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Is the dark matter particle its own antiparticle?

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We propose a test based on direct detection data that allows us to determine if the dark matter particle is different from its antiparticle. The test requires the precise measurement of the dark matter spin-independent direct detection cross sections off *three* different nuclei and consists of interpreting such signals in terms of self-conjugate (particle = antiparticle) dark matter to see if such interpretation is consistent. If it is not, the dark matter must be different from its antiparticle. We illustrate this procedure for two sets of target nuclei, $\{\mathrm{Xe}, \mathrm{Ar}, \mathrm{Si}\}$ and $\{\mathrm{Xe}, \mathrm{Ar}, \mathrm{Ge}\}$, identifying the regions of the parameter space where it is particularly feasible. Our results indicate that future signals in direct detection experiments, if sufficiently accurate, might be used to establish that the dark matter particle is not its own antiparticle—a major step towards the determination of the fundamental nature of the dark matter.

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I. INTRODUCTION

The existence of dark matter (DM) has been established, via its gravitational effects, through a variety of observations at different scales—from galaxies to the largest structures in the Universe. According to the most recent data, DM accounts for about 27% of the total energy density of the Universe and about 85% of its matter density [1]. And yet, the fundamental nature of the DM particle (e.g. its mass, spin, quantum numbers, etc.) remains a mystery, providing one of the most important open problems in particle and astroparticle physics today [2,3].

Within this context, it is essential to determine whether the DM particle is its own antiparticle. That is, whether it is a Majorana or a Dirac particle for fermion DM, or whether it is a real or a complex particle for scalar and vector DM. Among the multitude of models that have been proposed to account for the DM, it is not difficult to find suitable candidates for each of these cases—see e.g. [4–9]. The neutralino of the MSSM [4] and a heavy neutrino [10] supply, for example, well-known instances of Majorana and Dirac DM, respectively. But, is there a way to *experimentally* distinguish between these two possibilities?

Here we propose a test that allows us to determine if the DM particle is different from its antiparticle. It relies on direct detection data only and requires the precise measurement of the DM spin-independent cross section off three different nuclei. The idea is to interpret these measurements in terms of self-conjugate DM (particle = antiparticle) and see if that interpretation is consistent. If it is not, the DM particle must be different from its antiparticle. Figure 1 illustrates pictorially how the test works.

Throughout this paper, we assume that the DM consists of a single field—multicomponent dark matter scenarios [11,12] lie outside of the scope of this work. For clarity, in our discussion we will initially focus on fermion DM and the possibility of differentiating between Dirac and Majorana DM, but we later show that the test works the same way for scalar and vector **a**DM.

II. SPIN-INDEPENDENT CROSS SECTIONS

For a fermion DM particle, χ, the most general Lagrangian describing its spin-independent (SI) interactions with pointlike nucleons ($N = p, n$) is given by [13]

$$\mathcal{L}^{F}_{\mathrm{SI}} = \lambda_{N,e}\bar{\psi}_\chi\psi_\chi\bar{\psi}_N\psi_N + \lambda_{N,o}\bar{\psi}_\chi\gamma_\mu\psi_\chi\bar{\psi}_N\gamma^\mu\psi_N, \quad (1)$$

where $\lambda_{N,e}$ and $\lambda_{N,o}$ are dimensionful couplings that are determined by the underlying particle physics model and, for simplicity, are taken to be real. The indexes e and o indicate whether the corresponding operator is even or odd with respect to $\chi \leftrightarrow \bar{\chi}$ interchange. For a Majorana DM particle only the even operators are nonzero and the DM elastic scattering cross section off a pointlike nucleus takes the simple form

$$\sigma^{M}_{\mathrm{SI}} = \frac{4\mu_\chi^2}{\pi}[\lambda_p^M Z + \lambda_n^M (A - Z)]^2, \quad (2)$$

