Exploring Novel Signatures in Direct Neutralino Searches

J.D. Vergados\textsuperscript{1,2}

\textsuperscript{1} Theoretical Physics Division, University of Ioannina, Gr 451 10, Ioannina, Greece
\textsuperscript{2} T-DO, Theoretical Physics Division, LANL, Los Alamos, N.M. 87545.
E-mail: vergados@cc.uoi.gr

Abstract. Since the expected rates for neutralino-nucleus scattering are expected to be small, one should exploit all the characteristic signatures of this reaction. Such are: (i) In the standard recoil measurements the modulation of the event rate due to the Earth’s motion. (ii) In directional recoil experiments the correlation of the event rate with the sun’s motion. One now has both modulation, which is much larger and depends not only on time, but on the direction of observation as well, and a large forward-backward asymmetry. (iii) In non recoil experiments gamma rays following the decay of excited states populated during the Nucleus-LSP collision. Branching ratios of about 6 percent are possible (iv) novel experiments in which one observes the electrons produced during the collision of the LSP with the nucleus. Branching ratios of about 10 per cent are possible.

1 Introduction

It appears without doubts that dark matter constitutes about 30\% of the energy matter in the universe. The evidence comes from the cosmological observations [1], which when combined lead to:

$$\Omega_b = 0.05, \Omega_CDM = 0.30, \Omega_A = 0.65$$

and the rotational curves [2]. It is only the direct detection of dark matter, which will unravel the nature of the constituents of dark matter. In fact one such experiment, the DAMA, has claimed the observation of such signals, which with better statistics has subsequently been interpreted as modulation signals [3]. These data, however, if they are due to the coherent process, are not consistent with other recent experiments, see e.g. EDELWEISS and CDMS [4].

Supersymmetry naturally provides candidates for the dark matter constituents. In the most favored scenario of supersymmetry the LSP can be simply described as a Majorana fermion (LSP or neutralino), a linear combination of the neutral components of the gauginos and higgsinos [5-8]. We are not going to address issues related to SUSY in this paper, since they have already been addressed by other contributors to these proceeding. Most models predict nucleon cross sections much smaller the the present experimental limit \(\sigma_S \leq 10^{-5}pb\) for the coherent process. As we shall see below the constraint on the spin cross-sections is less stringent.
Since the neutralino is expected to be non relativistic with average kinetic energy \( < T > \approx 40\text{KeV}(m_\chi/100\text{GeV}) \), it can be directly detected mainly via the recoiling of a nucleus \((A,Z)\) in elastic scattering. In some rare instances the low lying excited states may also be populated \(^9\). In this case one may observe the emitted \(\gamma\) rays. Finally one may be able to observe the electrons produced in the LSP-nucleus collision.

In every case to extract from the data information about SUSY from the relevant nucleon cross section, one must know the relevant nuclear matrix elements \(^{10} - ^{11}\). The static spin matrix elements used in the present work can be found in the literature \(^9\).

Anyway 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 \(^{12}\) \(^^{13}\), assuming some velocity distribution \(^{12,13,14}\) \(^^{15}\) for the LSP. One also would like to exploit other signatures expected to show up in directional experiments \(^16\). Finally in a novel proposal one may be able to observe the reaction produced electrons \(^17\) instead of the standard nuclear recoils or even better to observe them in coincidence with the recoiling nuclei.

## 2 Rates

The differential non directional rate can be written as

\[
dR_{undir} = \frac{\rho(0) m}{m_\chi A m_N} d\sigma(u,v)|v| \quad (1)
\]

where \(d\sigma(u,v)\) was given above, \(\rho(0) = 0.3\text{GeV/cm}^3\) is the LSP density in our vicinity, \(m\) is the detector mass and \(m_\chi\) is the LSP mass.

