SEARCHING FOR RELIC NEUTRALINOS

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ABSTRACT

Theoretical expectations for direct and indirect searches for relic neutralinos are presented. Complementarity among various investigation means is discussed in connection with the values of the neutralino relic abundance.

1. Introduction

In the present report we discuss the theoretical expectations for detection of relic neutralinos either by the direct method (e.g. by measuring the nuclear recoil energy due to neutralino–nucleus elastic scattering) or by detecting indirect signals due to neutralino–neutralino annihilation occurring in the halo or inside celestial bodies (Sun and Earth).

Evidence for the presence of these relic neutralinos would obviously be of primary importance as a test of the standard Big Bang theory, independently of the fact that these Susy relic particles would or would not provide a large contribution to the total mass of the Universe. Should the relic neutralinos contribute substantially to the total density parameter Ω, their detection would also provide an extraordinary hint for a clarification of the long–standing dark matter issue. In fact, in this case, relic neutralinos would play a significant role as Cold Dark Matter (CDM) constituents.

In the following we adopt the usual assumptions that: i) R–parity is conserved, ii) the neutralino is the lightest supersymmetric particle (LSP). Very convenient theoretical frameworks where dark matter neutralino phenomenology may be easily studied are provided by the Minimal Supersymmetric Standard Model (MSSM) and by its implementation in a Supergravity theory (SUGRA). Here MSSM is meant to denote the minimal supersymmetric extension of the standard model where sleptons and squarks are taken as degenerate, with the exceptions for the stop particles.

The neutralino (χ) is defined as the lowest–mass linear combination of photino, zino and higgsinos.

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\[ \chi = a_1 \tilde{\gamma} + a_2 \tilde{Z} + a_3 \tilde{H}_1^0 + a_4 \tilde{H}_2^0 \] (1)

Here \( \tilde{\gamma} \) and \( \tilde{Z} \) are the fields obtained from the original U(1) and SU(2) neutral gauginos, \( \tilde{B} \) and \( \tilde{W}_3 \), by a rotation in terms of the Weinberg angle.

The neutralino mass \( m_\chi \) and the coefficients \( a_i \) depend on the parameters: \( \mu \) (Higgs mixing parameter), \( M_1, M_2 \) (masses of \( \tilde{B} \) and of \( \tilde{W}_3 \), respectively) and \( \tan \beta = v_u/v_d \) (\( v_u \) and \( v_d \) are the v.e.v.'s which give masses to up–type and down–type quarks). It is customary to employ the standard GUT relationship between \( M_1 \) and \( M_2 \): \( M_1 = (5/3) \tan^2 \theta_W M_2 \approx 0.5 M_2 \). We use this assumption here.

In the following for the parameters \( M_2 \) and \( \mu \) we will consider the ranges: \( 20 \text{ GeV} \leq M_2 \leq 6 \text{ TeV}, 20 \text{ GeV} \leq |\mu| \leq 3 \text{ TeV} \). \( \tan \beta \) will be taken at the representative value \( \tan \beta = 8 \).

For the evaluation of the neutralino relic abundance and of the event rates for direct and indirect neutralino detections one has also to assign values to the masses of a large number of particles, namely to the Higgs bosons and to the Susy scalar partners of leptons and quarks: sleptons (\( \tilde{l} \)) and squarks (\( \tilde{q} \)). In the MSSM scheme we consider here these values are assigned arbitrarily: a standard procedure consists in assuming mass degeneracy both for sleptons and for squarks except for the stop particles (\( \tilde{t}_L, \tilde{t}_R \)). As for the neutral Higgs bosons we recall that in the MSSM there are three neutral Higgs particles: two CP–even bosons \( h \) and \( H \) (of masses \( m_h, m_H \) with \( m_H > m_h \)) and a CP–odd one \( A \) (of mass \( m_A \)). Once a value for one of these masses (say, \( m_h \)) is assigned, the other two masses (\( m_A, m_H \)) are derived through mass relationships depending on radiative effects.

