SUSY DARK MATTER DETECTION, THE DIRECTIONAL RATE AND THE MODULATION EFFECT

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The detection of the theoretically expected dark matter is central to particle physics and cosmology. Current fashionable supersymmetric models provide a natural dark matter candidate which is the lightest supersymmetric particle (LSP). Such models combined with fairly well understood physics like the quark substructure of the nucleon and the nuclear structure (form factor and/or spin response function), permit the evaluation of the event rate for LSP-nucleus elastic scattering. The thus obtained event rates are, however, very low or even undetectable. So it is imperative to exploit the modulation effect, i.e. the dependence of the event rate on the earth's annual motion. Also it is useful to consider the directional rate, i.e. its dependence on the direction of the recoiling nucleus. In this paper we study such a modulation effect both in non directional and directional experiments. We calculate both the differential and the total rates using both isothermal, symmetric as well as only axially asymmetric, and non isothermal, due to caustic rings, velocity distributions. We find that in the symmetric case the modulation amplitude is small. The same is true for the case of caustic rings. The inclusion of asymmetry, with a realistic enhanced velocity dispersion in the galactocentric direction, yields an enhanced modulation effect, especially in directional experiments.

1 Introduction

In recent years the consideration of exotic dark matter has become necessary in order to close the Universe. Furthermore in order to understand the large scale structure of the universe it has become necessary to consider matter made up of particles which were non-relativistic at the time of freeze out. This is the cold dark matter component (CDM). The COBE data suggest that CDM is at least 60%. On the other hand during the last few years evidence has appeared from two different teams, the High-z Supernova Search Team and the Supernova Cosmology Project, which suggests that the Universe may be dominated by the cosmological constant $\Lambda$. As a matter of fact recent data the situation can be adequately described by a baryonic component $\Omega_B = 0.1$ along with the exotic components $\Omega_{CDM} = 0.3$ and $\Omega_\Lambda = 0.6$. In another analysis Turner gives $\Omega_m = \Omega_{CDM} + \Omega_B = 0.4$. Since the non exotic component cannot exceed 40% of the CDM there is room for the exotic WIMP's (Weakly Interacting Massive Particles). In fact the DAMA experiment has claimed the observation of one signal in
direct detection of a WIMP, which with better statistics has subsequently been interpreted as a modulation signal.

The above developments are in line with particle physics considerations. Thus, in the currently favoured supersymmetric (SUSY) extensions of the standard model, the most natural WIMP candidate is the LSP, i.e. the lightest supersymmetric particle. In the most favoured scenarios the LSP can be simply described as a Majorana fermion, a linear combination of the neutral components of the gauginos and Higgsinos.

Since this particle is expected to be very massive, $m_\chi \geq 30\,\text{GeV}$, and extremely non relativistic with average kinetic energy $T \leq 100\,\text{KeV}$, it can be directly detected mainly via the recoiling of a nucleus $(A,Z)$ in the elastic scattering process:

$$\chi + (A,Z) \rightarrow \chi + (A,Z)^*$$ (1)

($\chi$ denotes the LSP). In order to compute the event rate one needs the following ingredients:

1) An effective Lagrangian at the elementary particle (quark) level obtained in the framework of supersymmetry as described, e.g., in Refs. 1, 14.

2) A procedure in going from the quark to the nucleon level, i.e. a quark model for the nucleon. The results depend crucially on the content of the nucleon in quarks other than $u$ and $d$. This is particularly true for the scalar couplings as well as the isoscalar axial coupling.

3) Compute the relevant nuclear matrix elements using as reliable as possible many body nuclear wave functions. By putting as accurate nuclear physics input as possible, one will be able to constrain the SUSY parameters as much as possible. The situation is a bit simpler in the case of the scalar coupling, in which case one only needs the nuclear form factor.