The directional differential rate, in the direction \(\hat{e}\) of the recoiling nucleus, is:

\[
dR_{dir} = \frac{\rho(0) m}{m_\chi A m_N} |v| \hat{v}.\hat{e} \Theta(\hat{v}.\hat{e}) \frac{1}{2\pi} d\sigma(u,v) \delta(\sqrt{\frac{u}{\mu_r v}} - \hat{v}.\hat{e}) \quad (2)
\]

where \(\Theta(x)\) is the Heaviside function and:

\[
d\sigma(u,v) = \frac{du}{2(\mu_r b v)^2} [(\Sigma_S F(u)^2 + \Sigma_{spin} F_{11}(u))] \quad (3)
\]

where \(u\) the energy transfer \(Q\) in dimensionless units given by

\[u = \frac{Q}{Q_0}, \quad Q_0 = [m_p A b]^{-2} = 40 A^{-4/3} \text{MeV} \quad (4)\]

with \(b\) is the nuclear (harmonic oscillator) size parameter. \(F(u)\) is the nuclear form factor and \(F_{11}(u)\) is the spin response function associated with the isovector channel.

The scalar cross section is given by:

\[
\Sigma_S = (\frac{\mu_r}{\mu_r(p)})^2 \sigma_{p,\chi}^S \frac{A^2}{1 + \frac{f_1^S}{f_p^S} 2Z-A} \left[ 1 + \frac{f_1^S}{f_p^S} \right]^2 \approx \sigma_{N,\chi}^S \left( \frac{\mu_r(p)}{\mu_r} \right)^2 A^2 \quad (5)
\]
(since the heavy quarks dominate the isovector contribution is negligible). \( \sigma^S_{N,\chi^0} \) is the LSP-nucleon scalar cross section. The spin Cross section is given by:

\[
\Sigma_{\text{spin}} = (\frac{\mu_r}{\mu_r(p)})^2 \sigma^\text{spin}_{p,\chi^0} \zeta_{\text{spin}}, \quad \zeta_{\text{spin}} = \frac{1}{3(1 + \frac{p}{f_A})^2} S(u)
\]

\[
S(u) \approx S(0) = \left[ (\frac{f_0}{f_A}) \Omega_0(0))^2 + 2 \frac{f_0}{f_A} \Omega_0(0) \Omega_1(0) + \Omega_1(0))^2 \right]
\]

\( f_0, f_1 \) are the isoscalar and the isovector axial current couplings at the nucleon level \[19\].

3 Results

To obtain the total rates one must fold with LSP velocity and integrate the above expressions over the energy transfer from \( Q_{\text{min}} \) determined by the detector energy cutoff to \( Q_{\text{max}} \) determined by the maximum LSP velocity (escape velocity, put in by hand in the Maxwellian distribution), i.e. \( v_{\text{esc}} = 2.84 v_0 \) with \( v_0 \) the velocity of the sun around the center of the galaxy (229 K\( m/s \)).

3.1 Non directional rates

In a previous paper \[19\], we have shown that, ignoring the motion of the Earth, the total non directional rate is given by

\[
R = \bar{K} \left[ c_{\text{coh}}(A, \mu_r(A)) \sigma^S_{p,\chi^0} + c_{\text{spin}}(A, \mu_r(A)) \sigma^\text{spin}_{p,\chi^0} \zeta_{\text{spin}} \right] \tag{8}
\]

where \( \bar{K} = \frac{\rho(0)}{m_{\chi^0}} \frac{m_p}{m_p} \sqrt{\langle v^2 \rangle} \) and

\[
c_{\text{coh}}(A, \mu_r(A)) = \left[ \frac{\mu_r(A)}{\mu_r(p)} \right]^2 A t_{\text{coh}}(A), \quad c_{\text{spin}}(A, \mu_r(A)) = \left[ \frac{\mu_r(A)}{\mu_r(p)} \right]^2 \frac{t_{\text{spin}}(A)}{A} \tag{9}
\]

where \( t \) is the modification of the total rate due to the folding and nuclear structure effects. It depends on \( Q_{min} \), i.e. the energy transfer cutoff imposed by the detector and \( u = [\mu_r(bv_0\sqrt{2})^{-1} \). The parameters \( c_{\text{coh}}(A, \mu_r(A)) \), \( c_{\text{spin}}(A, \mu_r(A)) \), which give the relative merit for the coherent and the spin contributions in the case of a nuclear target compared to those of the proton, are tabulated in table 1 for energy cutoff, \( Q_{min} = 0 \), 10 keV. Via Eq. (8) we can extract the nucleon cross section from the data.