Implementation of MSSM with supergravity sets a much more constrained phenomenological framework, since SUGRA establishes strict relations between all the masses in play and the few fundamental theoretical parameters: \( A \) and \( B \) (appearing in the soft symmetry–breaking interaction terms), \( m_0 \) (common scalar mass at the GUT scale), \( m_{1/2} \) (common gaugino mass at the GUT scale) and \( \mu \). Furthermore, other specific theoretical requirements (features of the symmetry breaking, condition that the neutralino be the LSP, ...) strongly restrict the whole parameter space. This has important consequences; for instance, it constrains the neutralino to compositions with dominance of the gaugino components. It has to be noted that important constraints on the neutralino parameter space may be inferred from the recent data on \( b \to s + \gamma \) process. The precise nature of these constraints still requires further investigation, especially in view of the large uncertainties due to QCD–effects.

In the present note the emphasis is on the investigation power of various detection methods and on their complementarity. On purpose, the model adopted here for the calculations is as simple as possible (not too much constrained by theoretical requirements) with choices for the free masses that are only restricted by experimental bounds.

Our main concern is to discuss the minimal sensitivity required in experimental devices in order to undertake a significant investigation of neutralino dark matter. For this reason we present here evaluations where the smallest values compatible with
experimental lower bounds are assigned to the unknown masses; this usually provides maximal values for the signals. To be definite, in the following we will set the sfermion masses at the value \( m_\tilde{f} = 1.2 \, m_\chi \), when \( m_\chi > 45 \text{ GeV} \), \( m_\tilde{f} = 45 \text{ GeV} \) otherwise. Only the mass of the top squarks are assigned a larger value of 1 TeV. The Higgs mass \( m_h \) is set at the value of 50 GeV. The top mass is fixed at \( m_t = 170 \text{ GeV} \).

2. Neutralino Relic Abundance

For the computation of the direct and indirect event rates for neutralino one has to use a specific value for the neutralino density \( \rho_\chi \). Obviously, it would be inappropriate to assign to the neutralino local density \( \rho_\chi \) the standard value for the total dark matter density \( \rho_t = 0.3 \text{ GeV cm}^{-3} \), unless one specifically verifies that the neutralino relic abundance \( \Omega_\chi h^2 \) turns out to be at the level of an \((\Omega h^2)_{\text{min}}\) consistent with \( \rho_t \). This is why a correct evaluation of the event rates for \( \chi \) detection also requires a calculation of its relic abundance.

Thus we evaluate \( \Omega_\chi h^2 \) and we determine \( \rho_\chi \) by adopting a standard procedure\( ^1 \). when \( \Omega_\chi h^2 \geq (\Omega h^2)_{\text{min}} \), we put \( \rho_\chi = \rho_t \); when \( \Omega_\chi h^2 \) turns out to be less than \((\Omega h^2)_{\text{min}}\), we take

\[
\rho_\chi = \rho_t \frac{\Omega_\chi h^2}{(\Omega h^2)_{\text{min}}}.
\]

(2)

Here \((\Omega h^2)_{\text{min}}\) is set equal to 0.03.

For the neutralino relic abundance \( \Omega_\chi h^2 \) we employ the results of our previous work\( ^2 \). In Fig.1 we display regions of the \( M_2, \mu \) plane which are characterized by different values of \( \Omega_\chi h^2 \). Also shown in this figure are the iso–mass curves (dashed lines) and the iso–compositions curves (solid lines). Along an iso–composition line the composition parameter \( P \) defined as the gaugino fractional weight, i.e. \( P = a_1^2 + a_2^2 \), is kept fixed. In this figure, as well as in the following ones, only results for positive \( \mu \) are displayed.