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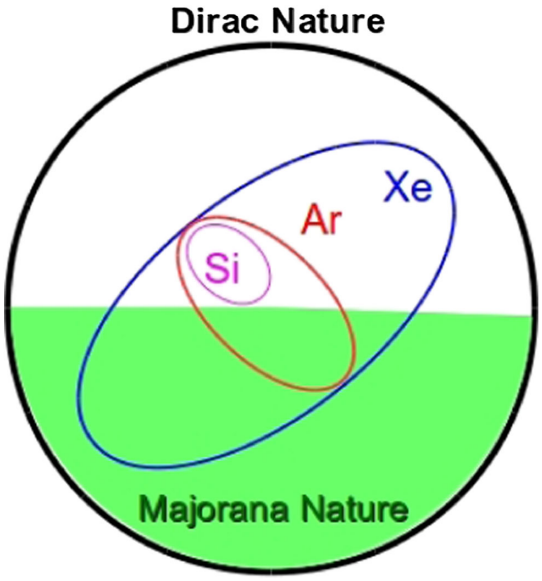

FIG. 1. An illustration of the test we are proposing: after combining direct detection data from three different nuclei (e.g. Xe, Ar, and Si) the Dirac nature of the DM could be singled out.

where $\lambda_N^M \equiv \lambda_{N,e}$, $\mu_\chi = M_\chi M_A/(M_\chi + M_A)$ is the WIMP-nucleus reduced mass, Z is the nucleus charge, and A is the total number of nucleons. For a Dirac DM particle, the even and odd operators are in general both present and there are two different spin-independent cross sections with nuclei—one for the DM particle ($\sigma_{\rm SI}$) and one for the DM antiparticle ($\bar{\sigma}_{\rm SI}$). It is useful to define, in this case, the parameters $\lambda_N^D \equiv (\lambda_{N,e} + \lambda_{N,o})/2$ and $\lambda_N^{\bar{D}} \equiv (\lambda_{N,e} - \lambda_{N,o})/2$, which respectively determine $\sigma_{\rm SI}$ and $\bar{\sigma}_{\rm SI}$. Within the standard WIMP framework, the DM particles and antiparticles are expected to have the same or very similar densities, so the experimentally relevant direct detection cross section for a Dirac DM particle, $\sigma_{\rm SI}^D$, is simply the average between $\sigma_{\rm SI}$ and $\bar{\sigma}_{\rm SI}$,

$$\sigma_{\rm SI}^D = \frac{4\mu_\chi^2}{\pi}\frac{1}{2}([\lambda_p^D Z + \lambda_n^D(A-Z)]^2 + [\lambda_p^{\bar{D}} Z + \lambda_n^{\bar{D}}(A-Z)]^2). \tag{3}$$

For definiteness, the spin-dependent contribution to the signal rate is taken to be negligible throughout our analysis. The event rate at a DM detector is then given by $R = \sigma_X I_X$, where σ_X is the Dirac or Majorana cross section off the nucleus X—Eqs. (2) or (3)—which is determined by the underlying particle physics model; I_X, on the other hand, depends on experimental, astrophysical, and nuclear physics inputs. Explicitly,

$$I_X = n_\chi N_T \int dE_R \int_{v_{\rm min}}^{v_{\rm max}} d^3v f(v) \frac{m_X}{2v\mu_X^2} F_X^2(E_R), \tag{4}$$

where n_χ is the local number density of DM particles, N_T is the number of target nuclei, v is the velocity of the DM particle, $f(v)$ is the DM velocity distribution, and F_X is the nuclear form factor. Usually, I_X is assumed to be given (e.g. by the standard halo model—see, however, [14–17] for alternative approaches), allowing us to translate the absence of signals in current experiments into upper bounds on the cross sections [18,19]. In the same way, an observed signal in a future experiment could be translated into a certain range for the cross section.

III. DIRAC OR MAJORANA DARK MATTER?

Since the direct detection cross sections for Dirac and Majorana DM have different functional dependencies, it should be possible to determine, given a certain number of observations, whether the experimental data is described by Eq. (2) or Eq. (3). That is, it seems feasible to distinguish Dirac DM from Majorana DM with just direct detection data. Our proposal to do so is to try to explain the direct detection signals in terms of Majorana DM, and check if that interpretation is consistent. If it is not, the DM must be a Dirac particle.

