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SOME ISSUES RELATED TO THE DIRECT DETECTION OF DARK MATTER.

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Abstract

In this paper we review the theoretical issues involved in the direct detection of supersymmetric (SUSY) dark matter. After a brief discussion of the allowed SUSY parameter space we focus on the determination of the traditional neutralino detection rates, in experiments which measure the energy of the recoiling nucleus, such as the coherent and spin induced rates and the dependence of the rate on the motion of the Earth (modulation effect). Then we examine the novel features appearing in directional experiments, which detect the recoiling nucleus in a given direction. Next we estimate the branching ratios for transitions to accessible excited nuclear levels. Finally we estimate the event rates leading to the atom ionization and subsequent detection of the outgoing electrons.

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1 Introduction

The combined MAXIMA-1 [1], BOOMERANG [2], DASI [3] and COBE/DMR Cosmic Microwave Background (CMB) observations [4] as well as the recent WMAP data [5] imply that the Universe is flat [6] and that most of the matter in the Universe is Dark, i.e. exotic. Crudely speaking and easy to remember one has:

$$\Omega_b = 0.05, \Omega_{CDM} = 0.30, \Omega_\Lambda = 0.65$$

for the baryonic, dark matter and dark energy fractions respectively.

These observations, however, do not tell us anything about the particle nature of dark matter. This can only be accomplished through direct observation. Many experiments are currently under way aiming at this goal.

Supersymmetry naturally provides candidates for the dark matter constituents [7],[8]-[11]. In the most favored scenario of supersymmetry the lightest supersymmetric particle (LSP) can be simply described as a Majorana fermion, a linear combination of the neutral components of the gauginos and higgsinos [7],[8]-[15].

In all calculations performed so far, the obtained event rates are quite low and perhaps unobservable in the near future. So one has to search for characteristic signatures associated with this reaction. Such are the modulation of the event rates with the motion of the Earth (modulation effect) and the correlation of the observed rates of directionally sensitive experiments with the motion of the sun [16,17]. Transitions to low energy excited nuclear states have also been considered [18]. Quite recently it has been found that the detection of electrons, following the collision of the neutralino with the nucleus may offer another option [19] to be exploited by the experiments.

2 The Essential Theoretical Ingredients of Direct Detection.

The possibility of dark matter detection hinges on the nature of its constituents. Here we will assume that such a constituent is the lightest supersymmetric particle or LSP. Since this particle is expected to be very massive, $m_\chi \geq 30\text{GeV}$, and extremely non relativistic with average kinetic energy $T \approx 50\text{ keV}(m_\chi/100\text{GeV})$, it can be directly detected [7]-[26] mainly via the recoiling of a nucleus (A,Z) in elastic scattering. In this paper, however, we will consider alternative possibilities.

The event rate for all such processes can be computed from 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 [15,23].
- (2) A well defined procedure for transforming the amplitude obtained using the previous effective Lagrangian from the quark to the nucleon level, i.e. a quark model for the nucleon. This step is not trivial, since the obtained results depend crucially on the content of the nucleon in quarks other than u and d.
- (3) Nuclear matrix elements [27]–[29],[18], [19], obtained with as reliable as possible many body nuclear wave functions. Fortunately in the most studied case of the scalar coupling the situation is quite simple, since then one needs only the nuclear form factor. Some progress has also been made in obtaining reliable static spin matrix elements and spin response functions [29],[18].

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 for the scalar interaction [13,15] (see also Arnowitt and Dutta [24]).

It is worth exploiting the contribution of the axial current in the direct neutralino detection, since, in addition, it may populate excited nuclear states, if they happen to be so low in energy that they become accessible to the low energy neutralinos [18]. Models which can lead to detectable spin cross sections have recently been proposed [20] [21] [22].