Furthermore we have seen that ignoring the isoscalar axial current and using \( \Omega_1^2 = 2.82 \) and \( \Omega_2^2 = 2.8 \) for \(^{127}\text{I}\) and \(^{19}\text{F}\) respectively we find:

\[
\frac{\sigma^\text{spin}_{p,\chi^0}}{\sigma^S_{p,\chi^0}} = \left[ \frac{c_{\text{coh}}(A, \mu_r(A))}{c_{\text{spin}}(A, \mu_r(A))} \right] \frac{3}{\Omega_1^2} \Rightarrow \approx 10^4 \quad \text{for} \quad A = 127 \quad \text{and} \quad \approx 10^2 \quad \text{for} \quad A = 19 \tag{10}
\]
Table 1. The factors \( c_{19} = c_{coh}(19, \mu_r(19)) \), \( s_{19} = c_{spin}(19, \mu_r(19)) \) and \( c_{127} = c_{coh}(127, \mu_r(127)) \), \( s_{127} = c_{spin}(127, \mu_r(127)) \) for two values of \( Q_{min} \).

| \( Q_{min} \) | \( m_\chi \) (GeV) |
|----------------|-----------------|
| keV            | 20   | 30   | 40   | 50   | 60   | 80   | 100  | 200  |
|----------------|------|------|------|------|------|------|------|------|
| 0              | \( c_{19} \) | 2080 | 2943 | 3589 | 4083 | 4471 | 5037 | 5428 | 6360 |
| 0              | \( s_{19} \)  | 5.7  | 8.0  | 9.7  | 10.9 | 11.9 | 13.4 | 14.4 | 16.7 |
| 0              | \( c_{127} \) | 37294| 63142| 84764| 101539|114295|131580|142290|162945|
| 0              | \( s_{127} \) | 2.2  | 3.7  | 4.9  | 5.8  | 6.5  | 7.6  | 8.4  | 10.4 |
| 10             | \( c_{19} \)  | 636  | 1314 | 1865 | 2302 | 2639 | 3181 | 3487 | 4419 |
| 10             | \( s_{19} \)  | 1.7  | 3.5  | 4.9  | 6.0  | 6.9  | 8.3  | 9.1  | 11.4 |
| 10             | \( c_{127} \) | 0    | 11660| 24080| 36243|45648 |58334 |69545 |83823 |
| 10             | \( s_{127} \) | 0    | 0.6  | 1.3  | 1.9  | 2.5  | 3.3  | 4.0  | 5.8  |

It is for this reason that the limit on the spin proton cross section extracted from both targets is much poorer. The form factor favors the lighter system [18] both for the spin and the coherent process, \( t(127) < t(19) \). In the case of the spin this advantage is not offset by the larger reduced mass. It is even enhanced by the spin ME (see Table 1). For the coherent process, however, the light nucleus is no match (see Table 1).

If the effects of the motion of the Earth around the sun are included, the total non directional rate is given by

\[
R = \bar{K} \left[ c_{coh}(A, \mu_r(A))\sigma_{p,\chi^0}^S (1 + \alpha(a, Q_{min})\cos \alpha) \right]
\]

and an analogous one for the spin contribution. \( \alpha \) is the modulation amplitude and \( \alpha \) is the phase of the Earth, which is zero around June 2nd. The modulation amplitude would be an excellent signal in discriminating against background, but unfortunately it is very small, less than two per cent. Furthermore for intermediate and heavy nuclei, it can even change sign for sufficiently heavy LSP [18].

3.2 Directional Rates.

Since the sun is moving around the galaxy in a directional experiment, i.e. one in which the direction of the recoiling nucleus is observed, one expects a strong correlation of the event rate with the motion of the sun. In fact the directional rate can be written as:

\[
R_{dir} = \frac{\kappa}{2\pi} \bar{K} \left[ c_{coh}(A, \mu_r(A))\sigma_{p,\chi^0}^S (1 + \alpha_m \cos \alpha_m \pi) \right]
\]

and an analogous one for the spin contribution. The modulation now is \( \alpha_m \pi \), with a shift \( \alpha_m \pi \) in the phase of the Earth \( \alpha \), depending on the direction of observation. \( \kappa/(2\pi) \) is the reduction factor of the unmodulated directional rate.
Fig. 1. The expected modulation amplitude $h_m$ for $A = 127$ in a direction outward from the galaxy on the left and perpendicular to the galaxy on the right as a function of the polar angle measured from the sun’s velocity. For angles less than $\pi/2$ it is irrelevant since the event rates are tiny.