To illustrate the basic idea behind this test, we first consider a simplified scenario. Let us assume, for example, that the DM cross section off the nuclei ${}^{A_X}_{Z_X}X$ and ${}^{A_Y}_{Z_Y}Y$ have been measured to be $\tilde{\sigma}_X$ and $\tilde{\sigma}_Y$, respectively. Interpreting these results in terms of Majorana DM implies, from Eq. (2), that

$$[\lambda_p^M Z_X + \lambda_n^M (A_X - Z_X)]^2 = \frac{\pi\tilde{\sigma}_X}{4\mu_\chi^2}, \tag{5}$$

$$[\lambda_p^M Z_Y + \lambda_n^M (A_Y - Z_Y)]^2 = \frac{\pi\tilde{\sigma}_Y}{4\mu_\chi^2}. \tag{6}$$

Each of these equations describes, in the plane $(\lambda_p^M, \lambda_n^M)$, two parallel lines with slopes $m_X = Z_X/(A_X - Z_X)$ and $m_Y = Z_Y/(A_Y - Z_Y)$. For $m_X \neq m_Y$ these lines would always intersect, in pairs, at four different points. These four values of $(\lambda_p^M, \lambda_n^M)$ would thus be consistent with both measurements (notice though that two of these solutions correspond to the global sign change $(\lambda_p^M, \lambda_n^M) \to (-\lambda_p^M, -\lambda_n^M)$, so only two solutions are actually different). Thus, two DM scattering signals off different nuclei are always consistent with Majorana DM. But, if the DM cross section off another nuclei, say V, were also measured and found to be $\tilde{\sigma}_V$, two things could happen with its corresponding parallel lines:

(1) At least one of them would pass through one of the two distinct points consistent with the X and Y measurements. In this case, we would have determined, up to a global sign, the values of λ_p^M and λ_n^M, but we could not say anything about the Dirac or Majorana nature of the DM particle.
(2) None of them would pass through one of the two distinct points consistent with the X and Y

measurements. In this case, the three measurements would be inconsistent and our interpretation in terms of a Majorana DM particle must be wrong. We would conclude, therefore, that the DM is a Dirac particle.

Thus, direct detection signals can be used, at least in principle, to exclude the possibility of Majorana DM, establishing the Dirac nature of the DM particle. But such signals could never demonstrate the Majorana nature of the DM particle or, equivalently, exclude a Dirac DM particle. The reason for this asymmetry is that the Dirac DM detection cross section can always be reduced to a Majorana form, but not the other way around.

To be able to say anything about the Dirac or Majorana nature of the DM particle, the observed signals must therefore be due to a Dirac particle. In that case, our problem consists in determining whether, for a given set of $\{\lambda_p^D, \lambda_p^{\bar{D}}, \lambda_n^D, \lambda_n^{\bar{D}}\}$, there exist values of λ_p^M and λ_n^M such that the system

$$\sigma_{\mathrm{SI},k}^M = \sigma_{\mathrm{SI},k}^D \quad \text{for } k = 1, 2, 3 \tag{7}$$

(where k denotes the different nuclei) is inconsistent. Notice that the reduced mass drops out from this equation and with it the dependence on the DM mass. Thus, whether the system in Eq. (7) is inconsistent or not does not depend on the mass of the DM particle. By the same token, one can see that this system is invariant under a global scaling of all the couplings, making the precise value of the cross sections irrelevant to the issue of Dirac vs. Majorana DM. Finally, this system depends on the number or protons and neutrons in the nuclei only through their ratio, $Z/(A-Z)$, which, as we have already argued, should take different values for the three nuclei considered. It turns out though that $Z/(A-Z)$ varies only between 1 and 0.65 for stable nuclei, and it is very similar for some of the nuclei that are of interest to DM experiments: about 1 for $\{\mathrm{Si}, \mathrm{Ca}, \mathrm{O}\}$, about 0.68 for $\{\mathrm{Xe}, \mathrm{W}\}$ and about 0.91 for $\{\mathrm{F}, \mathrm{Na}\}$. To help discriminate between Dirac and Majorana DM, only one element of each of these sets is actually useful.

Before proceeding, let us emphasize that there are some *special* cases in which direct detection experiments cannot differentiate between Dirac and Majorana DM, because the Majorana direct detection cross section takes exactly the same form as the Dirac one, namely: (i) When the Dirac fermion has either scalar or vector interactions but not both; (ii) When either σ_{SI} or $\bar{\sigma}_{\mathrm{SI}}$ vanishes for all nuclei; (iii) When the DM particle couples only to protons or neutrons but not to both; (iv) When the ratio between the coupling to the proton and to the neutron is the same for the DM particle and the antiparticle.