The results of Fig.1 can conveniently be reported in a \( \Omega_\chi h^2 \) vs. \( m_\chi \) plot, for fixed values of \( P \). This is done in Fig.2 where \( \Omega_\chi h^2 \) is plotted as a function of \( m_\chi \) for three representative neutralino compositions: i) a gaugino–dominated composition (\( P = 0.9 \)), ii) a composition of maximal gaugino–higgsino mixing (\( P = 0.5 \)), iii) a higgsino–dominated composition (\( P = 0.1 \)). As expected, out of the three compositions displayed in Fig.2, the gaugino–dominated state provides the largest values of \( \Omega_\chi h^2 \). In order to have more substantial values of \( \Omega_\chi h^2 \), one has to consider purer gaugino compositions (\( P \gtrsim 0.99 \)). The very pronounced dips in the plots of Fig.2 are due to the s–poles in the \( \chi–\chi \) annihilation cross section (exchange of the \( Z \) and of the neutral Higgses). The sharp decrease at 80–90 GeV is due to the opening of the \( W^+W^- \) and \( ZZ \) final states in the \( \chi–\chi \) annihilation. We remind that \( \Omega_\chi h^2 \propto (\langle \sigma_{\text{ann}} v \rangle_{\text{int}})^{-1} \), where \( \langle \sigma_{\text{ann}} v \rangle_{\text{int}} \) is the annihilation cross section times relative velocity, averaged over the neutralino thermal distribution, integrated from the freezing temperature down to the present temperature.
3. Indirect Detection at Neutrino Telescopes

Let us turn now to the indirect search for neutralino dark matter which can be performed by means of neutrino telescopes. Neutralinos, if present in our galactic halo as dark matter components, would be slowed down by elastic scattering off the nuclei of the celestial bodies (Sun and Earth) and then gravitationally trapped inside them. Due to the process of neutralino capture these macroscopic bodies could accumulate neutralinos which would subsequently annihilate in pairs. An important outcome of this \( \chi - \chi \) annihilation would be a steady flux of neutrinos from these celestial bodies.

The differential neutrino flux at a distance \( d \) from the annihilation region is given by

\[
\frac{dN_\nu}{dE_\nu} = \frac{\Gamma_A}{4\pi d^2} \sum_{F,f} B^{(F)}_{\chi \chi} \frac{dN_{f\nu}}{dE_\nu}
\]

(3)

where \( \Gamma_A \) is the annihilation rate and \( F \) denotes the \( \chi - \chi \) annihilation final states which are: 1) fermion–antifermion pairs, 2) pairs of neutral and charged Higgs bosons, 3) one gauge boson–one Higgs boson pairs, 4) pairs of gauge bosons; \( B^{(F)}_{\chi \chi} \) denotes the branching ratio into the fermion \( f \) (heavy quark or \( \tau \) lepton), in the channel \( F \); \( dN_{f\nu}/dE_\nu \) denotes the differential distribution of the neutrinos generated by the semileptonic decays of the fermion \( f \). The \( \nu_\mu \)'s, crossing the Earth, would convert into muons and generate a signal of up-going muons inside a neutrino telescope. Calculations of this muon flux from the original neutrino flux may be performed using standard procedures.

Particular care has to be taken in the evaluation of the annihilation rate \( \Gamma_A \). This quantity is given by

\[
\Gamma_A = \frac{C}{2} \tanh^2 \left( \frac{t}{\tau_A} \right)
\]

(4)

where \( t \) is the age of the macroscopic body \( (t = 4.5 \text{ Gyr for Sun and Earth}) \), \( \tau_A = (CC_A)^{-1/2} \), \( C \) is the capture rate of neutralinos in the macroscopic body and \( C_A \) is the annihilation rate per effective volume of the body. The capture rate \( C \) is provided by the formula

\[
C = \frac{\rho_\chi}{v_\chi} \sum_i \frac{\sigma_{\text{el},i}}{m_\chi m_i} (M_B f_i) \langle v_{\text{esc}}^2 \rangle_i X_i,
\]

