. This interaction gives rise to a differential cross section,

$$\frac{d\sigma}{dE} = A + B\,(\vec{v}\cdot\vec{s}) + B'(\vec{v}\,'\cdot\vec{s}) + \mathcal{O}(v^2), \tag{2}$$

for a WIMP particle χ (antiparticle $\bar{\chi}$) of incident velocity $\vec{v}$ to scatter a nucleus, initially at rest with polarization $\vec{s}$, to a recoil energy E and a final WIMP velocity $\vec{v}\,'$. Here,

$$A = \frac{G^2 m_N}{2\pi v^2}\Big[(a^2+b^2)(c^2+d^2)+(a^2-b^2)(c^2-d^2) -\frac{1}{2}(a^2+b^2)(c^2-d^2)-\frac{1}{2}(a^2-b^2)(c^2+d^2)\Big], \tag{3}$$

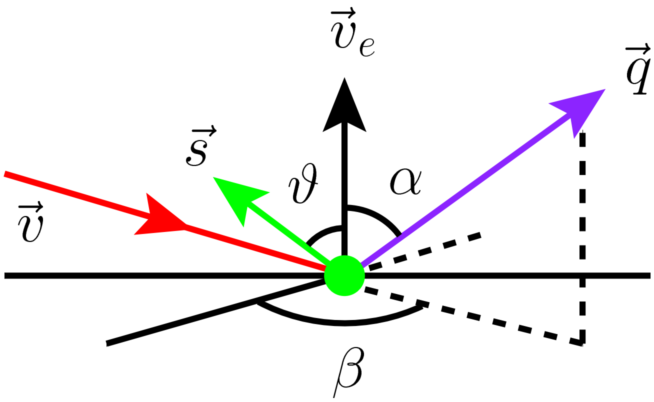

FIG. 1: An incident dark-matter particle with initial velocity $\vec{v}$ scatters from a detector nucleus with polarization $\vec{s}$ and recoil momentum $\vec{q}$. Earth's velocity $\vec{v}_e$ is chosen to lie along the z-axis and the recoil rate in Eq. (7) is differential in both polar angle α and azimuthal angle β.

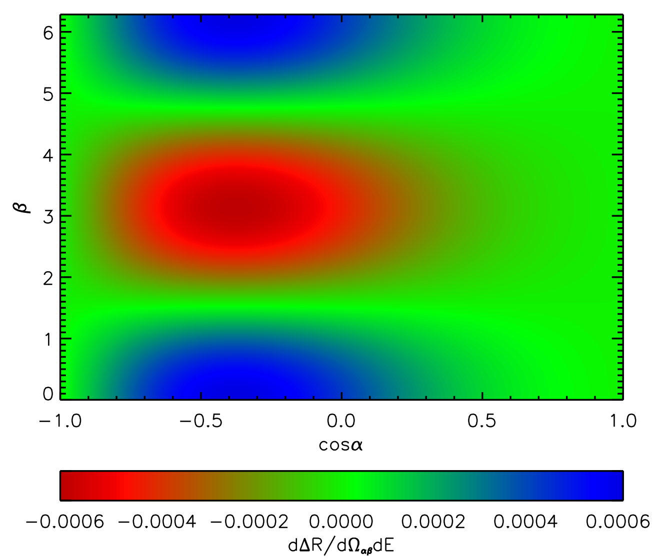

FIG. 2: Contour plot of the differential event rate, Eq. (12), in units of events/kg/day/keV/sr as a function of $\cos\alpha$, where α is the polar angle, and the azimuthal angle β, for fixed recoil energy $E = 30$ keV. We take the angle between the polarization and the detector velocity through the Galactic halo to be $\vartheta = 90°$. We also take $G = (100\,\mathrm{GeV})^{-2}$, and $m_\chi = 100$ GeV.

$$B_{\chi(\bar{\chi})} = \frac{G^2 m_N}{2\pi v^2}\Big[cd(a^2+b^2) \pm ab(c^2+d^2) \mp ab(c^2-d^2) + cd(a^2-b^2)\frac{m_\chi}{m_N}\Big], \quad (4)$$

$$B'_{\chi(\bar{\chi})} = \frac{G^2 m_N}{2\pi v^2}\Big[cd(a^2+b^2) \mp ab(c^2+d^2) \pm ab(c^2-d^2) + cd(a^2-b^2)\frac{m_\chi}{m_N}\Big]. \quad (5)$$

The dependence of the cross section, Eq. (2), on the dot product of a polar vector ($\vec{v}$ or $\vec{v}\,'$) with an axial vector ($\vec{s}$) is a manifestation of parity violation. Parity violation requires that at least three of the parameters a, b, c, and d be nonvanishing. While we leave a discussion of detailed models to future work, we do note that currently acceptable versions of Dirac-neutrino dark matter [11, 12] have such couplings. Related parity-violating couplings may also be found in recent models of composite dark matter [13] and models with light force carriers in the dark sector [14]. In the maximal-parity-violating case with a matter-antimatter asymmetry (no $\overline{\chi}$), we see that $a = -b = c = -d = 1/2$, $A = B = G^2 m_N (8\pi v^2)^{-1}$ and $B' = 0$. We will assume this case for our numerical work below.