IV. APPLICATION

Let us now go beyond the simplified framework introduced above and consider a more realistic setup. First of all, the scattering cross sections can only be measured up to a certain accuracy ($\Delta\sigma$). Thus, $\tilde{\sigma}_X$ in Eq. (5) should be replaced by $\tilde{\sigma}_X \pm \Delta\tilde{\sigma}_X$, with the result that the straight-line solutions actually consists of bands of finite width, and the intersecting points become overlapping regions. Clearly, the larger the uncertainty in the cross sections the more difficult it will be to distinguish Dirac from Majorana DM. Regarding the expected uncertainty on the determination of the cross sections, several previous works have already estimated its size under different conditions [20,21]. An accuracy of order 10% seems to be achievable for the fiducial astrophysical setup [20] and a light DM particle, $M_\chi \lesssim 100$ GeV. To simplify the analysis, throughout the rest of the paper the DM mass is set to 100 GeV, and the accuracy in the determination of the cross sections is taken to be the same for all targets.

Second, the targets used in DM detection experiments often include multiple isotopes of the same element. Xenon, Germanium and Silicon, for example, consist of 7, 5, and 3 different isotopes with abundances larger than 1%, respectively (see e.g. [22]). For nuclei with multiple isotopes, the event rate is thus modified to $R = \sum_i \eta_i \sigma_{X_i} I_{X_i} \approx I_X \sum_i \eta_i \sigma_{X_i}$, where the sum is over isotopes X_i with fractional abundance η_i, and, in the last step, we used the fact that the I_{X_i} do not vary much for different i. The cross sections discussed in the previous section should, therefore, be replaced by the weighted sum over the multiple isotopes for a given target: $\sigma_X \to \sum_i \eta_i \sigma_{X_i}$. The left-hand side of Eq. (5), for instance, becomes a sum of several terms, and the solution no longer consists of two parallel lines (or bands) but rather of elongated ellipses.

Finally, we also need to ensure that the resulting cross sections are consistent with current data and that they lie, in a broad sense, within the sensitivity that could be reached by future experiments. Our task is then to find a set of three nuclei and given values for $\{\lambda_p^D, \lambda_p^{\bar{D}}, \lambda_n^D, \lambda_n^{\bar{D}}\}$ such that, under these conditions, an interpretation of the expected spin-independent signals in terms of Majorana DM can be excluded.

Let us take $\{\mathrm{Xe}, \mathrm{Ar}, \mathrm{Si}\}$ as our set of three nuclei where spin-independent signals are assumed to have been observed. Xenon not only sets the strongest limits on the spin-independent direct detection cross section [18,19] at high DM masses, but it is also the target of choice for a new generation of experiments that are currently taking data [23] or are expected to run in the near future [24]. Argon was used by the DarkSide experiment [25] and features in some ongoing projects aiming at ton-scale detectors [26,27]. The choice of Silicon as the third nucleus is motivated by having a ratio $Z/(A-Z)$ close to 1–significantly larger than for Xe and Ar–and by the fact that it was previously used by the CDMS collaboration as a DM target [28]. Figure 2 shows, for a specific parameter point, the regions in the plane $(\lambda_p^M, \lambda_n^M)$ that are consistent with each observation: Xe (red), Ar (blue) and Si (green).