Once the LSP-nucleon cross section is known, the LSP-nucleus cross section can be obtained. The differential cross section with respect to the energy transfer Q for a given LSP velocity v can be cast in the form

$$d\sigma(u, v) = \frac{du}{2(\mu_r bv)^2} [(\bar{\Sigma}_S F^2(u) + \bar{\Sigma}_{spin} F_{11}(u))] \quad (1)$$

where we have used a dimensionless variable u , proportional to Q , which is found convenient for handling the nuclear form factors

Table 1

The static spin matrix elements for various nuclei. For light nuclei the calculations are from Divari et al (see text) . For ^{127}I the results are from Ressel and Dean (see text) (*) and the Jyvaskyla-Ioannina collaboration (private communication)(**). For ^{209}Pb they were obtained previously (see text).

	^{19}F	^{29}Si	^{23}Na	$^{127}I^*$	$^{127}I^{**}$	$^{207}Pb^+$
$[\Omega_0(0)]^2$	2.610	0.207	0.477	3.293	1.488	0.305
$[\Omega_1(0)]^2$	2.807	0.219	0.346	1.220	1.513	0.231
$\Omega_0(0)\Omega_1(0)$	2.707	-0.213	0.406	2.008	1.501	-0.266
μ_{th}	2.91	-0.50	2.22			
μ_{exp}	2.62	-0.56	2.22			
$\frac{\mu_{th}(spin)}{\mu_{exp}}$	0.91	0.99	0.57			

[26] $F(u)$, $F_{11}(u)$, namely $u = \frac{Q}{Q_0}$, $Q_0 \approx 40 \times A^{-4/3}$ MeV. μ_r is the reduced LSP-nucleus mass and b is (the harmonic oscillator) nuclear size parameter. Furthermore

$$\bar{\Sigma}_S = \sigma_{p,\chi^0}^S A^2 \mu_r^2, \bar{\Sigma}_{spin} = \mu_r^2 \sigma_{p,\chi^0}^{spin} \zeta_{spin}, \zeta_{spin} = \frac{1}{3(1 + \frac{f_A^0}{f_A^1})^2} S(u)(2)$$

σ_{p,χ^0}^{spin} and σ_{p,χ^0}^s are the nucleon cross-sections associated with the spin and the scalar interactions respectively and

$$S(u) = [(\frac{f_A^0}{f_A^1} \Omega_0(0))^2 \frac{F_{00}(u)}{F_{11}(u)} + 2 \frac{f_A^0}{f_A^1} \Omega_0(0) \Omega_1(0) \frac{F_{01}(u)}{F_{11}(u)} + \Omega_1(0))^2](3)$$

The definition of the spin response functions F_{ij} , with $i, j = 0, 1$ isospin indices, can be found elsewhere [29].

Some static spin matrix elements [29], [27], [26] for some nuclei of interest are given in table 1

3 Rates

The differential non directional rate can be written as:

$$dR_{undir} = \frac{\rho(0)}{m_\chi} \frac{m}{Am_N} d\sigma(u, v) |v| \quad (4)$$

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

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

$$dR_{dir} = \frac{\rho(0)}{m_\chi} \frac{m}{Am_N} |v| \hat{v} \cdot \hat{e} \Theta(\hat{v} \cdot \hat{e}) \frac{1}{2\pi} d\sigma(u, v) \quad (5)$$

$$\delta\left(\frac{\sqrt{u}}{\mu_r v b \sqrt{2}} - \hat{v} \cdot \hat{e}\right), \quad \Theta(x) = \begin{cases} 1, & x > 0 \\ 0, & x < 0 \end{cases}$$

The LSP is characterized by a velocity distribution. For a given velocity distribution $f(\mathbf{v}')$, with respect to the center of the galaxy, One can find the velocity distribution in the lab frame $f(\mathbf{v}, \mathbf{v}_E)$ by writing $\mathbf{v}' = \mathbf{v} + \mathbf{v}_E$, $\mathbf{v}_E = \mathbf{v}_0 + \mathbf{v}_1$. \mathbf{v}_0 is the sun's velocity (around the center of the galaxy), which coincides with the parameter of the Maxwellian distribution, and \mathbf{v}_1 the Earth's velocity (around the sun). Thus the above expressions for the rates must be folded with the LSP velocity distribution. We will distinguish two possibilities:

(1) The direction of the recoiling nucleus is not observed.