We now calculate the distribution of recoil energies and directions assuming that the detector moves with velocity $\vec{v}_e$ (which throughout we will take to be along the $\hat{z}$ axis) through the Galactic halo. If we were to ignore directional information, then we would simply calculate a (single) differential event rate dR/dE. If we were to consider the combined recoil energy/direction distribution for an unpolarized detector (as considered in Refs. [7, 8]), then we would calculate a double-differential rate $dR/dE/d\cos\alpha$, where $\cos\alpha \equiv \hat{v}_e \cdot \hat{q}$, and $\hat{q}$ is the direction of the nuclear recoil. If, however, the detector has a spin polarization $\vec{s}$, which we take to be in the x-z plane, at an angle ϑ from the z axis, then there may be an additional dependence on the azimuthal angle β, about the z axis, between the recoil direction $\hat{q}$ and $\hat{s}$. We must therefore in this case calculate a *triple*-differential event rate $dR/dE/d\cos\alpha/d\beta$.

We begin by writing the triple differential cross section $dR/dEd\Omega$ as by demanding $\hat{v}\cdot\hat{q} = q/2\mu v$, where μ is the reduced mass of the WIMP-nucleus system, and q is the recoil momentum. Then [8],

$$\frac{d\sigma}{dEd\Omega} = \frac{1}{2\pi}\frac{d\sigma}{dE}\delta\left(\cos\gamma - \frac{q}{2\mu v}\right) = \frac{v}{2\pi}\frac{d\sigma}{dE}\delta(\vec{v}\cdot\hat{q} - v_q), \quad (6)$$

where $v_q = q/2\mu$ is the nuclear recoil velocity, $d\Omega = d\cos\alpha\, d\beta$ is a differential solid angle, and $\delta(x)$ is the Dirac delta function.

The differential event rate [8] per unit detector mass is

$$\frac{dR}{dE\,d\Omega} = \frac{n_\chi}{2\pi m_N}\int \frac{d\sigma}{dE}\,\delta\left(\vec{v}\cdot\hat{q} - v_q\right) v^2 f(\vec{v}\,)\, d^3v\,, \quad (7)$$

where n_χ is the local WIMP number density, and $f(\vec{v}\,)$ is the dark-matter velocity distribution in the lab frame. To isolate the polarization dependence in the general case, we subtract signals with opposite spin orientations,

$$\frac{d\Delta R}{dE\,d\Omega} \equiv \frac{dR(\vec{s})}{dE\,d\Omega} - \frac{dR(-\vec{s})}{dE\,d\Omega} = \frac{n_\chi}{\pi m_N}\int B\,(\vec{v}\cdot\vec{s}\,)\,\delta\left(\vec{v}\cdot\hat{q} - v_q\right) v^2 f(\vec{v}\,)\, d^3v. \quad (8)$$

We assume a standard Maxwellian halo, for which

$$f(\vec{v}\,) = \frac{1}{N}\, e^{-(\vec{v}+\vec{v}_e)^2/v_0^2} \qquad (|\vec{v}+\vec{v}_e| < v_{\rm esc}), \tag{9}$$

$$N = \pi v_0^2 \left[\sqrt{\pi} v_0\, {\rm Erf}(v_{\rm esc}/v_0) - 2\, e^{-v_{\rm esc}^2/v_0^2}\right], \tag{10}$$

where $v_0 = 200$ km/s is the halo velocity dispersion and $v_{\rm esc} = 500$ km/s is the escape speed from the Galactic halo.