Table 2. The parameters $t$, $h$, $\kappa$, $h_m$ and $\alpha_m$ for $Q_{\text{min}} = 0$. The results shown are for the light systems. $+x$ is radially out of the galaxy ($\Theta = \pi/2, \Phi = 0$), $+z$ is in the the sun’s motion and $+y$ vertical to the plane of the galaxy so that $((x, y, z)$ is right-handed. $\alpha_m = 0, 1/2, 1, 3/2$ implies that the maximum occurs on June, September, December and March 2nd respectively.

| type | t | h | dir | $\kappa$ | $h_m$ | $\alpha_m$ |
|------|---|---|-----|---------|------|--------|
| dir  | +z| 0.0068 | 0.227 | 1       |      |        |
| dir  | +(-)x| 0.080 | 0.272 | 3/2(1/2) |      |        |
| dir  | +(-)y| 0.080 | 0.210 | 0 (1)   |      |        |
| -z   | 0.395 | 0.060 | 0      |        |      |        |
| all  | 1.00 |      |       |        |      |        |
| all  | 0.02 |      |       |        |      |        |

relative to the non-directional one. The parameters $\kappa$, $h_m$, $\alpha_m$ strongly depend on the direction of observation. We prefer to use the parameters $\kappa$ and $h_m$, since, being ratios, are expected to be less dependent on the parameters of the theory. In the case of $A = 127$ we exhibit the the angular dependence of $h_m$ for an LSP mass of $m_\chi = 100\text{GeV}$ in Fig. 1. We also exhibit the parameters $t$, $h$, $\kappa$, $h_m$ and $\alpha_m$ for the target $A = 19$ in Table 2 (for the other light systems the results are almost identical).

The asymmetry is quite large in the direction of the sun’s motion is large $18$, $\approx 0.97$. In the plane perpendicular to the sun’s velocity the asymmetry equals the modulation.

For a heavier nucleus the situation is a bit complicated. Now the parameters $\kappa$ and $h_m$ depend on the LSP mass as well. (see Figs 2 and 3). The asymmetry and the shift in the phase of the Earth are similar to those of the $A = 19$ system.
3.3 Transitions to excited states

Incorporating the relevant kinematics and integrating the differential event rate \( dR/du \) from \( u_{\text{min}} \) to \( u_{\text{max}} \) we obtain the total rate as follows:

\[
R_{\text{exc}} = \int_{u_{\text{exc}}}^{u_{\text{max}}} \frac{dR_{\text{exc}}}{du} \left(1 - \frac{u_{\text{exc}}^2}{u^{2}}\right) du, \\
R_{\text{gs}} = \int_{u_{\text{min}}}^{u_{\text{max}}} \frac{dR_{\text{gs}}}{du} du
\]  

where \( u_{\text{exc}} = \frac{\mu_{r}E_{x}A_{m}N_{Q}}{Q_{0}} \) and \( E_{x} \) is the excitation energy of the final nucleus, \( u_{\text{max}} = \left(y/a\right)^{2} - \left(E_{x}/Q_{0}\right) \), \( y = v/\upsilon_{0} \), and \( u_{\text{min}} = Q_{\text{min}}/Q_{0} \), \( Q_{\text{min}} \) (imposed by the detector energy cutoff) and \( u_{\text{max}} = (y_{\text{esc}}/a)^{2} \) is imposed by the escape velocity (\( y_{\text{esc}} = 2.84 \)).

