Nuclear target effect on dark matter detection rate

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Expected event rates for a number of dark matter nuclear targets were calculated in the effective low-energy minimal supersymmetric standard model, provided the lightest neutralino is the dark matter Weakly Interacting Massive Particle (WIMP). These calculations allow direct comparison of sensitivities of different dark matter detectors to intermediate mass WIMPs expected from the measurements of the DArk MAtter (DAMA) experiment.

I. INTRODUCTION

Weakly Interacting Massive Particles (WIMPs) are among the most popular candidates for the relic cold dark matter (DM). There is some revival of interest to the WIMP-nucleus spin-dependent interaction from both theoretical (see e.g. [1, 2, 3, 6, 7, 8, 9]) and experimental (see e.g. [10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20]) points of view. There are some proposals aimed at direct DM detection with relatively low-mass isotope targets [10, 11, 12, 13, 14, 15] as well as some first attempts to design and construct a DM detector which is sensitive to the nuclear recoil direction [21, 22, 23, 24, 25, 26, 27]. Kinematically, low-mass targets make preference for the low-mass WIMPs (due to $M_{\text{Target}} \approx M_{\text{WIMP}}$) and are more sensitive to the spin-dependent WIMP-nucleus interaction as well [1, 2, 3, 7, 28, 29, 30]. On the other hand, WIMPs with masses about 100 GeV/c$^2$ follow from the results of the DArk MAtter (DAMA) experiment. This collaboration claimed observation of the first evidence for the dark matter signal due to registration of the annual modulation effect [31, 32, 33]. Aimed for more than one decade at the DM particle direct detection, the DAMA experiment with 100-kg highly radio-pure NaI(Tl) scintillator detectors successfully operated till July 2002 at the Gran Sasso National Laboratory of the I.N.F.N. On the basis of the results obtained for over 7 annual cycles (107731 kg-day total exposure) the effectiveness of the WIMP model-independent annual modulation signature was demonstrated and the WIMP presence in the galactic halo is strongly supported at 6.3 $\sigma$ C.L. [32]. The main result of the DAMA observation of the annual modulation signature is the low-mass region of the WIMPs ($40 < M_{\text{WIMP}} < 150$ GeV/c$^2$), provided these WIMPs are cold dark matter particles. It is obvious that such a serious claim should be verified by other independent measurements. To reliably confirm or reject the DAMA
II. EVENT RATES AND EFFECTIVE LOW-ENERGY MSSM

A dark matter event is an elastic scattering of a relic WIMP $\chi$ from a target nucleus $A$ producing a nuclear recoil $E_R$ which can be detected by a suitable detector. The differential event rate in respect to the recoil energy is the subject of experimental measurements. The rate depends on the distribution of the WIMPs in the solar vicinity $f(v)$ and the cross section of WIMP-nucleus elastic scattering [28, 30, 32, 35, 36, 37, 38, 39, 40, 41]. The differential event rate per unit mass of the target material can be given as a sum of spin-dependent (SD) and spin-independent (SI) contributions, parameterized via spin-independent ($\sigma_{SI}$) and spin-dependent ($\sigma_{SD}$) WIMP-nucleon interaction cross sections [32, 34]:

$$\frac{dR(E_R)}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \int_{v_{\text{min}}}^{v_{\text{max}}} dv f(v) v \frac{d\sigma}{dq^2}(v, q^2) = \kappa_{SI}(E_R, m_\chi) \sigma_{SI} + \kappa_{SD}(E_R, m_\chi) \sigma_{SD}. \quad (1)$$

The nuclear recoil energy $E_R = q^2/(2M_A)$ is typically about $10^{-6}m_\chi$. The number of nuclei per unit of target mass is $N_T$ and $M_A$ is the target nucleus mass. The effective spin WIMP-nucleon cross section $\sigma_{SD}$ and the coupling mixing angle $\theta$ were introduced [32, 42] in such a way that SD WIMP-proton and SD WIMP-neutron interaction cross sections have the form $\sigma_{SD}^p = \sigma_{SD} \cdot \cos^2 \theta$, and $\sigma_{SD}^n = \sigma_{SD} \cdot \sin^2 \theta$. Further notations are:

$$\kappa_{SI}(E_R, m_\chi) = N_T \frac{\rho_\chi M_A}{2m_\chi \mu_p^2} B_{SI}(E_R) \left[ M_A^2 \right],$$

$$\kappa_{SD}(E_R, m_\chi) = N_T \frac{\rho_\chi M_A}{2m_\chi \mu_p^2} B_{SD}(E_R) \left[ \frac{4J+1}{J} \left( \langle S_p \rangle \cos \theta + \langle S_n \rangle \sin \theta \right)^2 \right], \quad (2)$$

$$B_{SI,SD}(E_R) = \frac{\langle v \rangle}{\langle v^2 \rangle} F_{SI,SD}^2(E_R) I(E_R).$$

Here $\langle S_p(n) \rangle$ is the spin of the proton (neutron) averaged over all nucleons in the nucleus $A$. The dimensionless integral $I(E_R)$ is dark-matter-particle velocity distribution correction, which result an experiment should have the same or better sensitivity to the annual modulation signal. At the same time one should know an expected rate in his own detector, provided the DAMA result is correct. Motivated by the DAMA evidence predictions for the direct DM detection rate in a Ge-73 detector within the framework of the so-called effective low-energy minimal supersymmetric standard model (effMSSM) are given in [34]. Here the analysis of [34] is extended and the expected WIMP detection rates are recalculated in the effMSSM for other DM-interesting isotope targets on the basis of the data base from [34]. Similar expectations are obtained as well by means of direct recalculations of the DAMA constraints [32] into detection rates for other targets. This allows one to estimate the prospects to confirm or to reject the DAMA result by other DM search experiments.
reduces the rate for large enough momentum transfer:

\[ I(E_R) = \frac{\langle v^2 \rangle}{\langle v \rangle} \int_{x_{\text{min}}} f(x) dx = \frac{\sqrt{\pi}}{2 \sqrt{\pi(1 + 2 \eta^2)}} \text{erf}(\eta) + 2 \eta e^{-\eta^2}[\text{erf}(x_{\text{min}} + \eta) - \text{erf}(x_{\text{min}} - \eta)], \]

where we assume that in our Galaxy rest frame WIMPs have the Maxwell-Boltzmann velocity distribution and use the dimensionless Earth speed with respect to the halo \( \eta = 1 \), \( x_{\text{min}}^2 = \frac{3}{4} \frac{M_A E_R}{\mu_A^2 v^2} \), \( \mu_A = \frac{m_\chi M_A}{m_\chi + M_A} \). The error function is \( \text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x dt e^{-t^2} \). The velocity variable is the dispersion \( \bar{v} \approx 270 \text{ km/c} \). The mean WIMP velocity \( \langle v \rangle = \sqrt{\frac{2}{3} \bar{v}} \). For the WIMP mass density in our Galaxy the value \( \rho_\chi = 0.3 \text{ GeV/cm}^3 \) is used. We also assume both form-factors \( F_{\text{SI,SD}}^2(E_R) \) in the simplest Gaussian form following [43, 44]. In particular, this allows rather simple formulas to be used, which are suitable for our comparative consideration. The total direct detection rate \( R(\epsilon, \varepsilon) \) can be obtained by integrating differential rate (1) over the recoil energy interval from the threshold energy \( \epsilon \) to the maximal energy \( \varepsilon \). To accurately estimate the event rate \( R(\epsilon, \varepsilon) \) one needs to know a number of quite uncertain astrophysical and nuclear structure parameters as well as the very specific characteristics of an experimental setup (see, for example, discussions in [32, 45]). In this paper it is enough to assume these uncertainties to be almost the same for all target materials considered. Furthermore, one should calculate cross sections \( \sigma_{\text{SD}} \) and \( \sigma_{\text{SI}} \) within the framework of, for example, some SUSY-based theory or take them from experimental data. In [34] both \( \sigma_{\text{SD}} \) and \( \sigma_{\text{SI}} \) have already been calculated within a phenomenological SUSY model whose parameters are defined directly at the electroweak scale (see e.g. [3, 4, 5, 30, 38, 39, 46, 47, 48, 49, 50, 51, 52, 53]). This effective scheme of the MSSM is called the effMSSM in [35], and later the low-energy effective supersymmetric theory (LEEST) in [54, 55]. The effMSSM parameter space is determined by entries of the mass matrices of neutralinos, charginos, Higgs bosons, sleptons and squarks. The list of free parameters includes \( \tan \beta \), the ratio of neutral Higgs boson vacuum expectation values; \( \mu \), the bilinear Higgs parameter of the superpotential; \( M_{1,2} \), soft gaugino masses; \( M_A \), the CP-odd Higgs mass; \( m_{\tilde{Q}}^2, m_{\tilde{U}}^2, m_{\tilde{D}}^2 \) (\( m_{\tilde{L}}^2, m_{\tilde{E}}^2 \)), squark (slepton) mass parameters squared for the 1st and 2nd generation; \( m_{\tilde{Q}_3}^2, m_{\tilde{T}}^2, m_{\tilde{B}}^2 \) (\( m_{L_3}^2, m_{\tau}^2 \)), squark (slepton) mass parameters squared for the 3rd generation; \( A_t, A_b, A_\tau \), soft trilinear couplings for the 3rd generation. The third gaugino mass parameter \( M_3 \) defines the mass of the gluino in the model and is determined by means of the GUT assumption \( M_2 = 0.3 M_3 \). The intervals of the randomly scanned MSSM parameter space in [34] were narrowed to fit the DAMA-inspired domain of the lower masses of the LSP (\( m_\chi < 200 \text{ GeV} \)). The current experimental upper limits on sparticle and Higgs masses from the Particle Data Group as well as the limits on the rare \( b \to s\gamma \) decay have been imposed. For each point in the MSSM parameter space (MSSM model) the relic density of the light
neutralinos $\Omega \chi h^2$ was evaluated with the code [47, 48, 49] based on DarkSUSY [56] with the allowance for all coannihilation channels with two-body final states that can occur between neutralinos, charginos, sleptons, stops and sbottoms as long as their masses are $m_i < 2m_\chi$.