To evaluate the integral in Eq. (8), we choose the spin vector to be in the direction $\hat{s} = (\sin\vartheta, 0, \cos\vartheta)$, the initial WIMP-velocity direction to be $\hat{v} = (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$, and the recoil direction to be $\hat{q} = (\sin\alpha\cos\beta, \sin\alpha\sin\beta, \cos\alpha)$. We then use the relation $\delta(g(v)) = \delta(v - v_1)/|g'(v_1)|$ for the Dirac delta function, where $g'(v)$ denotes differentiation with respect to v, and v_1 satisfies $g(v_1) = 0$. This occurs when $v = v_q/g(\theta,\phi,\alpha,\beta) \equiv v_1$, where $g(\theta,\phi,\alpha,\beta) = \cos\alpha\cos\theta + \sin\alpha\sin\theta\cos(\phi-\beta)$. There is $\cos\theta$ dependence in the integrand in Eq. (8) through the $\cos\theta$ dependence of $f(\vec{v})$, and there is θ and ϕ dependence through

$$\vec{v}\,'\cdot\vec{s} = v's\left[\cos\theta\cos\vartheta + \sin\theta\sin\vartheta\cos\phi\right]. \tag{11}$$

Performing the v integral in Eq. (8), we obtain

$$\frac{d\Delta R}{dE\, d\cos\alpha\, d\beta} = \frac{G^2 n_\chi}{8N\pi^2}\int_{-1}^{1} dx \int_0^{2\pi} d\phi \frac{v'^2\, \vec{v}\,'\cdot\vec{s}}{|g(\theta,\phi,\alpha,\beta)|} \times e^{-(v'^2+v_e^2+2v'v_e x)/v_0^2} \times\Theta(v'-v_{\rm min})\Theta(v_{\rm esc}-v'), \tag{12}$$

where v' and g both carry dependence on θ and ϕ. Here, $v_{\rm min} = (m_N E/2\mu^2)^{1/2}$ is the minimum WIMP velocity[1] required to produce a nuclear recoil energy E, and $\Theta(x)$ is the unit step function. The polarization-induced breaking of the azimuthal symmetry about $\vec{v}_e$ prevents us from going further analytically, as can be done otherwise [8], but the remaining double integral is straightforward to evaluate numerically.

Figs. 2, 3, and 4 show numerical results for $d\Delta R/dE/d\cos\alpha/d\beta$, the polarization-dependent part of the triple-differential event rate, as a function of the recoil energy E, polar angle α, and azimuthal angle β of the recoil nucleus. The key feature here is the β (azimuthal-angle) dependence in Figs. 2 and 4 which would not arise without parity-violating interactions and particle-antiparticle asymmetry. The dependence of $dR/dE/d\cos\alpha$ also depends on the polarization, as shown in Fig. 3, even without azimuthal-angle information. Fig. 5 shows the differential recoil spectra $(1/R)(dR/dE)$ (blue curve, color online) and $(1/|\Delta R|)(d|\Delta R|/dE)$ (red curve) obtained by integrating over the angular dependence in Eqs. (7) and (8) respectively. Thus, a polarization-dependent detection rate can be sought even without directional information.

Since the detector will be fixed in the Earth frame, the daily revolution of the Earth provides a natural mod-

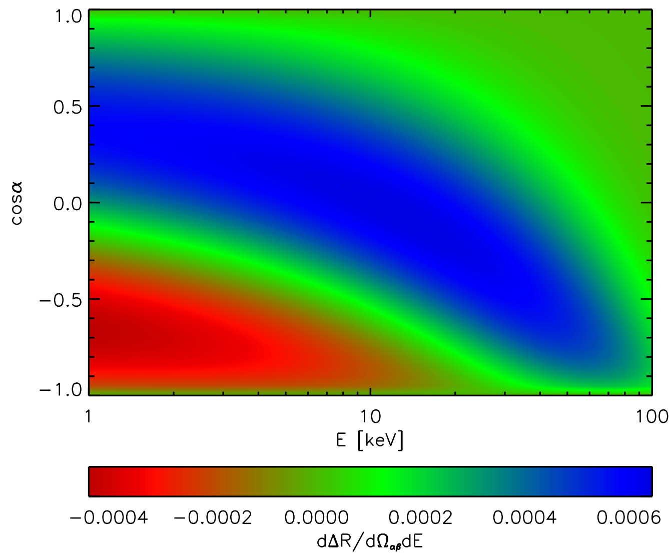

FIG. 3: Contour plot of the differential event rate, Eq. (12), in units of events/kg/day/keV/sr as a function of $\cos\alpha$ and the recoil energy E, for fixed azimuthal angle $\beta = 0$. We assume $\vartheta = 90°$, $G = (100\,{\rm GeV})^{-2}$, and $m_\chi = 100$ GeV.

