Direct detection signals of dark matter with magnetic dipole moment

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Abstract

A neutral dark matter (DM) particle with a magnetic dipole moment has a very different direct detection phenomenology with respect to standard candidates. This is due to the peculiar functional form of the differential cross section for scattering with nuclei. Such a candidate could be a bound state of charged particles, as the neutron or an atom, or a fundamental particle coupled to heavier charged states, much like a Dirac neutrino. We analyze here the direct detection signals of DM with magnetic dipole moment, both the recoil rate and its modulation, and show that they are very different from those expected in standard scenarios. For this candidate, contrary to the common lore, the time of maximum signal depends on the recoil energy as well as on the target material. The observation of different modulations by experiments employing different targets would be a strong indication in favour of this type of DM particles.

Scattering rate

Direct DM detection experiments try to measure the recoil energy E_R a nucleus initially at rest in the detector acquires after scattering with a DM particle with initial velocity $\boldsymbol{v}$ in the detector's rest frame. The differential scattering rate on a nuclide T, neglecting factors inessential to this discussion, is

$$\frac{dR_T}{dE_R}(E_R,t) \sim \int_{v\geqslant v_{min}(E_R)} v\, f(\boldsymbol{v},t)\, \frac{d\sigma_T}{dE_R}(v,E_R)\, d^3v\,, \quad (1)$$

where the v factor comes from the DM flux. $f(\boldsymbol{v},t)$ is the DM velocity distribution in Earth's frame, which depends on time due to Earth's motion around the Sun. $v_{min}(E_R)$ is the minimum speed a DM particle must have to impart a fixed E_R to a target nucleus, and its functional form is dictated by the scattering kinematics. In the case of elastic scattering treated here, there is a one-to-one correspondence between v_{min} and E_R, and **these variables can be used interchangeably**.

The interaction Lagrangian of a Dirac fermion DM particle χ with magnetic moment μ is $\mathscr{L} = (\mu/2)\,\bar\chi\sigma_{\mu\nu}\chi F^{\mu\nu}$. The differential cross section for elastic scattering off of a target nucleus with atomic number Z and magnetic moment μ_T is

$$\frac{d\sigma_T}{dE_R} = \underbrace{\left(\frac{1}{E_R} - \frac{\#}{v^2}\right)\mu^2\alpha Z^2 F_C^2(E_R)}_{\text{dipole-charge interaction}} + \underbrace{\frac{@}{v^2}\mu^2\mu_T^2 F_M^2(E_R)}_{\text{dipole-dipole interaction}}\,, \quad (2)$$

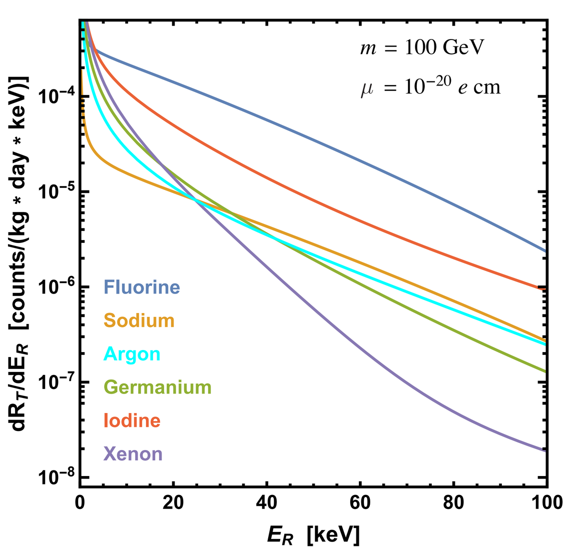
with # and @ two factors of no interest here. $F_C(E_R)$ and $F_M(E_R)$ are the Coulomb and magnetic form factors, respectively related to the spin-independent (SI) and spin-dependent (SD) form factors. Two features are worth noting: *(i)* the **$1/E_R$ behavior** dominating the low-energy spectrum (see figures below), and *(ii)* the **non-factorizable velocity dependence** (colors in formulas mark different velocity dependences). In contrast, for the usual SI and SD interactions we have $d\sigma_T/dE_R \propto F^2(E_R)/v^2$, with $F(E_R)$ the appropriate form factor. Performing the velocity integral in Eq. (1) we can write the differential scattering rate as