Since the obtained rates are very low, one would like to be able to exploit the modulation of the event rates due to the earth’s revolution around the sun. To this end one adopts a folding procedure assuming some distribution of velocities for the LSP. One also would like to know the directional rates, by observing the nucleus in a certain direction, which correlate with the motion of the sun around the center of the galaxy and the motion of the Earth.

The calculation of this cross section has become pretty standard. One starts with representative input in the restricted SUSY parameter space as described in the literature. We will adopt a phenomenological procedure taking universal soft SUSY breaking terms at $M_{\text{GUT}}$, i.e., a common mass for all scalar fields $m_0$, a common gaugino mass $M_{1/2}$ and a common trilinear scalar coupling $A_0$, which we put equal to zero (we will discuss later the influence of non-zero $A_0$’s). Our effective theory below $M_{\text{GUT}}$ then depends on the parameters:

$$m_0, \, M_{1/2}, \, \mu_0, \, \alpha_G, \, M_{\text{GUT}}, \, h_t, \, h_b, \, h_\tau, \, \tan \beta,$$
where \( \alpha_G = g_G^2/4\pi \) (\( g_G \) being the GUT gauge coupling constant) and \( h_t, h_b, h_\tau \) are respectively the top, bottom and tau Yukawa coupling constants at \( M_{GUT} \). The values of \( \alpha_G \) and \( M_{GUT} \) are obtained as described in Ref.\textsuperscript{12}. For a specified value of \( \tan \beta \) at \( M_S \), we determine \( h_t \) at \( M_{GUT} \) by fixing the top quark mass at the center of its experimental range, \( m_t(m_t) = 166 \text{GeV} \). The value of \( h_\tau \) at \( M_{GUT} \) is fixed by using the running tau lepton mass at \( m_Z \), \( m_\tau(m_Z) = 1.746 \text{GeV} \). The value of \( h_b \) at \( M_{GUT} \) used is such that:

\[
m_b(m_Z)^{\overline{SM}} = 2.90 \pm 0.14 \text{ GeV}.
\]

after including the SUSY threshold correction. The SUSY parameter space is subject to the following constraints:

1.) The LSP relic abundance will satisfy the cosmological constrain:

\[
0.09 \leq \Omega_{LSP} h^2 \leq 0.22
\]  \hspace{1cm} (2)

2.) The Higgs bound obtained from recent CDF \textsuperscript{28} and LEP2 \textsuperscript{29}, i.e. \( m_h > 113 \text{ GeV} \).

3.) We will limit ourselves to LSP-nucleus cross sections for the scalar coupling, which gives detectable rates

\[
4 \times 10^{-7} \text{ pb} \leq \sigma^{nucleon}_{\text{scalar}} \leq 2 \times 10^{-5} \text{ pb} \]  \hspace{1cm} (3)

We should remember that the event rate does not depend only on the nucleon cross section, but on other parameters also, mainly on the LSP mass and the nucleus used in target. The condition on the nucleon cross section imposes severe constraints on the acceptable parameter space. In particular in our model it restricts \( \tan \beta \) to values \( \tan \beta \approx 50 \). We will not elaborate further on this point, since it has already appeared \textsuperscript{13}.

2 Expressions for Extracting of the Nucleon Cross Section from the Data.

The effective Lagrangian describing the LSP-nucleus cross section can be cast in the form \textsuperscript{14}

\[
L_{\text{eff}} = -\frac{G_F}{\sqrt{2}} \{ (\bar{\chi}_1 \gamma^\lambda \gamma_5 \chi_1) J_\lambda + (\bar{\chi}_1 \chi_1) J \} \]  \hspace{1cm} (4)

where

\[
J_\lambda = \bar{N} \gamma_\lambda (f_0^0 + f_V^1 \tau_3 + f_A^0 \gamma_5 + f_A^1 \gamma_5 \tau_3) N, \quad J = \bar{N} (f_0^0 + f_A^1 \tau_3) N \]  \hspace{1cm} (5)