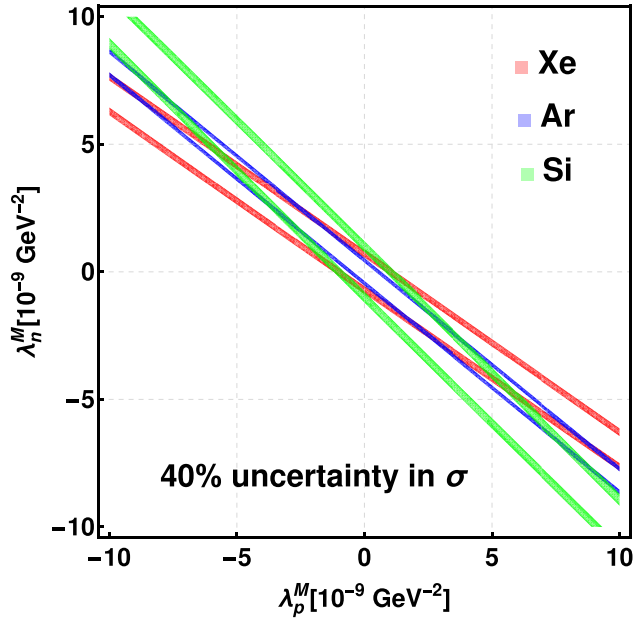

FIG. 2. The regions in the plane $(\lambda_p^M, \lambda_n^M)$ consistent with a Majorana interpretation of the signals expected in three different targets: Xe (red), Ar (blue) and Si (green). Since these regions do not overlap, a Majorana DM particle can be excluded. The width of the bands is the result of a 40% uncertainty assumed in the determination of the cross sections with the nuclei. The assumed signal is due to a Dirac DM particle of 100 GeV mass and couplings $\{\lambda_p^D, \lambda_p^{\bar{D}}, \lambda_n^D, \lambda_n^{\bar{D}}\} = \{6.7, 2.0, -5.6, -1.0\} \times 10^{-9}\ \mathrm{GeV}^{-2}$, which, if one assumes isospin conservation (as is usually done when presenting experimental limits), corresponds to dark matter-nucleon cross sections of [22] $\{0.9, 0.3, 1\} \times 10^{-10}$ pb, respectively, for $\{\mathrm{Xe}, \mathrm{Ar}, \mathrm{Si}\}$.

The width of the bands is set by a 40% uncertainty assumed in the determination of the cross sections. Even though they look like straight lines, the consistent regions for Xe and Si are actually ellipses that extend up to $|\lambda_{p,n}^M| \sim 40 \times 10^{-9}\ \mathrm{GeV}^{-2}$. As expected, the slopes of the bands are determined by the ratio $Z/(A-Z)$. We verified numerically, and it can also be directly seen in the figure, that these three regions never overlap. Consequently, the DM has to be a Dirac particle.

Summarizing, we have shown, for the first time, not only that it is possible to experimentally differentiate between Majorana and Dirac DM but also that it can be achieved with just direct detection data.

V. DETAILED ANALYSIS

To get a better sense of how feasible it is to distinguish Dirac from Majorana DM using the test described above, we now generalize our previous discussion in two ways. First, we consider, in addition to $\{\mathrm{Xe}, \mathrm{Ar}, \mathrm{Si}\}$, a second set of three nuclei: $\{\mathrm{Xe}, \mathrm{Ar}, \mathrm{Ge}\}$. Germanium detectors currently provide the most stringent constraints on the scattering cross section at low DM masses [29,30], and prominently feature in the EURECA project [31]. The complementarity of $\{\mathrm{Xe}, \mathrm{Ar}, \mathrm{Ge}\}$, in fact, has been considered in previous works [20,32–34]. Regarding the discrimination between Dirac and Majorana DM, a disadvantage of Ge is that its ratio $Z/(A-Z)$ is not that different from that of Xe and Ar. In any case, using this second set should give us an idea of how our results depend on the target nuclei. Second, we study the full parameter space relevant for spin-independent direct detection searches, which consists of $\lambda_p^D, \lambda_n^D, \lambda_p^{\bar{D}}, \lambda_n^{\bar{D}}$. After randomly scanning this parameter space we computed the DM cross sections off $\{\mathrm{Xe}, \mathrm{Ar}, \mathrm{Si}(\mathrm{Ge})\}$ and the uncertainty required to exclude a Majorana DM particle. The resulting sample of models is shown, projected onto the plane $(|\lambda_n^D/\lambda_p^D|, |\lambda_n^{\bar{D}}/\lambda_p^{\bar{D}}|)$, in figure 3, enforcing an accuracy larger than 0.1%. The top and bottom panel correspond respectively to the results for the target set $\{\mathrm{Xe}, \mathrm{Ar}, \mathrm{Si}\}$ and $\{\mathrm{Xe}, \mathrm{Ar}, \mathrm{Ge}\}$, whereas the colors indicate the maximum allowed uncertainty (M.U.) in the determination of the