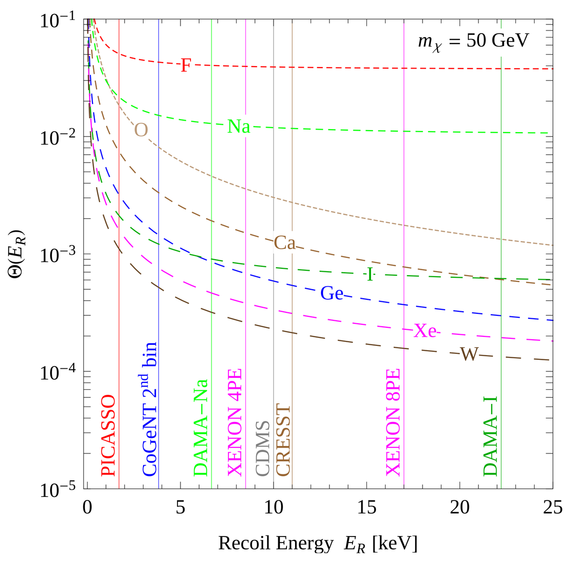
$$\frac{dR_T}{dE_R}(E_R,t) = r_0(E_R,t) + r_1(E_R,t) \quad (3)$$

with

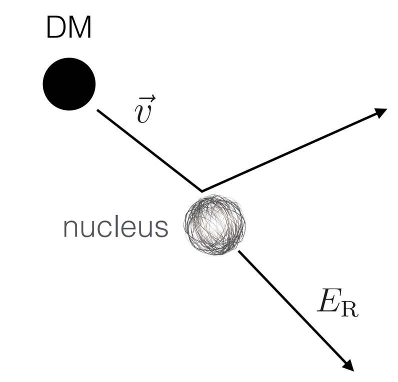
$$r_n(E_R,t) \propto \eta_n(v_{min},t) \equiv \int_{v\geqslant v_{min}} v^{2n}\,\frac{f(\boldsymbol{v},t)}{v}\, d^3v \quad (4)$$

for DM with magnetic moment, in contrast to $dR_T/dE_R \propto \eta_0$ for SI/SD couplings. The peculiar recoil energy spectrum of this interaction, featuring the $1/E_R$ divergence at low recoil energy, can be observed in the first plot below, showing the time-averaged rate $\langle dR_T/dE_R\rangle$ for a 100 GeV DM particle. The second plot shows the ratio $\Theta(E_R)$ between the time-averaged rate for magnetic moment DM and that for DM with SI interactions (with arbitrary normalization), for a 50 GeV DM particle. The target-dependent interplay of the dipole-charge and dipole-dipole terms in Eq. (2), which plays a major role for nuclei with large magnetic moments such as F (used e.g. in PICO) and Na, I (used e.g. in DAMA), **may be exploited** to establish whether DM particles interact with nuclei through a magnetic dipole moment in case of detection.





Crash course on direct detection



DM particles bound to the halo of our galaxy have speeds $v \sim 10^{-3}c$ (the galactic escape speed is ~ 500 km/s). If these particles interact with baryonic matter and have mass above few GeV, scattering off atomic nuclei at rest can produce detectable nuclear recoils with recoil energy E_R of few (tens of) keV.

The scattering rate in Eq. (1) depends on the type of interactions and on the velocity distribution of the DM. The most common interactions are the *spin-dependent* (SD) interaction, where the DM couples to the nuclear spin, and the *spin-independent* (SI) interaction. They arise e.g. from interaction Lagrangians such as $\bar\chi\chi\bar N N$, $\bar\chi\gamma^\mu\chi\bar N\gamma_\mu N$ (SI), and $\bar\chi\gamma^\mu\gamma^5\chi\bar N\gamma_\mu\gamma^5 N$ (SD), with N the nucleon field.

The standard assumption for the DM distribution in the Milky Way is the *Standard Halo Model*, an isothermal sphere at rest with respect to the galaxy. In this model the DM velocity distribution is an isotropic Maxwellian truncated at the galactic escape speed.