Two cosmologically interesting regions are considered in [34]. One is $0.1 < \Omega \chi h^2 < 0.3$ and the other is the WMAP-inspired region $0.094 < \Omega \chi h^2 < 0.129$ [57, 58]. Further details can be found in [34].

III. RESULTS AND DISCUSSION

A. Calculations in effMSSM

Integrating the differential rate (1) from the recoil energy threshold $\epsilon$ to some maximal energy $\varepsilon$ one obtains the total detection rate $R(\epsilon, \varepsilon)$ as a sum of the SD and SI terms:

$$R(\epsilon, \varepsilon) = R_{\text{SI}}(\epsilon, \varepsilon) + R_{\text{SD}}(\epsilon, \varepsilon) = \int_{\epsilon}^{\varepsilon} dE R_{\kappa_{\text{SI}}}(E, m_\chi) \sigma_{\text{SI}} + \int_{\epsilon}^{\varepsilon} dE R_{\kappa_{\text{SD}}}(E, m_\chi) \sigma_{\text{SD}}. \quad (3)$$

In [34] estimations of the ideal total expected rate $R(0, \text{inf})$ for WIMPs with $M_{\text{WIMP}} < 200 \text{ GeV}/c^2$ in a $^{73}\text{Ge}$ detector are obtained within the effMSSM. Here, with $\sigma_{\text{SD}}$ and $\sigma_{\text{SI}}$ already calculated in [34], new estimates of the integrated event rate $R(\epsilon, \varepsilon)$ for WIMP masses smaller than 200 GeV/c$^2$ are obtained for a number of DM targets. For definiteness, the recoil energy threshold $\epsilon = 5 \text{ KeV}$ (and sometimes $\epsilon = 10 \text{ KeV}$) with the maximal energy $\varepsilon = 50 \text{ keV}$ are used.