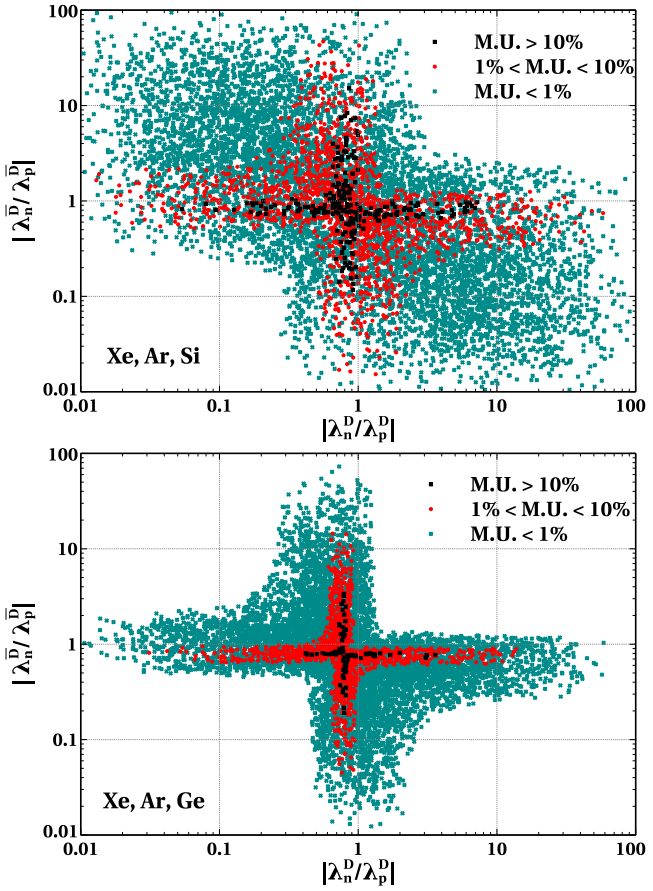

FIG. 3. Scatter plots of λ_n^D/λ_p^D versus $\lambda_n^{\bar{D}}/\lambda_p^{\bar{D}}$ for our sample of points for Xe, Ar, Si and Xe, Ar, Ge target sets. The color code indicates the maximum allowed uncertainty (M.U.) in the measurement of the cross sections that enables to distinguish Dirac from Majorana DM: dark cyan for points with M.U. $< 1\%$, red for points with $1\% <$ M.U. $< 10\%$, and black for points featuring M.U. $> 10\%$.

cross sections that enables to distinguish Dirac from Majorana DM: dark cyan for points with M.U. $< 1\%$, red for points with $1\% <$ M.U. $< 10\%$, and black for points featuring M.U. $> 10\%$. Notice, in particular, that the black points–the most interesting ones–lie just below the line $|\lambda_n^D/\lambda_p^D| = 1$ or $|\lambda_n^{\bar{D}}/\lambda_p^{\bar{D}}| = 1$. All such points turn out to fulfill $\lambda_n^D/\lambda_p^D < 0$ or $\lambda_n^{\bar{D}}/\lambda_p^{\bar{D}} < 0$. That is, they all feature a relative minus sign, and therefore a partial cancellation, between the neutron and the proton contributions to the cross section for either the DM particle or the antiparticle.

In our scans we found no points with a maximum allowed uncertainty larger than 60% for the set including Si and 20% for the set including Ge. These results suggest that future experiments should at least reach that level of precision to be able to differentiate Dirac from Majorana DM, and that the target set $\{\mathrm{Xe}, \mathrm{Ar}, \mathrm{Si}\}$ offers better prospects in this regard.

VI. SCALAR AND VECTOR DARK MATTER

Our results so far are valid if the DM particle is a fermion but they can be straightforwardly generalized to scalar and vector DM. If the DM particle is a scalar field (ϕ_χ), the effective Lagrangian describing its spin-independent interactions with nucleons is written as

$$\mathcal{L}_{\mathrm{SI}}^S = 2\lambda_{N,e} M_\chi \phi_\chi^\dagger \phi_\chi \bar{\psi}_N \psi_N + i\lambda_{N,o}[\phi_\chi^\dagger(\partial_\mu \phi_\chi) - (\partial_\mu \phi_\chi^\dagger)\phi_\chi]\bar{\psi}_N \gamma^\mu \psi_N, \quad (8)$$

with $\lambda_{N,o} = 0$ for a real scalar. The spin-independent cross sections are given by the same expression as the Majorana (real scalar) and Dirac (complex scalar) cases–Eqs. (2) and (3). Hence, it is possible to differentiate real scalar DM from complex scalar DM in exactly the way already explained for fermion DM.