The non-directional differential rate is now given by:

$$\left\langle \frac{dR_{undir}}{du} \right\rangle = \left\langle \frac{dR}{du} \right\rangle = \frac{\rho(0)}{m_\chi} \frac{m}{Am_N} \sqrt{\langle v^2 \rangle} \left\langle \frac{d\Sigma}{du} \right\rangle \quad (6)$$

where

$$\left\langle \frac{d\Sigma}{du} \right\rangle = \int \frac{|v|}{\sqrt{\langle v^2 \rangle}} f(\mathbf{v}, \mathbf{v}_E) \frac{d\sigma(u, v)}{du} d^3\mathbf{v} \quad (7)$$

(2) The direction \hat{e} of the recoiling nucleus is observed.

In this case the directional differential rate is given as above with:

$$\begin{aligned} \left\langle \left(\frac{d\Sigma}{du} \right)_{dir} \right\rangle &= \int \frac{\mathbf{v} \cdot \hat{e} \Theta(\mathbf{v} \cdot \hat{e})}{\sqrt{\langle v^2 \rangle}} f(\mathbf{v}, \mathbf{v}_E) \frac{d\sigma(u, v)}{du} \\ &\quad \frac{1}{2\pi} \delta\left(\frac{\sqrt{u}}{\mu_r b v} - \hat{v} \cdot \hat{e}\right) d^3\mathbf{v} \end{aligned} \quad (8)$$

To obtain the total rates one must integrate the two previous expressions over the energy transfer from Q_{min} determined by the detector energy cutoff to Q_{max} determined by the maximum LSP velocity (escape velocity, put in by hand in the Maxwellian distribution), i.e. $v_{esc} = 2.84 v_0$, $v_0 = 229 \text{ Km/s}$.

4 Results

We will specialize the above results in the following cases:

4.1 Non directional unmodulated rates

Ignoring the motion of the Earth the total non directional rate is given by

$$R = \bar{R} t(a, Q_{min}) \quad (9)$$

$$\bar{R} = \frac{\rho(0)}{m_{\chi^0}} \frac{m}{Am_p} \left(\frac{\mu_r}{\mu_r(p)} \right)^2 \sqrt{\langle v^2 \rangle} [\sigma_{p,\chi^0}^S A^2 + \sigma_{p,\chi^0}^{spin} \zeta_{spin}]$$

where t is the modification of the total rate due to the folding and nuclear structure effects. t depends on Q_{min} , i.e. the energy

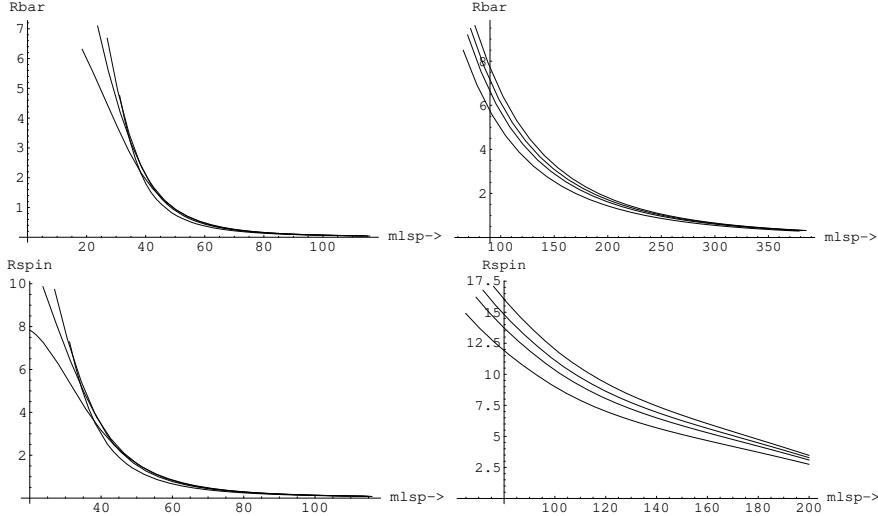


Fig. 1. On top: The quantity \bar{R} , \approx event rate for $Q_{\min} = 0$, associated with the spin contribution in the case of the $A = 19$ system (for the definition of the parameters see text). bottom: The event rate, associated with the spin contribution in the case of the $A = 127$ system (for notation see our earlier work [18]).

transfer cutoff imposed by the detector and the parameter a introduced above. All SUSY parameters, except the LSP mass, have been absorbed in \bar{R} .