The calculated event rates $R(5, 50)$ and the rate ratios for different targets are depicted as scatter plots in Figs. [1] [8]. For example, in Fig. [1] one can see total, $R(5, 50)$, spin-independent, $R(5, 50)_{\text{SI}}$ and spin-dependent $R(5, 50)_{\text{SD}}$ event rates expected in $^{73}\text{Ge}$-target together with their ratio $R(5, 50)_{\text{SD}}/R(5, 50)_{\text{SI}}$ as functions of the WIMP mass. It is always interesting to trace some interplay between SD and SI contributions to the total event rate. To this end correlations between the total rate $R(5, 50)$ and its SD fraction as well as correlations between the total rate $R(5, 50)$ and the SD-to-SI ratio $R(5, 50)_{\text{SD}}/R(5, 50)_{\text{SI}}$ are also given in Fig. [1]. All open symbols in the figures correspond to the case when the WMAP constraint on the relic neutralino density $0.094 < \Omega \chi h^2 < 0.129$ is taken into account. The relevant filled symbols show the rates which one would expect if an extra DAMA constraint, $1 \cdot 10^{-7} \text{ pb} < \sigma_{\text{SI}} < 3 \cdot 10^{-5} \text{ pb}$, is imposed on SI cross sections. It is seen that in the last case (filled symbols) the SI rates are at least two orders of magnitude larger than the SD one and the large total rate values ($R > 0.01 \text{ events/day/kg}$) are saturated only by the SI interactions. If one ignores these filled symbols (i.e. the DAMA-inspired extra constraint $1 \cdot 10^{-7} \text{ pb} < \sigma_{\text{SI}} < 3 \cdot 10^{-5} \text{ pb}$), then the
FIG. 1: Expected in $^{73}\text{Ge}$ total $R(5, 50)$, SI and SD event rates $R(5, 50)_{\text{SI}}$ and $R(5, 50)_{\text{SD}}$ (upper panel) as well as the ratio $R(5, 50)_{\text{SD}}/R(5, 50)_{\text{SI}}$ (lower left panel) as functions of WIMP mass. Correlations between the total rate $R(5, 50)$ and the SD fraction in $R(5, 50)$ is given in the lower middle panel. Correlations between the total rate $R(5, 50)$ and the ratio $R(5, 50)_{\text{SD}}/R(5, 50)_{\text{SI}}$ is given in the lower right panel. Open symbols correspond to the WMAP constraint $0.094 < \Omega h^2 < 0.129$. Closed symbols give rates with an extra DAMA constraint $1 \cdot 10^{-7} \text{ pb} < \sigma_{\text{SI}}^p < 3 \cdot 10^{-5} \text{ pb}.

FIG. 2: The same as in Fig. 1 but for CF$_4$. 
SD contribution does not look very suppressed and the SD contribution alone can saturate the total event rate, but only when the rate itself is rather small ($R \approx 0.001\text{ events/day/kg}$). These features take place for all heavy enough targets, therefore the corresponding figures for NaI, CsI, and Xe target are not given.

It is well known that a fluorine-containing target is the best one for detection and measurement of the spin-dependent WIMP-nucleus interaction (see e.g. [28, 29]). Figure 2 shows that the SD rate in CF$_4$ is indeed the biggest one and for a large number of points (MSSM models) the SD contribution dominates. Nevertheless it is also seen that it is not correct to completely ignore the SI contribution to the total expected rate in the fluorine target [8, 34] because the SI rate is almost the same as the SD one. Furthermore, at a current level of the DM detector sensitivity, when the DAMA-inspired large SI contributions are not yet completely excluded (filled symbols in Fig. 2), the SD contribution in CF$_4$, $R(5,50)_{\text{SD}}$, is smaller than the SI one, $R(5,50)_{\text{SI}}$. The ratios of the total, SI and SD rates in the CF$_4$ and $^{73}$Ge targets are presented in Fig. 3 as a function of WIMP mass.