For our purposes it is adequate to estimate the ratio of the rate to the excited state divided by that to the ground state (branching ratio) as a function of the LSP mass. This can be cast in the form:

\[
BRR = \frac{S_{\text{exc}}(0) \Psi_{\text{exc}}(u_{\text{exc}}, u_{\text{max}})[1 + h_{\text{exc}}(u_{\text{exc}}, u_{\text{max}}) \cos \alpha]}{S_{\text{gs}}(0) \Psi_{\text{gs}}(u_{\text{min}})[1 + h(u_{\text{min}}) \cos \alpha]}
\]  

in an obvious notation [13]. \( S_{\text{gs}}(0) \) and \( S_{\text{exc}}(0) \) are the static spin matrix elements. As we have seen their ratio is essentially independent of supersymmetry, if the isoscalar contribution is neglected. For \(^{127}\text{I}\) it was found [9] to be about 2. The functions \( \Psi \) are given as follows:

\[
\Psi_{\text{gs}}(u_{\text{min}}) = \int_{u_{\text{min}}}^{(y/a)^{2}} \frac{S_{\text{gs}}(u)}{S_{\text{gs}}(0)} F_{11}^{\text{gs}}(u) \left[\psi(a\sqrt{u}) - \psi(y_{\text{esc}})\right] du
\]
\[ \Psi_{\text{exc}}(u_{\text{exc}}, u_{\text{max}}) = \int_{u_{\text{exc}}}^{u_{\text{max}}} \frac{S_{\text{exc}}(u)}{S_{\text{exc}}(0)} F_{11}^{\text{exc}}(u) (1 - \frac{u_{\text{exc}}^2}{u^2}) \left[ \psi(a\sqrt{u}(1 + u_{\text{exc}}/u)) - \psi(y_{\text{esc}}) \right] du \]  

(16)

The functions \( \psi \) arise from the convolution with LSP velocity distribution. The obtained results are shown in Fig. 4.

Fig. 4. The ratio of the rate to the excited state divided by that of the ground state as a function of the LSP mass (in GeV) for \(^{127}\)I. We assumed that the static spin matrix element of the transition from the ground to the excited state is a factor of 1.9 larger than that involving the ground state, but the functions \( F_{11}(u) \) are the same. On the left we show the results for \( Q_{\text{min}} = 0 \) and on the right for \( Q_{\text{min}} = 10 \text{ KeV} \).

3.4 Detecting recoiling electrons following the LSP-nucleus collision.

During the LSP-nucleus collision we can have the ionization of the atom. One thus may exploit this signature of the reaction and try to detect these electrons [17]. These electrons are expected to be of low energy and one thus may have a better chance of observing them in a gaseous TPC detector. In order to avoid complications arising from atomic physics we have chosen as a target \(^{20}\)Ne. Furthermore, to avoid complications regarding the allowed SUSY parameter space, we will present our results normalized to the standard neutralino nucleus cross section. The thus obtained branching ratios are independent of all parameters of supersymmetry except the neutralino mass. The numerical results given here apply in the case of the coherent mode. If, however, we limit ourselves to the ratios of the relevant cross sections, we do not expect substantial changes in the case of the spin induced process.

The ratio of the our differential (with respect of the electron energy) cross section divided by the total cross section of the standard neutralino-nucleus elastic scattering, nuclear recoil experiments (nrec), takes [17] the form:

\[
\frac{d\sigma(T)}{\sigma_{\text{nrec}}} = \frac{1}{4} \sum_{n\ell} p_{n\ell} |\phi_{n\ell}(2m_eT)|^2 \\
\int_{-1}^{1} d\xi_1 \int_{-1}^{1} d\xi_2 \frac{d\xi K(\xi + \Lambda)^2}{2} \frac{|F(\mu_\tau \nu(\xi + \Lambda))|^2}{\int_{0}^{1} 2\xi d\xi |F(2\mu_\tau \nu\xi)|^2} m_e k dT. 
\]  

(17)
where

\[ K = \frac{p_x - k}{p_x}, \quad K = \sqrt{p_x^2 + k^2 - 2k p_x \xi} \], \quad \xi_1 = \hat{p}_x \hat{k}, \quad \xi = \hat{q} \hat{K}, \]

\[ \xi_L = \sqrt{\frac{m_x}{\mu_r} \left[ 1 + \frac{1}{K^2} \left( \frac{T - \epsilon_{nl}}{T_x} - 1 \right) \right]} \] and \( 2 \frac{\mu_r}{m_x} p_x \xi = 2 \mu_r v \xi \) is the momentum \( q \) transferred to the nucleus and \( F(q) \) is the nuclear form factor. The outgoing electron energy lies in the range \( 0 \leq T \leq \frac{\mu_r}{m_x} T_x - \epsilon_{nl} \). Since the momentum of the outgoing electron is much smaller than the momentum of the incoming neutralino, i.e. \( K \approx 1 \), the integration over \( \xi_1 \) can be trivially performed.