Via Eq. (9) we can, if we wish, extract the nucleon cross section from the data. For most of the allowed parameter space the obtained results are undetectable. As it has already been mentioned it is possible to obtain detectable rates in the case of the coherent mode. Such results have, e.g. been obtained by Cerdido *et al* [30] with non universal set of parameters and the Florida group [31].

For the target ^{19}F are shown in Fig. 1 (top), while for ^{127}I the corresponding results are shown in Fig. 1.

4.2 Modulated Rates

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

$$R = \bar{R} t [(1 + h(a, Q_{\min}) \cos \alpha)] \quad (10)$$

Table 2

The parameters t , h , κ , h_m and α_m for the isotropic Gaussian velocity distribution and $Q_{min} = 0$. The results presented are associated with the spin contribution, but those for the coherent mode are similar. The results shown are for the light systems. For intermediate and heavy nuclei there is a dependence on the LSP mass. $+x$ is radially out of the galaxy ($\Theta = \pi/2, \Phi = 0$), $+z$ is in the sun's direction of motion ($\Theta = 0$) and $+y$ is vertical to the plane of the galaxy ($\Theta = \pi/2, \Phi = \pi/2$) so that (x, y, z) is right-handed. $\alpha_m = 0, 1/2, 1, 3/2$ means that the maximum occurs on the 2nd of June, September, December and March respectively.

type	t	h	dir	κ	h_m	α_m
dir			+z	0.0068	0.227	1
			+(-)x	0.080	0.272	3/2(1)
			+(-)y	0.080	0.210	0 (1)
			-z	0.395	0.060	0
all	1.00					
all		0.02				

with h the modulation amplitude and α 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 (see table 2). Furthermore for intermediate and heavy nuclei, it can even change sign for sufficiently heavy LSP. So in our opinion a better signature is provided by directional experiments, which measure the direction of the recoiling nucleus.

4.3 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. The directional rate can be written as:

$$R_{dir} = \frac{t_{dir}}{2\pi} \bar{R} [1 + h_m \cos(\alpha - \alpha_m \pi)] \quad (11)$$

$$= \frac{\kappa}{2\pi} \bar{R} t [1 + h_m \cos(\alpha - \alpha_m \pi)]$$

where h_m is the modulation, α_m is the shift in the phase of the Earth α and $\kappa/(2\pi)$ is the reduction factor of the unmodulated directional rate relative to the non-directional one. The parameters κ , h_m , α_m depend on the direction of observation: The above parameters are shown in Table 2 parameter t_{dir} for a typical LSP mass 100 GeV is shown in for the targets $A = 19$. For heavier targets the depend on the LSP mass [16].

4.4 Rates to excited states

Transitions to excited states are possible only for nuclear systems characterized by excited states at sufficiently low energies with quantum numbers, which allow for Gamow-Teller transitions. One such system is ^{127}I , which, fortunately, can serve as a target for the recoil experiment.

This nucleus has a ground state $5/2^+$ and a first excited state a $7/2^+$ at 57.6 keV . As it has already been mentioned it is a popular target for dark matter detection. As a result the structure of its ground state has been studied theoretically by a lot of groups (for references see [18]). We find $\Omega_0^2 = \Omega_1^2 = \Omega_0 \Omega_1 = 0.164$, 0.312 for the ground state and the excited state respectively.