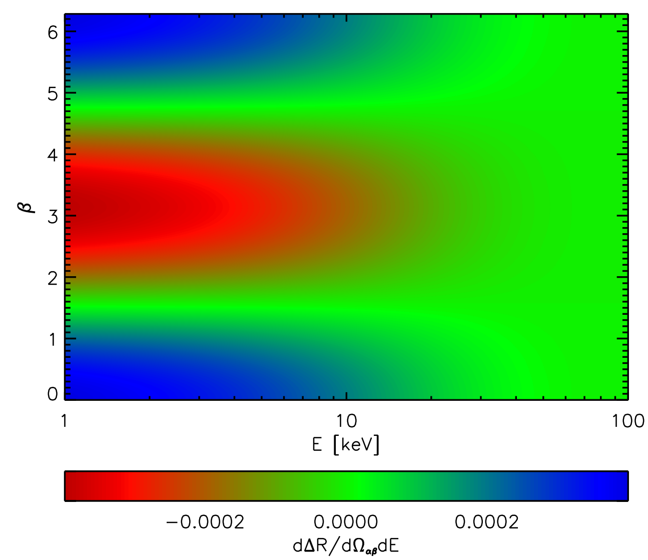

FIG. 4: Contour plot of the differential event rate, Eq. (12), in units of events/kg/day/keV/sr as a function of E and β for fixed polar angle $\alpha = 45°$. We assume $\vartheta = 90°$, $G = (100\,{\rm GeV})^{-2}$, and $m_\chi = 100$ GeV.

[1] The analysis can be generalized to inelastic dark matter [15] by using $v_{\rm min} = [\Delta + (m_N E/\mu)]\,(2m_N E)^{-1/2}$.

ulation of the detector orientation with respect to the Earth's velocity through the halo. This can be used to isolate the dark-matter signal from systematic experimental effects (e.g., variations in sensitivity of the detetor with recoil direction) that might mimic such a signal. The rotation of the Earth around the Sun provides an additional systematic check.

A quick estimate shows that the experimental exposure needed to isolate polarization dependence may be feasible. Consider, for example, a WIMP candidate with total detection rate $R_{\rm tot}$. Since the polarization modulated amplitude is velocity suppressed, $\Delta R/R_{\rm tot} \sim v \sim 10^{-3}$, it is necessary to observe approximately 3×10^6 total events for a 3σ discovery. For the purpose of illustration, we can compare this benchmark figure with those of the DAMA experiment. If the DAMA NaI results are due to dark matter with a total scattering rate $R_{\rm tot} \sim 0.5$ kg $\cdot$ day with a cumulative exposure of ~ 1 ton $\cdot$ yr $\sim 4 \times 10^5$ kg $\cdot$ day [16], then a future experiment with polarized nuclei observing the same dark matter interactions will need to amass an exposure roughly an order of magnitude larger than DAMA's to observe this signal. While larger than those of current detectors, this exposure is within the scale of those considered for development within the next decade [17]. The detector would not only have to be larger, but also be polarized and possibly have direction sensitivity, neither of which are true of DAMA. More precise estimates of detection rates will also require proper consideration of nuclear form factors and, depending on the nucleus, of nuclear spins $J > 1/2$.

While we have focussed here on WIMP-nucleon scattering, similar ideas may apply to detection schemes based on dark-matter–electron scattering [18], in which the signal may conceivably be enhanced by the larger scattering rates associated with more abundant lower-mass dark-matter candidates. The increased relative velocity between the dark-matter particle and the target particle (an atomic electron) may also enhance the polarization dependence.

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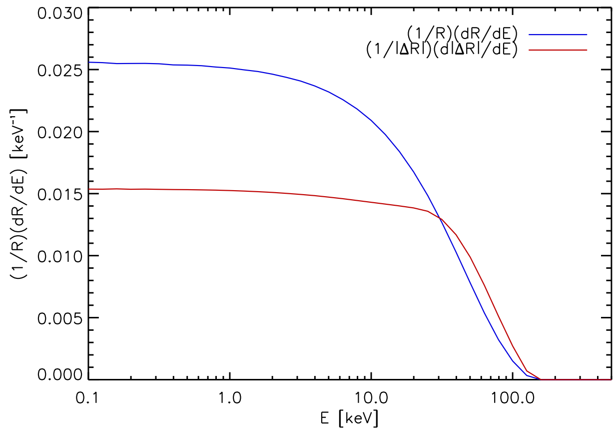

FIG. 5: Plot of the differential event rate $(1/R)(dR/dE)$ (red, color online) and polarization-dependent differential event rate $1/(|\Delta R|)d|\Delta R|/dE$ (blue) after numerically integrating over α and β. As before, we assume $\vartheta = 90°$, $G = (100\,\text{GeV})^{-2}$, and $m_\chi = 100$ GeV.

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