We remind the reader that the LSP- nucleus cross-section \( \sigma_{n rec} \) takes the form:

\[ \sigma_{n rec} = \left( \frac{\mu_r}{\mu_r(p)} \right)^2 A^2 \sigma_p \int_0^1 2d\xi \left[ F(2 \mu_r v \xi) \right]^2 \] (18)

In the case of \(^{20}\text{Ne} \) he binding energies and the occupation probabilities are given by \( [17] \):

\[ \epsilon_{nl} = (-0.870, -0.048, -0.021), \quad p_{nl} = (2/10, 2/10, 6/10). \] (19)

in the obvious order: (1s, 2s, 2p). In Fig.5 we show the differential rate of our process, divided by the total nuclear recoil event rate, for each orbit as well as the total rate in our process divided by that of the standard rate as a function of the electron threshold energy with 0 threshold energy in the standard process. We obtained our results using appropriate form factor \( [11] \).

From these plots we see that, even though the differential rate peaks at low energies, there remains substantial strength above the electron energy of 0.2 keV, which is the threshold energy for detecting electrons in a Micromegas detector, like the one recently \( [20] \) proposed.

**Fig. 5.** Shown on the left is the differential rate, divided by the total rate associated with the nuclear recoils, as a function of the electron energy \( T \) (in keV). Each atomic orbit involved in the target \(^{20}\text{Ne} \) is included separately. The full line, the short-dashed line and the long-dashed line correspond to the orbits 1s, 2s and 2p respectively. Shown on the right is the ratio of the total rate for the novel process divided by that of the standard process as a function of the electron threshold energy, assuming zero threshold energy for the standard process. This ratio may increase if such a threshold is included.
4 Conclusions

Since the expected event rates for direct neutralino detection are very low\[5,8\], in the present work we looked for characteristic experimental signatures for background reduction, such as:

- Standard recoil experiments
  Here the relevant parameters are $t$ and $h$. For light targets they are essentially independent of the LSP mass \[18\], essentially the same for both the coherent and the spin modes. The modulation is small, $h \approx 0.2\%$, but it may increase as $Q_{\text{min}}$ increases. Unfortunately, for heavy targets even the sign of $h$ is uncertain for $Q_{\text{min}} = 0$. The situation improves as $Q_{\text{min}}$ increases, but at the expense of the number of counts.

- Directional experiments \[16\] Here we find a correlation of the rates with the velocity of the sun as well as that of the Earth. One encounters reduction factors $\kappa/2\pi$, which depend on the angle of observation. The most favorable factor is small, $\approx 1/4\pi$ and occurs when the nucleus is recoiling opposite to the direction of motion of the sun. As a bonus one gets modulation, which is three times larger, $h_m \approx 0.06$. In a plane perpendicular to the sun’s direction of motion the reduction factor is close to $1/12\pi$, but now the modulation can be quite high, $h_m \approx 0.3$, and exhibits very interesting time dependent pattern (see Table 2. Further interesting features may appear in the case of non standard velocity distributions \[15\].

- Transitions to Excited states
  We find that branching ratios for transitions to the first excited state of $^{127}\text{I}$ is relatively high, about $10\%$. The modulation in this case is much larger $h_{\text{exc}} \approx 0.6$. We hope that such a branching ratio will encourage future experiments to search for characteristic $\gamma$ rays rather than recoils.

- Detection of ionization electrons produced in the LSP collision
  Our results indicate that one can be optimistic about using the emitted electrons in the neutralino nucleus collisions for the direct detection of the LSP. This novel process may be exploited by the planned TPC low energy electron detectors. By achieving low energy thresholds of about 0.25 keV, the branching ratios are approximately 10 percent. They can be even larger, if one includes low energy cutoffs imposed by the detectors in the standard experiments, not included in the above estimate.
  As we have seen the background problems associated with the proposed mechanism are not worse than those entering the standard experiments. In any case coincidence experiments with x-rays, produced following the de-excitation of the residual atom, may help reduce the background events to extremely low levels.

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