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Integrating in dark matter astrophysics at direct detection experiments

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ABSTRACT

We study the capabilities of the Majorana Demonstrator, a neutrinoless double-beta decay experiment currently under construction at the Sanford Underground Laboratory, as a light WIMP detector. For a cross section near the current experimental bound, the Majorana Demonstrator should collect hundreds or even thousands of recoil events. This opens up the possibility of simultaneously determining the physical properties of the dark matter and its local velocity distribution, directly from the data. We analyze this possibility and find that allowing the dark matter velocity distribution to float considerably worsens the WIMP mass determination. This result is traced to a previously unexplored degeneracy between the WIMP mass and the velocity dispersion. We simulate spectra using both isothermal and Via Lactea II velocity distributions and comment on the possible impact of streams. We conclude that knowledge of the dark matter velocity distribution will greatly facilitate the mass and cross section determination for a light WIMP.

1. Introduction

Direct detection experiments offer the possibility of a non-gravitational detection of dark matter (DM), the most common form of matter in the Universe [1]. Swift progress is being made in this field, with the LUX and XENON1T experiments aiming to push the bound on the spin-independent cross section of a 100 GeV WIMP all the way to the 10^{-47} cm^{-2} level. A no less dramatic development may occur on the light WIMP front ($\lesssim 10$ GeV), where the improvement relative to the current bound may be even greater, as a result of the Majorana Demonstrator [2,3] (see Fig. 1). If the light WIMP cross section lies near its current bound, the Majorana Demonstrator is poised to collect hundreds or even thousands of recoil events. This would open up an interesting possibility of not only discovering the DM particle, but also accurately measuring its properties. Here, we explore this possibility and the issues that arise in connection with it.

Light WIMPs are not without theoretical or experimental motivation. For example, on the theoretical side, 1–10 GeV DM is typical in models relating the baryon and DM abundances [4–10] (see [11] and references therein for recent work). In these models, the DM has a nonzero particle–antiparticle asymmetry, thereby suppressing the indirect signatures of DM annihilation.[1] Establishing such low-mass DM at a collider will be difficult since although the Tevatron and the LHC can detect the missing energy associated with light DM, they lose sensitivity to the mass of DM when it is much less than 100 GeV (see e.g., [13]). The missing energy could then be attributed to a variety of sources, from novel neutrino interactions [14] to extra-dimensional particles [15,16]. Hence, low-threshold direct detection experiments such as the Majorana Demonstrator may offer the best way to test this well-motivated class of models.

On the experimental side, the interest of the community has been piqued by the CoGeNT and DAMA experiments, which have claimed signs of light dark matter [17,18]. Most recent hints in this mass window come from the CDMS experiment [19]. With its remarkable sensitivity, the Majorana Demonstrator is expected to resoundingly refute or confirm these results. Here, we choose to remain agnostic about them and assume that the DM is just at the border of what is allowed by the null results [20–23] (see the black curves in Fig. 1 for current constraints). If the CoGeNT/DAMA/CDMS signals are confirmed, the Majorana Demonstrator will see even more events than we consider below.

If the Majorana Demonstrator indeed sees hundreds or thousands of DM events, the experiment will obviously try to determine the DM mass and cross section from this data. The accuracy of this determination, on very general grounds, is expected to depend on our knowledge of the "beam", which in this case is provided by the local dark matter distribution. As we discuss below, its characteristics are uncertain. Two approaches to this uncertainty could be taken. One is to rely on models of the Galactic halo (analytical and/or numerical), the other is to try to extract *both* the DM physics and astrophysics directly from the data. Previous studies examining the effect of astrophysical uncertainty on

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[1] See, however, [12] for a counterexample.

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mass and cross section determination [24–33] involve some combinations of these approaches (though none deal with such light WIMPs).

Below, we highlight both approaches and then concentrate on the second one, which may become feasible with large statistics and hence the DEMONSTRATOR may be the most appropriate place to test it. We will quantify how much simultaneously fitting for the DM properties and astrophysics degrades the determination of the DM mass. We will show that the culprit responsible for the degradation is a degeneracy that exists between the light WIMP mass and the DM velocity.

To avoid any confusion, we stress from the outset that for the present purpose astrophysics obviously cannot be "integrated out", along the lines of [34,35]. The power of the "integrating out" technique is that it allows mapping the results of one experiment into another in an astrophysics-free manner (see [36,37] and [38] for applications to recent experiments). For the purpose of measuring the DM properties, the astrophysics needs to instead be "integrated in".

In the next section we review the basic theory of direct detection. In Section 3 we discuss our fit methodology and mock-up of the MAJORANA DEMONSTRATOR. In the first subsection of Section 4 we present the results of fits to the mass, cross section and the local velocity dispersion, assuming the "true" (input) velocity distribution is Maxwell–Boltzmann. In Section 4.2, we examine to what extent light DM is sensitive to different forms of the velocity distribution by inputing the distribution from the high-resolution N-body simulation, Via Lactea II. In Section 4.3 we comment on the degeneracy at heavier masses ($m_\chi \sim 100$ GeV) and in Section 4.4 we briefly touch on the signatures of streams. We summarize our conclusions in Section 5.