For vector DM, the situation is entirely analogous–see e.g. [13] for the relevant Lagrangian. Putting together the results for fermion DM with the generalization to scalar and vector DM just discussed, it can be concluded that the test can potentially tell the DM particle apart from its antiparticle.

VII. OUTLOOK AND CONCLUSIONS

Once direct detection signals are observed, a joint likelihood analysis would be required to combine the data from the different experiments, to properly include all the relevant uncertainties, and to assign a precise statistical meaning to the exclusion of a self-conjugate dark matter particle. In addition, a more comprehensive list of possible effective operators [35] could be included in the analysis.

We have proposed a test that may determine if the DM particle is different from its antiparticle. The minimum requirement to be able to do so was found to be the precise measurement of the DM spin-independent scattering cross section with three different nuclei. The test consists in checking the consistency of these measurements with their interpretation in terms of Majorana or real dark matter. If an inconsistency is found, the DM should be, within the straightforward assumtions we make, a Dirac or complex particle. As an illustration, we considered the target sets $\{\mathrm{Xe}, \mathrm{Ar}, \mathrm{Si}\}$ and $\{\mathrm{Xe}, \mathrm{Ar}, \mathrm{Ge}\}$, and showed that, provided the scattering cross sections are determined with a precision better than 60% and 20% respectively, there exist parameter space points for which the Dirac or complex nature of the DM particle can be established. Our results suggest that the observation of spin-independent signals in future direct detection experiments might be used to elucidate the fundamental nature of the dark matter particle.

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[1] P. A. R. Ade *et al.*, Planck 2015 results. XIII. Cosmological parameters, Astron. Astrophys. **594**, A13 (2016).
[2] G. Bertone, D. Hooper, and J. Silk, Particle dark matter: Evidence, candidates and constraints, Phys. Rep. **405**, 279 (2005).
[3] J. Silk *et al.*, Particle Dark Matter: Observations, Models and Searches (Cambridge University Press, Cambridge, 2010).
[4] G. Jungman, M. Kamionkowski, and K. Griest, Supersymmetric dark matter, Phys. Rep. **267**, 195 (1996).
[5] J. R. Primack, D. Seckel, and B. Sadoulet, Detection of cosmic dark matter, Annu. Rev. Nucl. Part. Sci. **38**, 751 (1988).
[6] V. Silveira and A. Zee, Scalar phantoms, Phys. Lett. B **161**, 136 (1985).
[7] C. Arina and N. Fornengo, Sneutrino cold dark matter, a new analysis: Relic abundance and detection rates, J. High Energy Phys. 11 (2007) 029.
[8] G. Servant and T. M. P. Tait, Is the lightest Kaluza-Klein particle a viable dark matter candidate?, Nucl. Phys. **B650**, 391 (2003).