In presenting our results it is advantageous to compute the branching ratio. In addition to factoring out most of the uncertainties connected with the SUSY parameters and the structure of the nucleon, we expect the ratio of the two spin matrix elements to be more reliable than their absolute values. Taking the ratio of the static spin matrix elements to be 1.90 and assuming that the spin response functions are identical, we calculated the branching ratio, which is exhibited in Figs 2 and 3. We notice that the dependence on Q_{min} is quite mild. From Figs 2 and 3 we notice that the relative modulation is higher when the phase space is restricted by Q_{min} and E_{exc} at the expense, of course, of the total

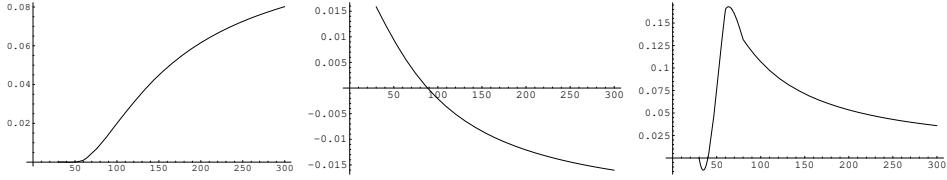


Fig. 2. On the left we show the ratio of the rate to the excited state divided by that of the ground state for ^{127}I assuming that the static spin matrix element of the transition from the ground to the excited state is a factor of 1.902 larger than that involving the ground state, but the spin response functions are the same. Next to it we show the modulation amplitudes for the ground and the excited states respectively. The results were obtained for no threshold cut off ($Q_{min} = 0$).

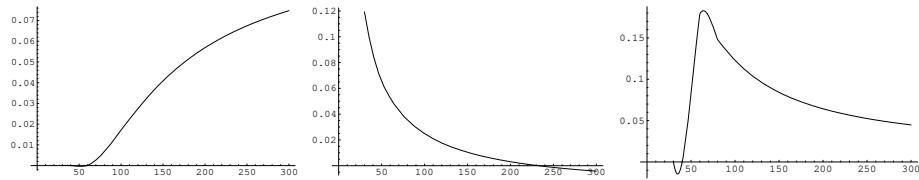


Fig. 3. The same as in Fig. 2 for a lower energy cutoff of $Q_{min} = 10\text{keV}$. number of counts.

4.5 Detection of ionization electrons

The differential cross section for the LSP nucleus scattering leading to emission of electrons in the case of non relativistic neutralinos takes the form:

$$d\sigma(k) = \frac{1}{v} \frac{m_e}{E_e} |M|^2 \frac{d^3\mathbf{q}}{(2\pi)^3} \frac{d^3\mathbf{k}}{(2\pi)^3} (2\pi)^3 \frac{1}{2(2\ell+1)} \sum_{n\ell m} p_{n\ell} [\tilde{\phi}_{n\ell m}(\mathbf{k})]^2 2\pi \delta(T_\chi + \epsilon_{n\ell} - T - \frac{q^2}{2m_A} - \frac{(\mathbf{p}_0 - \mathbf{k} - \mathbf{q})^2}{2m_\chi}) \quad (12)$$

where v is the oncoming LSP velocity, M is the invariant amplitude, known from the standard neutralino nucleus cross section, T and \mathbf{k} are the kinetic energy and momentum of the outgoing electron, q is the momentum transferred to the nucleus and $\epsilon_{n\ell}$ is the binding energy of the initial electron. $\tilde{\phi}_{n\ell m}(\mathbf{k})$ is the fourier transform of the bound electron wave function, i.e its wave function in momentum space. $p_{n\ell}$ is the probability of finding the electron in the $n\ell$ orbit [19].

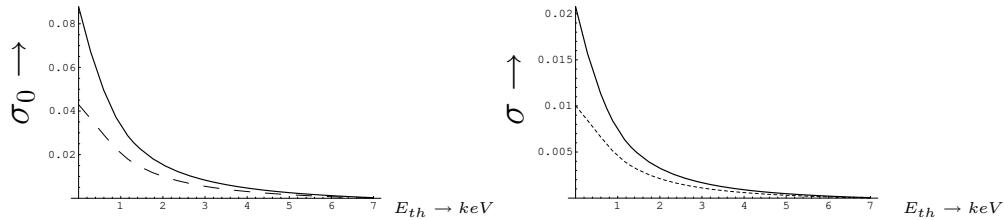


Fig. 4. The cross section for ionization divided by the standard LSP nucleus cross section as a function of the threshold energy. The full line results by including the $1s$, $2s$ and $2p$ orbitals, while the dashed line is obtained considering the $1s$ orbital alone

In order to avoid any complications arising from questions regarding the allowed SUSY parameter space, we will present our results normalized to the cross section of the standard neutralino nucleus cross section, which is fairly well known. One then can perform the needed integrals to obtain the total cross sections.