*FIG. 3: Ratios $R(5,50)_{\text{CF}_4}/R(5,50)_{^{73}\text{Ge}}$ of the total (top panel), SI (middle) and SD (bottom) rate as functions of WIMP mass. No relic density constraint is imposed in the left column. Open symbols in the right column correspond to the WMAP constraint $0.094 < \Omega h^2 < 0.129$. Filled symbols give these ratios for the rates obtained with an extra DAMA SI constraint, $1 \cdot 10^{-7}$ pb $< \sigma_{\text{SI}}^p < 3 \cdot 10^{-5}$ pb.*
FIG. 4: Expected in the CH$_4$ target the total $R(5, 50)$, SI and SD event rates $R(5, 50)_{\text{SI}}$ and $R(5, 50)_{\text{SD}}$ (upper panel) as well as the ratio $R(5, 50)_{\text{SD}}/R(5, 50)_{\text{SI}}$ (lower left panel) as functions of WIMP mass. Correlations between the total rate $R(5, 50)$ and the SD fraction in $R(5, 50)$ is given in the lower middle panel. Correlations between the total rate $R(5, 50)$ and the ratio $R(5, 50)_{\text{SD}}/R(5, 50)_{\text{SI}}$ is given in the lower right panel. Open symbols correspond to the WMAP constraint $0.094 < \Omega h^2 < 0.129$. Closed symbols give rates with an extra DAMA SI constraint, $1 \cdot 10^{-7}$ pb $< \sigma_{\text{SI}}^p < 3 \cdot 10^{-5}$ pb.

FIG. 5: The same as in Fig. 4 but for $^3$He.
on the relic density of neutralinos in the effMSSM. The increase of these ratios at very low WIMP masses reflects better sensitivity of fluorine to smaller WIMP masses than that of germanium. Open symbols in the right panel of Fig. 3 depict these ratios when the WMAP constraint \(0.094 < \Omega \chi h^2 < 0.129\) is imposed on the calculated neutralino relic density. Filled symbols give these ratios for the rates obtained with an extra DAMA SI constraint, \(1 \cdot 10^{-7} \text{ pb} < \sigma_{\text{SI}} < 3 \cdot 10^{-5} \text{ pb}\). The sensitivity of CF\(_4\) to the SD WIMP interaction is about ten times as large as the SD sensitivity of \(^{73}\text{Ge}\). At the same time, the CF\(_4\) sensitivity to the SI WIMP interaction is less than 0.1–0.05 of the SI sensitivity of \(^{73}\text{Ge}\). As a result, the total expected rate in \(^{73}\text{Ge}\) is a bit larger than in a very spin-sensitive CF\(_4\) target. The right panel in Fig. 3 shows that the relic density WMAP and extra DAMA constraints make this conclusion stricter. The expected total rate in a heavy enough \(^{73}\text{Ge}\) target is about ten times as large as the total expected rate in the CF\(_4\) target.

FIG. 6: Ratios \(R(5,50)_{^{3}\text{He}}/R(5,50)_{^{73}\text{Ge}}\) of the total (top panel), SI (middle) and SD (bottom) rate as functions of WIMP mass. No relic density constraint is imposed in the left column. Open symbols in the right column correspond to the WMAP constraint \(0.094 < \Omega \chi h^2 < 0.129\). Filled symbols give these ratios for rates obtained with an extra DAMA SI constraint, \(1 \cdot 10^{-7} \text{ pb} < \sigma_{\text{SI}} < 3 \cdot 10^{-5} \text{ pb}\).

Figures 4 and 5 show the total, SD and SI expected event rates in the CH\(_4\) and \(^3\text{He}\) targets which contain the lightest nonzero-spin nuclei, interesting for direct DM search. Absolute values of the total, SD, and SI rates in these materials are visibly smaller than in the fluorine-containing CF\(_4\) and germanium targets (Figs. 4-7), especially when the extra WMAP (left
FIG. 7: Ratios $R(5, 50)^{CH_4}/R(5, 50)^{73Ge}$ of the total (top panel), SI (middle) and SD (bottom) rate as functions of WIMP mass. No relic density constraint is imposed in the left column. Open symbols in the right column correspond to the WMAP constraint $0.09 < \Omega h^2 < 0.129$. Filled symbols give these ratios for rates obtained with an extra DAMA SI constraint, $1 \cdot 10^{-7}$ pb $< \sigma^p_{SI} < 3 \cdot 10^{-5}$ pb.

FIG. 8: The same as in Fig. 7 but for NaI and $^{73}$Ge.
panel) and DAMA (filled symbols) constraints are imposed.