We have neglected the uninteresting pseudoscalar and tensor currents. Note that, due to the Majorana nature of the LSP, \( \bar{\chi}_1 \gamma^\lambda \chi_1 = 0 \) (identically).
With the above ingredients the differential cross section can be cast in the form

$$d\sigma(u,v) = \frac{du}{2(\mu_r b u)^2} [\bar{\Sigma}_S + \bar{\Sigma}_V \frac{v^2}{c^2}] F^2(u) + \bar{\Sigma}_{spin} F_{11}(u)$$  \hspace{1cm} (6)

$$\bar{\Sigma}_S = \sigma_0 (\frac{\mu_r(A)}{\mu_r(N)})^2 \{ A^2 [ (f_0^0 - f_1^1 A - 2Z) ]^2 \} \simeq \sigma_{p,\chi_0} A^2 (\frac{\mu_r(A)}{\mu_r(N)})^2$$  \hspace{1cm} (7)

$$\bar{\Sigma}_{spin} = \sigma_{spin,\chi_0} \zeta_{spin}$$  \hspace{1cm} (8)

$$\zeta_{spin} = \frac{(\frac{\mu_r(A)}{\mu_r(N)})^2}{3(1 + \frac{\mu_r(A)}{f_A^0})^2} \frac{f_A^0}{f_A^1} \frac{F_{00}(u)}{F_{11}(u)} + \frac{f_A^0}{f_A^1} \Omega_0(0) \Omega_1(0) \frac{F_{01}(u)}{F_{11}(u)}$$  \hspace{1cm} (9)

$$\bar{\Sigma}_V = \sigma_{V,\chi_0} \zeta_V$$  \hspace{1cm} (10)

$$\zeta_V = \frac{(\frac{\mu_r(A)}{\mu_r(N)})^2}{(1 + \frac{\mu_r(A)}{f_A^0})^2} A^2 (1 - \frac{f_A^0}{f_A^1} \frac{A - 2Z}{A})^2 \frac{v^2}{c^2} \frac{1}{(2\mu_r b)^2} \frac{2\eta + 1}{(1 + \eta)^2} \langle v^2 \rangle$$  \hspace{1cm} (11)

$$\sigma_{p,\chi_0}^i = \text{proton cross-section, } i = S, spin, V \text{ given by:}$$

$$\sigma_{S,\chi_0}^i = \sigma_0 (\frac{f_A^0}{f_A^0})^2 (\frac{\mu_r(N)}{m_N})^2 \text{ (scalar), (the isovector scalar is negligible, i.e. }$$

$$\sigma_S^i = \sigma_n^S)$$

$$\sigma_{spin,\chi_0}^i = \sigma_0 (f_A^0 + f_A^1)^2 (\frac{\mu_r(N)}{m_N})^2 \text{ (spin), } \sigma_{p,\chi_0}^V = \sigma_0 (f_A^0 + f_A^1)^2 (\frac{\mu_r(N)}{m_N})^2 \text{ (vector) \hspace{1cm} (vector)}$$

where \(m_N\) is the nucleon mass, \(\eta = m_z/m_N A\), and \(\mu_r(A)\) is the LSP-nucleus reduced mass, \(\mu_r(N)\) is the LSP-nucleon reduced mass and

$$\sigma_0 = \frac{1}{2\pi} (G_F m_N)^2 \simeq 0.77 \times 10^{-38} \text{ cm}^2$$  \hspace{1cm} (12)

$$u = \frac{q^2 b^2}{2}, \hspace{0.5cm} Q = Q_0 u, \hspace{0.5cm} Q_0 = \frac{1}{A m_N b^2}$$  \hspace{1cm} (13)

where \(b\) is the harmonic oscillator size parameter, \(q\) is the momentum transfer to the nucleus, and \(Q\) is the energy transfer to the nucleus.