References

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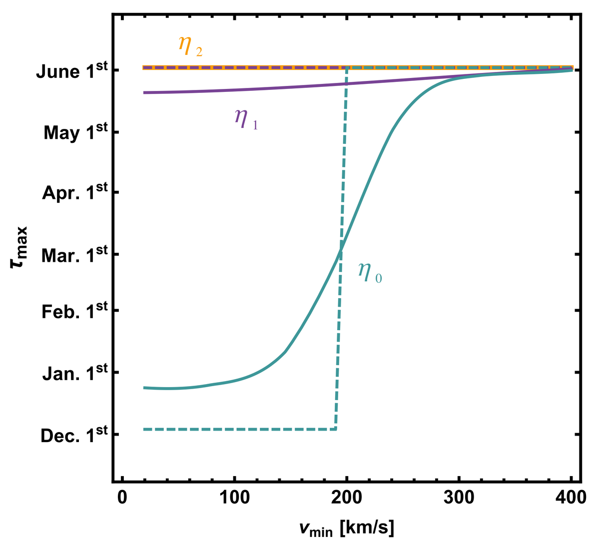
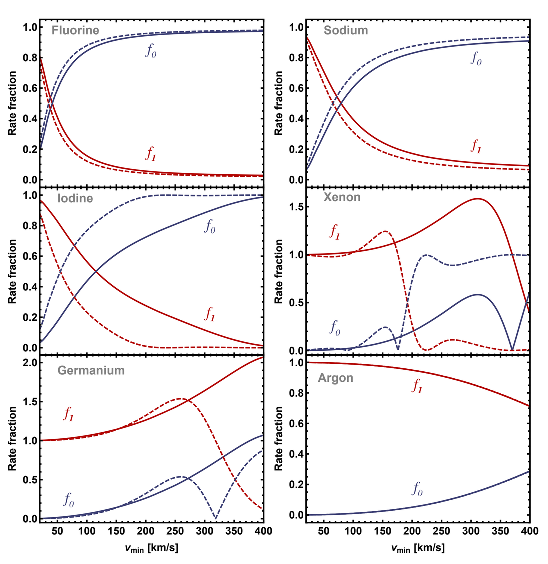
Time dependence





In general, the scattering rate depends on time through the velocity integral in Eq. (1). The first plot above displays the time of maximum of η_0 and η_1 (see Eq. (4)) in the Standard Halo Model (solid lines include the effect of the gravitational potential of the Sun on the DM velocity distribution, dashed lines ignore it). If the target and velocity dependences can be factored in the differential rate, as happens e.g. for the SI/SD interactions where $dR_T/dE_R \propto \eta_0$, the rate depends on time through a single velocity integral, the same function for all targets. Quantities such as the time of maximum rate t_{max} (as well as the fractional amplitudes and phases in a Fourier expansion of the signal) are then independent of the target material when expressed as functions of v_{min} (as opposite to E_R).

For DM with a magnetic dipole, this feature is spoiled by the target-dependent interplay of terms with different velocity dependences ($1/E_R$ and $1/v^2$ in Eq. (2), r_0 and r_1 in Eq. (3)). The second plot above shows the relative size of these terms in the time-averaged rate,

$$f_0 \equiv \left|\frac{\langle r_0\rangle}{\langle r_0 + r_1\rangle}\right|, \qquad f_1 \equiv \left|\frac{\langle r_1\rangle}{\langle r_0 + r_1\rangle}\right|. \quad (5)$$

r_1 always dominate at low recoil energies thanks to the $1/E_R$ enhancement, while r_0 always dominates at large enough E_R. This implies that the **time dependence of the rate is dictated by η_1 at low v_{min} and by η_0 at large v_{min}**. This behavior is apparent in the plots below, showing t_{max} as a function of both v_{min} (left) and E_R (right); the small arrows in the first plot indicate some experimental thresholds.

As one can see, r_0 gets to dominate the rate at low enough v_{min} to produce a detectable feature in t_{max} only in target nuclei with a sizeable magnetic moment, and/or for large enough DM masses.

The plots above show a fully differential (unintegrated) distribution, but a putative signal will realistically need to be binned. As shown in the last two plots below, **it should be possible to distinguish** DM with magnetic dipole interactions from DM with SI/SD interactions relying on the time dependence of the rate alone, by integrating the signal in 1 keV bins. Integration above a certain threshold as performed e.g. in PICO will lead to indistinguishable signals. The observation of a different time of maximum signal by experiments employing different targets would be a **strong indication** in favour of this type of DM particles.