For all detectors with heavy enough target mass (NaI, CsI, Xe, etc) the absolute values of the total, SI and SD rates look very similar with the only possible exception in the domain of very low-mass WIMPs (when a target contains some light isotope like, for example, Na in the NaI target). In Figure 8 a set of NaI-to-$^{73}$Ge rate ratios, $R(5,50)_{\text{NaI}}/R(5,50)_{^{73}\text{Ge}}$, is given for illustration of the behavior. All depicted ratios are of the order of unity. Only for very low WIMP masses (less than 10 GeV/$c^2$) and with the WMAP constraint neglected the rates in NaI start to clearly dominate over the rates in $^{73}$Ge due to kinematically preferable WIMP interaction with Na. This low-WIMP-mass growth of the ratios is absent in the CsI and Xe targets. Furthermore, for these materials the rates in $^{73}$Ge dominate in the low-mass WIMP region.

B. Calculations with DAMA constraints

In the previous section the WIMP-nucleon $\sigma_{SD}$ and $\sigma_{SI}$ cross sections which enter event rate were taken from theoretical calculations in the effMSSM[34]. Another source of these cross sections is, for example, the DAMA experiment[32]. With formulas[10–13] the DAMA(NaI) constraints on $\sigma_{SD}$ and $\sigma_{SI}$ from[32] can be phenomenologically transformed into the allowed
FIG. 10: Variations of expected spin-independent contributions to the event rate, $R(5, 50)_{\text{SI}}$, in a number of targets followed from the DAMA-allowed cross sections $\sigma_{\text{SD}}$ and $\sigma_{\text{SI}}$.

FIG. 11: The same as in Fig. 10 but for the spin-dependent contributions $R(5, 50)_{\text{SD}}$.

regions for the detection rates with other targets. The results of these recalculations are given in Figs. 9, 11 for the total, SI and SD expected rates $R(10, 50)$ in a number of representative materials for a DM detector. Here the threshold of 10 keV is used. The values of the expected
rate can vary within the columns without any conflict with the DAMA-allowed $\sigma_{\text{SD}}$ and $\sigma_{\text{SI}}$ regions. The left (right) parts of these figures contain rate restrictions for the odd-neutron (odd-proton) group model nonzero-spin nuclei (see e.g. [4]). Some of the highest rate values, for example in $^{73}\text{Ge}$, are already excluded by measurements [16]. In particular, from Figs. 9–11 one can see that all fluorine-containing targets (LiF, CF$_4$, C$_2$F$_6$ and CaF$_2$, etc) have almost the same sensitivity to the both SD and SI WIMP-nucleus interactions. Among all materials considered a detector with a $^{73}\text{Ge}$, $^{129}\text{Xe}$, or NaI target has better prospects to confirm or to reject the DAMA result due to the largest values of the lower bounds for the total rate ($R(10, 50) > 0.06 - 0.08 \text{ events/day/kg}$). If, for example, one ignores the SI WIMP interaction (Fig. 10), then all materials have almost the same prospects to detect DM particles with the only exception of CH$_4$.

IV. CONCLUSION

Expected event rates for a number of dark matter target materials are calculated in the effective low-energy minimal supersymmetric standard model (effMSSM), provided the lightest neutralino is the dark matter Weakly Interacting Massive Particle (WIMP). The results obtained are based on previous evaluations of the neutralino-proton (neutron) spin and scalar cross sections for the neutralino masses $m_\chi < 200 \text{ GeV/c}^2$ [34]. The performed calculations allow direct comparison of sensitivities of different dark matter setups to the WIMPs expected from the measurements of the DAMA experiment. In particular, it is shown that detectors with a $^{73}\text{Ge}$, $^{129}\text{Xe}$, and NaI target have better prospects to confirm or to reject the DAMA result.

It is worth noting, that to get very accurate predictions for the event rate one has to take into account a number of quite uncertain astrophysical and nuclear parameters and specific features of a real setup. We considered only a simple spherically symmetric isothermal WIMP velocity distribution [59, 60] and do not go into detail of any possible and in principle important uncertainties (and/or modulation effects) of the Galactic halo WIMP distribution [21, 61, 62, 63, 64, 65, 66]. For simplicity we use the Gaussian scalar and spin nuclear form-factors from [44, 67]. We believe it is relevant for our comparative study because the very influence of the factors is suppressed in the rate ratios.

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