In the above expressions \(F(u)\) is the nuclear form factor and

$$F_{\rho \rho'}(u) = \sum_{\lambda,\kappa} \frac{\Omega_{\rho'}^{(\lambda,\kappa)}(u)}{\Omega_{\rho'}(0)} \frac{\Omega_{\rho}^{(\lambda,\kappa)}(u)}{\Omega_{\rho}(0)}, \hspace{1cm} \rho, \rho' = 0, 1$$  \hspace{1cm} (14)

are the spin form factors \(^{14}\) (\(\rho, \rho'\) are isospin indices) Both form factors are normalized to one at \(u = 0\). \(\Omega_0 (\Omega_1)\) are the static isoscalar (isovector) spin matrix elements.
The non-directional event rate is given by:
\[ R = R_{\text{non-dir}} = \frac{dN}{dt} = \frac{\rho(0)}{m} \frac{m}{AmN} \sigma(u, v)|v| \]
(15)

Where \( \rho(0) = 0.3 \text{GeV/cm}^3 \) is the LSP density in our vicinity and \( m \) is the detector mass. The differential non-directional rate can be written as
\[ dR = dR_{\text{non-dir}} = \frac{\rho(0)}{m} \frac{m}{AmN} d\sigma(u, v)|v| \]
(16)

where \( d\sigma(u, v) \) was given above.

The directional differential rate in the direction \( \hat{e} \) is given by:
\[ dR_{\text{dir}} = \frac{\rho(0)}{m} \frac{m}{AmN} v.\hat{e} H(v.\hat{e}) \frac{1}{2\pi} d\sigma(u, v) \]
(17)

where \( H \) the Heaviside step function. The factor of \( 1/2\pi \) is introduced, since the differential cross section of the last equation is the same with that entering the non-directional rate, i.e. after an integration over the azimuthal angle around the nuclear momentum has been performed. In other words, crudely speaking, \( 1/(2\pi) \) is the suppression factor we expect in the directional rate compared to the usual one. The precise suppression factor depends, of course, on the direction of observation. In spite of their very interesting experimental signatures, we will not be concerned here with directional rates. The mean value of the non-directional event rate of Eq. (16), is obtained by convoluting the above expressions with the LSP velocity distribution \( f(v, v_E) \) with respect to the Earth, i.e. is given by:
\[ \langle dR \rangle = \frac{\rho(0)}{m} \frac{m}{AmN} \int f(v, v_E)|v| \frac{d\sigma(u, v)}{du} d^3v \]
(18)

The above expression can be more conveniently written as
\[ \langle dR \rangle = \frac{\rho(0)}{m} \frac{m}{AmN} \sqrt{\langle v^2 \rangle} \langle \frac{d\Sigma}{du} \rangle \]
(19)

where
\[ \langle \frac{d\Sigma}{du} \rangle = \int \frac{|v|}{\sqrt{\langle v^2 \rangle}} f(v, v_E) \frac{d\sigma(u, v)}{du} d^3v \]
(20)

After performing the needed integrations over the velocity distribution, to first order in the Earth’s velocity, and over the energy transfer \( u \) the last expression takes the form
\[ R = \bar{R} t \left[ 1 + h(a, Q_{\text{min}})\cos\alpha \right] \]
(21)

where \( \alpha \) is the phase of the Earth (\( \alpha = 0 \) around June 2nd) and \( Q_{\text{min}} \) is the energy transfer cutoff imposed by the detector. In the above expressions \( \bar{R} \) is the rate obtained in the conventional approach by neglecting the
folding with the LSP velocity and the momentum transfer dependence of the differential cross section, i.e. by

\[ R = \frac{\rho(0)}{m_{\chi}} \frac{m}{M_{N}} \sqrt{\langle v^2 \rangle} [\bar{\Sigma}_S + \bar{\Sigma}_{\text{spin}} + \frac{\langle v^2 \rangle}{c^2} \bar{\Sigma}_V] \] (22)

where \( \bar{\Sigma}_i, i = S, V, \text{spin} \) have been defined above, see Eqs (7) - (10). It contains all the parameters of the SUSY models. The modulation is described by the parameter \( h \). Once the rate is known and the parameters \( t \) and \( h \), which depend only on the LSP mass, the nuclear form factor and the velocity distribution the nucleon cross section can be extracted and compared to experiment.