[9] T. Hambye, Hidden vector dark matter, J. High Energy Phys. 01 (2009) 028.
[10] G. Belanger, A. Pukhov, and G. Servant, Dirac neutrino dark matter, J. Cosmol. Astropart. Phys., 01 (2008) 009.
[11] K. R. Dienes and B. Thomas, Dynamical dark matter: I. Theoretical overview, Phys. Rev. D **85**, 083523 (2012).
[12] S. Profumo, K. Sigurdson, and L. Ubaldi, Can we discover multi-component WIMP dark matter?, J. Cosmol. Astropart. Phys. 12 (2009) 016.
[13] G. Belanger, F. Boudjema, A. Pukhov, and A. Semenov, Dark matter direct detection rate in a generic model with micrOMEGAs 2.2., Comput. Phys. Commun. **180**, 747 (2009).
[14] G. Duda, A. Kemper, and P. Gondolo, Model independent form factors for spin independent neutralino-nucleon scattering from elastic electron scattering data, J. Cosmol. Astropart. Phys. 04 (2007) 012.
[15] C. Kelso, C. Savage, M. Valluri, K. Freese, G. S. Stinson, and J. Bailin, The impact of baryons on the direct detection of dark matter, J. Cosmol. Astropart. Phys. 08 (2016) 071.
[16] J. D. Sloane, M. R. Buckley, A. M. Brooks, and F. Governato, Assessing astrophysical uncertainties in direct detection with galaxy simulations (2016).
[17] N. Bozorgnia, F. Calore, M. Schaller, M. Lovell, G. Bertone, C. S. Frenk, R. A. Crain, J. F. Navarro, J. Schaye, and T. Theuns, Simulated Milky Way analogues: Implications for dark matter direct searches, J. Cosmol. Astropart. Phys. 05 (2016) 024.
[18] E. Aprile *et al.*, Dark Matter Results from 225 Live Days of XENON100 Data, Phys. Rev. Lett. **109**, 181301 (2012).
[19] D. S. Akerib *et al.*, Results from a Search for Dark Matter in the Complete LUX Exposure, Phys. Rev. Lett. **118**, 021303 (2016).
[20] M. Pato, L. Baudis, G. Bertone, R. R. de Austri, L. E. Strigari, and R. Trotta, Complementarity of dark matter direct detection targets, Phys. Rev. D **83**, 083505 (2011).
[21] L. Roszkowski, E. Maria Sessolo, S. Trojanowski, and A. J. Williams, Reconstructing WIMP properties through an interplay of signal measurements in direct detection, Fermi-LAT, and CTA searches for dark matter, J. Cosmol. Astropart. Phys. 08 (2016) 033.
[22] J. L. Feng, J. Kumar, D. Marfatia, and D. Sanford, Isospin-violating dark matter, Phys. Lett. B **703**, 124 (2011).
[23] E. Aprile, The XENON1T Dark Matter Search Experiment (Springer, Dordrecht, 2012), Vol. 148, p. 93.
[24] T. Marrodán Undagoitia and L. Rauch, Dark matter direct-detection experiments, J. Phys. G **43**, 013001 (2016).
[25] P. Agnes *et al.*, First results from the DarkSide-50 dark matter experiment at Laboratori Nazionali del Gran Sasso, Phys. Lett. B **743**, 456 (2015).
[26] C. E. Aalseth *et al.*, The DarkSide Multiton Detector for the direct dark matter search, Adv. High Energy Phys. 15 (**2015**) 541362.
[27] J. Calvo *et al.*, Status of ArDM-1t: First observations from operation with a full ton-scale liquid argon target, arXiv:1505.02443.
[28] R. Agnese *et al.*, Silicon Detector Dark Matter Results from the Final Exposure of CDMS II, Phys. Rev. Lett. **111**, 251301 (2013).
[29] R. Agnese *et al.*, Search for Low-Mass Weakly Interacting Massive Particles with SuperCDMS, Phys. Rev. Lett. **112**, 241302 (2014).
[30] R. Agnese *et al.*, New Results from the Search for Low-Mass Weakly Interacting Massive Particles with the CDMS Low Ionization Threshold Experiment, Phys. Rev. Lett. **116**, 071301 (2016).
[31] G. Angloher *et al.*, EURECA Conceptual Design Report, Phys. Dark Univ. **3**, 41 (2014).
[32] M. Pato, What can(not) be measured with ton-scale dark matter direct detection experiments, J. Cosmol. Astropart. Phys. 10 (2011) 035.
[33] S. D. McDermott, H.-B. Yu, and K. M. Zurek, The dark matter inverse problem: Extracting particle physics from scattering events, Phys. Rev. D **85**, 123507 (2012).
[34] B. J. Kavanagh, M. Fornasa, and A. M. Green, Probing WIMP particle physics and astrophysics with direct detection and neutrino telescope data, Phys. Rev. D **91**, 103533 (2015).
[35] A. Liam Fitzpatrick, W. Haxton, E. Katz, N. Lubbers, and Y. Xu, The effective field theory of dark matter direct detection, J. Cosmol. Astropart. Phys. 02 (2013) 004.