In addition, of course, one must convolute the above expression with the velocity distribution to obtain both the differential cross section as well the total cross section as a function of the neutralino mass. We will not, however, address these issues here.

We will now apply the above formalism for a typical case, namely $m_\chi = 100 \text{ GeV}$ and $T_\chi = \langle T_\chi \rangle = 50 \text{ keV}$, which is the average energy for this mass. We will also use as a target ^{19}F , which is considered in the standard nuclear recoil experiments. The obtained results are essentially identical to those for ^{20}Ne , which is a popular gaseous TPC counter currently being considered for detection of low energy neutrinos produced in triton decay.

The binding energies employed [32] are

$$\epsilon_{0s} = -0.870, \epsilon_{2s} = -0.048, \epsilon_{2p} = -0.021$$

Our results were obtained considering one electron per atom and weighing each orbit with the probabilities $p_{n\ell} = (2/10, 2/10, 6/10)$ in the above order. The total cross section for this process divided by that of the standard LSP-nucleus cross section is shown in Fig. 4, without the inclusion of the nuclear form factor on the left and using appropriate form factor [29] on the right. From this plot we see that the introduction of the nuclear form factor decreases the

branching ratio by a factor of about 4. This reduction maybe somewhat less, if the convolution with the velocity distribution is included.

5 Conclusions

In the present paper we have discussed the parameters, which describe the event rates for direct detection of SUSY dark matter. In the coherent case, only in a small segment of the allowed parameter space the rates are above the present experimental goals [13,15,24], which, of course, may be improved by two or three orders of magnitude in the planned experiments [33]-[37]. In the case of the spin contribution only in models with large higgsino components of the LSP one can obtain rates, which may be detectable, but in this case, except in special models, the bound on the relic LSP abundance may be violated. Thus in both cases the expected rates are small. Thus one feels compelled to look for characteristic experimental signatures for background reduction, such as correlation of the event rates with the motion of the Earth (modulation effect) and angular correlation of the directional rates with the direction of motion of the sun on top of their seasonal modulation. Such experiments are currently under way, like the UKDMC DRIFT PROJECT experiment [38], the Micro-TPC Detector of the Kyoto-Tokyo collaboration [39] and the TOKYO experiment [40].

The relative parameters t and h in the case for light nuclear targets are essentially independent of the LSP mass, but they depend on the energy cutoff, Q_{min} . For $Q_{min} = 0$ they are exhibited in Table 2. They are essentially the same for both the coherent and the spin modes. For intermediate and heavy nuclei they depend on the LSP mass [16].

In the case of the directional rates it is instructive to first summarize our results regarding the reduction of the directional rate compared to the usual rate, given by $\kappa/(2\pi)$. The factors κ de-

pend, of course, on the angles of observation (see Table 2). Second we should emphasize the importance of the modulation of the directional rates. In the favored direction the modulation is not very large, but still it is three times larger compared to that of the non directional case. In the plane perpendicular to the sun's motion the modulation is quite large (see Table 2).

Coming to transitions to excited states we believe that branching ratios of the size obtained here for ^{127}I are very encouraging to the experiments aiming at γ ray detection, following the de-excitation of the nucleus.

Regarding the detection of the emitted electrons in the LSP-nucleus collision we find that, even though the distribution peaks at low energies, there remains substantial strength above 0.2 keV, which is the threshold energy of a Micromegas detector, like the one recently [41] proposed. We should emphasize that this region is below the threshold of the nuclear recoils.

We thus hope that, in spite of the experimental difficulties, some of the above signatures can be exploited by the experimentalists.

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