2. Basics

While the nature of WIMP-nucleus scattering is obviously unknown, in the vast majority of existing scenarios the scattering is mediated by a sufficiently heavy mediator particle (compared to the momentum transfer in the direct detection process). Upon integrating out the exchanged particle, in the usual effective field theory approach, one finds that all the physics of the DM-nucleus scattering is contained in a set of higher dimensional operators. Several studies of the range of possibilities have been carried out [39–41]. A complete analysis would in principle examine how each of these operators is sensitive to astrophysical uncertainties in turn — a daunting, but eventually necessary task. Here, mainly for clarity, we will vary the astrophysics while restricting ourselves to the simplest and most-studied interaction form: isospin-conserving, spin-independent scattering that depend on neither the incoming DM velocity nor the exchanged momentum. Such a cross section could come from a scalar interaction $(\bar{q}q)(\overline{X}X)$ (such as from Higgs-exchange for a neutralino, e.g. [42]) or a vector interaction $(\bar{q}\gamma_\mu q)(\overline{X}\gamma^\mu X)$ (arising from the exchange of a Z' vector boson). A complementary study was carried out in [43] where the authors instead fixed the astrophysics and considered a set of particle physics choices.

To obtain the average differential rate per unit detector mass of a WIMP of mass m_X scattering on a target nucleus of mass m_N, one convolves the cross section with the DM velocity distribution (see [42,44] for reviews),

$$\frac{dR}{dE_R} = \frac{\rho_\odot}{m_N m_X}\left\langle v\frac{d\sigma}{dE_R}\right\rangle = \frac{\rho_\odot}{m_N m_X}\int_{v_{\min}(E_R)}^{\infty} d^3v\, v f\big(\vec{v}+\vec{v}_e(t)\big)\frac{d\sigma}{dE_R}, \tag{1}$$

where μ_N is the DM-nucleus reduced mass, $\vec{v}_e(t)$ is the velocity of the laboratory observer with respect to the galactic rest frame, $f(v)$ is the local DM velocity distribution in the rest frame of the galaxy, and $\rho_\odot$ the local DM density. The quantity $v_{\min}(E_R)$ is the minimum DM velocity in the lab frame to produce a nuclear recoil of energy E_R; for elastic scattering, $v_{\min}(E_R) = \sqrt{m_N E_R/2\mu_N^2}$.

For spin- and momentum-independent interactions, the differential cross section can be written as

$$\frac{d\sigma}{dE_R} = \frac{m_N}{2\mu_N^2 v^2}\sigma_{SI}^N F^2(E_R, A), \tag{2}$$

where $F(E_R, A)$ is the nuclear form factor. We use the Helm form factor, which can be found in [45]. The spin-independent DM-nucleus cross section is

$$\sigma_{SI}^N = \sigma_n \frac{\mu_N^2}{\mu_n^2}\frac{[f_p Z + f_n(A-Z)]^2}{f_n^2}, \tag{3}$$

where μ_n is the DM-nucleon reduced mass, and f_p and f_n are the DM couplings to protons and neutrons respectively. Throughout, we will make the standard simplifying assumption of isospin-conserving scattering, $f_p = f_n = 1$. With these assumptions, the scattering rate simplifies to

$$\frac{dR}{dE_R} = \frac{\rho_\odot \sigma_n}{2\mu_n^2 m_X} A^2 F^2(E_R, A) g(v_{\min}), \tag{4}$$

where $g(v_{\min})$ is the mean inverse speed,

$$g(v_{\min}) \equiv \int_{v_{\min}}^{\infty} \frac{f(\vec{v}+\vec{v}_e(t))}{v} d^3v. \tag{5}$$

The astrophysical uncertainties in principle affect both the local density $\rho_\odot$ and the velocity distribution $f(v)$. In this Letter, we adopt the standard fiducial value of the local DM density $\rho_\odot = 0.3\ \text{GeV/cm}^3$ and focus on velocities. With this framework, the unknown quantities are the DM mass m_X, scattering cross section σ_n and $f(v)$ or, equivalently, $g(v_{\min})$.

2.1. Velocity distributions

While an order of magnitude estimate of the event rate can often be obtained by simply using the average velocity of a DM particle in the halo [1], for a quantitative measurement of the DM properties the knowledge of the dark velocity distribution is required. A canonical framework has emerged in the field, in which the DM halo is taken to be an isothermal, Maxwell–Boltzmann (MB) distribution [46,47], with a cut-off corresponding to the escape speed. In the galactic rest frame the distribution,

$$f_{MB}(\vec{v}) = \begin{cases} Ne^{-v^2/v_0^2}, & v < v_{esc}, \\ 0, & v > v_{esc}, \end{cases} \tag{6}$$

is fully specified by just two parameters: its dispersion v_0 and the local escape speed v_{esc}. The relevant velocity integral Eq. (5) and the normalization constant N have a closed form expression (see Appendix A). Assuming an idealized isothermal halo, with a $\rho \propto r^{-2}$ DM density profile, the dispersion v_0 could further be equated to the circular speed, v_e. The circular speed is observable and is measured to be $\langle v_e(t)\rangle = 230$ km/s [48,49]. This framework is being used by all experimental collaborations in reporting their results in terms of m_X and σ_n.

We would like to get a sense of the impact of astrophysical uncertainties on these results. Even if one chooses to stick with the assumption of an idealized isothermal halo, an important uncertainty comes from the error on the circular speed, which is