The total directional event rates can be obtained in a similar fashion by by integrating Eq. (17) with respect to the velocity as well as the energy transfer \( u \). We find

\[ R_{\text{dir}} = R[t_0/4\pi] \left| (1 + h_1(a,Q_{\text{min}})\cos\alpha)e_z \cdot e - h_2(a,Q_{\text{min}})\cos\alpha e_y \cdot e + h_3(a,Q_{\text{min}})\sin\alpha e_x \cdot e \right| \] (23)

We remind that the z-axis is in the direction of the sun’s motion, the y-axis is perpendicular to the plane of the galaxy and the x-axis is in the galactocentric direction. The effect of folding with LSP velocity on the total rate is taken into account via the quantity \( t_0 \), which depends on the LSP mass. All other SUSY parameters have been absorbed in \( R \). We see that the modulation of the directional total event rate can be described in terms of three parameters \( h_l, l=1,2,3 \). In the special case of \( \lambda = 0 \) we essentially have one parameter, namely \( h_1 \), since then we have \( h_2 = 0.117 \) and \( h_3 = 0.135 \). Given the functions \( h_l(a,Q_{\text{min}}) \) one can plot the the expression in Eq. (23) as a function of the phase of the earth \( \alpha \).

3 The Scalar Contribution- The Role of the Heavy Quarks

The coherent scattering can be mediated via the the neutral intermediate Higgs particles (h and H), which survive as physical particles. It can also be mediated via s-quarks, via the mixing of the isodoublet and isosinglet s-quarks of the same charge. In our model we find that the Higgs contribution becomes dominant and, as a matter of fact the heavy Higgs H is more important (the Higgs particle A couples in a pseudoscalar way, which does not lead to coherence). It is well known that all quark flavors contribute \( \Upsilon \), since the relevant couplings are proportional to the quark masses. One encounters in the nucleon not only the usual sea quarks (\( u\bar{u}, d\bar{d} \) and \( s\bar{s} \)) but the heavier quarks \( c, b, t \) which couple to the nucleon via two gluon exchange, see e.g. Drees et al \( \Upsilon \) and references therein.
As a result one obtains an effective scalar Higgs-nucleon coupling by using effective quark masses as follows

\[ m_u \rightarrow f_u m_N, \quad m_d \rightarrow f_d m_N, \quad m_s \rightarrow f_s m_N \]

\[ m_Q \rightarrow f_Q m_N, \quad \text{(heavy quarks c, b, t)} \]

where \( m_N \) is the nucleon mass. The isovector contribution is now negligible. The parameters \( f_q, q = u, d, s \) can be obtained by chiral symmetry breaking terms in relation to phase shift and dispersion analysis. Following Cheng and Cheng, we obtain:

\[ f_u = 0.021, \quad f_d = 0.037, \quad f_s = 0.140 \quad \text{(model B)} \]
\[ f_u = 0.023, \quad f_d = 0.034, \quad f_s = 0.400 \quad \text{(model C)} \]

We see that in both models the s-quark is dominant. Then to leading order via quark loops and gluon exchange with the nucleon one finds:

\[ f_Q = 2/27(1 - \sum q f_q) \]

This yields:

\[ f_Q = 0.060 \quad \text{(model B)}, \quad f_Q = 0.040 \quad \text{(model C)} \]

There is a correction to the above parameters coming from loops involving s-quarks and due to QCD effects. Thus for large \( \tan \beta \) we find:

\[ f_c = 0.060 \times 1.068 = 0.064, \quad f_t = 0.060 \times 2.048 = 0.123, \quad f_b = 0.060 \times 1.174 = 0.070 \quad \text{(model B)} \]
\[ f_c = 0.040 \times 1.068 = 0.043, \quad f_t = 0.040 \times 2.048 = 0.082, \quad f_b = 0.040 \times 1.174 = 0.047 \quad \text{(model B)} \]

For a more detailed discussion we refer the reader to Refs. 18, 19.

4 Results and Discussion

The three basic ingredients of our calculation were the input SUSY parameters (see sect. 1), a quark model for the nucleon (see sect. 3) and the velocity distribution combined with the structure of the nuclei involved (see sect. 2). We will focus our attention on the coherent scattering and present results for the popular target \( ^{127}\text{I} \). We have utilized two nucleon models indicated by B and C which take into account the presence of heavy quarks in the nucleon. We also considered energy cut offs imposed by the detector, by considering two typical cases \( Q_{\text{min}} = 10, 20 \) KeV. The thus obtained results for the unmodulated total non directional event rates \( \bar{R}_t \) in the case of the symmetric isothermal model for a typical SUSY parameter choice are shown in Fig. 1. Special attention was paid to the the directional rate and its modulation due to the annual motion of the earth in the case of isothermal models. The case of non isothermal models, e.g. caustic rings, is more complicated and it will not be further discussed here. As expected, the parameter \( t_0 \), which contains the effect of the nuclear form factor and the LSP velocity dependence, decreases as the reduced mass increases.

We will concentrate in the case of isothermal models we will limit and restrict ourselves to the discussion of the directional rates. In the special case...
Figure 1. The Total detection rate per \((kg - target)yr\) vs the LSP mass in GeV for a typical solution in our parameter space in the case of \(^{127}I\) corresponding to model B (thick line) and Model C (fine line). For the definitions see text.

As expected, the parameter \(t_0\), decreases as the reduced mass increases. These are shown in tables 1-2 for various values of \(Q_{min}\) and \(\lambda\). \(h_2\) and \(h_3\) are constant, 0.117 and 0.135 respectively, in the symmetric case. On the other hand \(h_1\), \(h_2\) and \(h_3\) substantially increase in the presence of asymmetry. For the differential rate the reader is referred to our previous work \(^{24,25}\).

5 Conclusions

In the present paper we have discussed the parameters, which describe the event rates for direct detection of SUSY dark matter. It is well known \(^4\) the event rates are quite small and only in a small segment of the allowed parameter space they are above the present experimental goals. One, therefore,
Table 1. The quantities $t^0$ and $h_1$ for $\lambda = 0$ in the case of the target $^{53}I^{127}$ for various LSP masses and $Q_{min}$ in KeV (for definitions see text). Only the scalar contribution is considered. Note that in this case $h_2$ and $h_3$ are constants equal to 0.117 and 0.135 respectively.

| Quantity | $Q_{min}$ | 10  | 30  | 50  | 80  | 100 | 125 | 250 |
|----------|-----------|-----|-----|-----|-----|-----|-----|-----|
| $t^0$    | 0.0       | 1.960 | 1.355 | 0.886 | 0.552 | 0.442 | 0.360 | 0.212 |
| $h_1$    | 0.0       | 0.059 | 0.048 | 0.037 | 0.029 | 0.027 | 0.025 | 0.023 |
| $t^0$    | 10.       | 0.000 | 0.365 | 0.383 | 0.280 | 0.233 | 0.194 | 0.119 |
| $h_1$    | 10.       | 0.000 | 0.086 | 0.054 | 0.038 | 0.033 | 0.030 | 0.025 |
| $t^0$    | 20.       | 0.000 | 0.080 | 0.153 | 0.136 | 0.11  | 0.102 | 0.065 |
| $h_1$    | 20.       | 0.000 | 0.123 | 0.073 | 0.048 | 0.041 | 0.036 | 0.028 |

Table 2. The same as in the previous, but for the value of the asymmetry parameter $\lambda = 1.0$.

| Quantity | $Q_{min}$ | 10  | 30  | 50  | 80  | 100 | 125 | 250 |
|----------|-----------|-----|-----|-----|-----|-----|-----|-----|
| $t^0$    | 0.0       | 2.429 | 1.825 | 1.290 | 0.837 | 0.678 | 0.554 | 0.330 |
| $h_1$    | 0.0       | 0.192 | 0.182 | 0.170 | 0.159 | 0.156 | 0.154 | 0.150 |
| $h_2$    | 0.0       | 0.146 | 0.144 | 0.141 | 0.139 | 0.139 | 0.138 | 0.138 |
| $h_3$    | 0.0       | 0.232 | 0.222 | 0.211 | 0.204 | 0.202 | 0.200 | 0.198 |
| $t^0$    | 10.       | 0.000 | 0.354 | 0.502 | 0.410 | 0.349 | 0.295 | 0.184 |
| $h_1$    | 10.       | 0.000 | 0.241 | 0.197 | 0.174 | 0.167 | 0.162 | 0.154 |
| $h_2$    | 10.       | 0.000 | 0.157 | 0.146 | 0.142 | 0.140 | 0.140 | 0.138 |
| $h_3$    | 10.       | 0.000 | 0.273 | 0.231 | 0.213 | 0.208 | 0.205 | 0.200 |
| $t^0$    | 20.       | 0.000 | 0.047 | 0.169 | 0.186 | 0.170 | 0.150 | 0.100 |
| $h_1$    | 20.       | 0.000 | 0.297 | 0.226 | 0.190 | 0.179 | 0.172 | 0.159 |
| $h_2$    | 20.       | 0.000 | 0.177 | 0.153 | 0.144 | 0.142 | 0.141 | 0.139 |
| $h_3$    | 20.       | 0.000 | 0.349 | 0.256 | 0.224 | 0.216 | 0.211 | 0.203 |

is looking for characteristic signatures, which will aid the experimentalists in reducing background. These are two: a) The non directional event rates, which are correlated with the motion of the Earth (modulation effect) and b) the directional event rates, which are correlated with both the velocity of the sun, around the center of the Galaxy, and the velocity of the Earth. We separated our discussion into two parts. The first deals with the elementary aspects, SUSY parameters and nucleon structure, and is given in terms of the nucleon cross-section. The second deals with nucleon and nuclear effects. In
the second step we also studied the dependence of the rates on the energy cut-off imposed by the detector.

Even though the actual velocity dependence may arise out of a combination of isothermal and non isothermal contributions \[26\] in the present paper we focused on isothermal models. Detectable rates are possible with some choices of the input parameters. A typical graph for the total unmodulated rate is shown Fig. [1]. We will concentrate more on the directional rates, which are described in terms of the parameters \(t_0, h_1, h_2\) and \(h_3\). To simplify matters these parameters are given in Tables 1-2 for directions of observation close to the three axes \(x, y, z\). We see that the unmodulated rate scales by the \(\cos\theta_s\), with \(\theta_s\) being the angle between the direction of observation and the velocity of the sun. The reduction factor of the total directional rate, along the sun’s direction of motion, compared to the total non directional rate depends, of course, on the nuclear parameters, the reduced mass and the asymmetry parameter \(\lambda\) \[25\]. It is given by the parameter \(f_{\text{red}} = t_0/(4\pi t_0) = \kappa/(2\pi)\). We find that \(\kappa\) is around 0.6 for no asymmetry and around 0.7 for maximum asymmetry (\(\lambda = 1.0\)). In other words it is not very different from the naively expected \(f_{\text{red}} = 1/(2\pi)\), i.e. \(\kappa = 1\). The modulation of the directional rate increases with the asymmetry parameter \(\lambda\) and it depends, of course, on the direction of observation. For \(Q_{\min} = 0\) it can reach values up to 23\%. Values up to 35\% are possible for large values of \(Q_{\min}\), but they occur at the expense of the total number of counts.

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