(5)

where \( v_\chi \) is the neutralino mean velocity, \( \sigma_{\text{el},i} \) is the cross section of the neutralino elastic scattering off the nucleus \( i \) of mass \( m_i \) (for some properties of the elastic \( \chi \)-nucleus cross section see next Sect.4 and Ref. 15), \( M_B f_i \) is the total mass of the element \( i \) in the body of mass \( M_B \), \( \langle v_{\text{esc}}^2 \rangle_i \) is the square escape velocity averaged over the distribution of the element \( i \), \( X_i \) is a factor which takes account of kinematical properties occurring in the neutralino–nucleus interactions. \( C_A \) is given by.
\[ C_A = \frac{<\sigma_{\text{ann}}v>_0}{V_0} \left( \frac{m_\chi}{20 \text{ GeV}} \right)^{3/2} \]  

where \(<\sigma_{\text{ann}}v>_0\) is the annihilation cross section times relative velocity, averaged over the neutralino thermal distribution, at present temperature. \(V_0\) is defined as \(V_0 = (3m^2_{\text{Pl}}T/(2\rho \times 10 \text{ GeV}))^{3/2}\) where \(T\) and \(\rho\) are the central temperature and the central density of the celestial body. For the Earth \((T = 6000 \text{ K}, \rho = 13 \text{ g} \cdot \text{cm}^{-3})\) \(V_0 = 2.3 \times 10^{25} \text{ cm}^3\), for the Sun \((T = 1.4 \times 10^7 \text{ K}, \rho = 150 \text{ g} \cdot \text{cm}^{-3})\) \(V_0 = 6.6 \times 10^{28} \text{ cm}^3\).

For the computation of the capture rate (and then also of \(\tau_A\)) one has to use a specific value for the neutralino density \(\rho_\chi\) according to the procedure explained in Sect.2.

The results of our evaluations for the quantities \(C\), \(C_A\) and \(\Gamma_A\) are reported in Ref. 11,12. From these results it turns out that: i) for the Sun, the equilibrium between capture and annihilation is reached over the whole \(m_\chi\) range; ii) in the case of the Earth, equilibrium is not reached for \(m_\chi > \sim m_W\), because of the substantial suppression introduced in \(\Gamma_A\) by the factor \(\tanh^2(t/\tau_A)\).

Now we report some of our results about the flux of the up–going muons in the case of \(\chi–\chi\) annihilation in the Earth. In Fig.3 we show the fluxes of the up–going muons as functions of \(m_\chi\) for a number of values of the neutralino composition \(\tilde{P}\), for \(\chi–\chi\) annihilation in the Earth. The threshold for the muon energy is \(E_{\mu}^{\text{th}} = 2 \text{ GeV}\). We recall here that the present experimental upper bound for signals coming from the Earth is \(4.0 \times 10^{-14} \text{ cm}^{-2} \text{ s}^{-1} \) (90 % C.L.) [14]. By comparing this upper limit with our fluxes we see that the regions explored by Kamiokande (at our representative point: \(\tan \beta = 8, m_h = 50 \text{ GeV}\)) concern the mass range \(50 \text{ GeV} \lesssim m_\chi \lesssim 65 \text{ GeV}\). These regions are illustrated in Fig.4 in a \(M_2–\mu\) plot. In this figure we also display the regions which could be explored by a neutrino telescope with an improvement factor of 10 (and of 100) in sensitivity.

The location and the shape of the most easily explorable regions in the \(M_2–\mu\) plane depend on the Earth chemical composition and on the neutralino composition in terms of the gaugino, higgsino components. In fact the capture rate of neutralinos is more effective when neutralino mass matches the mass of some of the main components of the Earth and when the neutralino is a large gaugino–higgsino mixture. Because of these two properties the signal is maximal along iso–mass lines in the range 50–65 GeV, with elongations along iso–composition lines of sizeable mixing.

In Fig.5 we report the fluxes for up–going muons as functions of \(m_\chi\) due to \(\chi–\chi\) annihilation in the Sun. As before the threshold for the muon energy is \(E_{\mu}^{\text{th}} = 2 \text{ GeV}\). The evaluated fluxes are below the present experimental upper limit of Kamiokande: \(6.6 \times 10^{-14} \text{ cm}^{-2} \text{ s}^{-1} \) (90 % C.L.) [14]. The regions explorable by a neutrino telescope with an improvement factor of 10 (and of 100) in sensitivity respect to the present Kamiokande sensitivity are displayed in Fig.6. Here the regions that are more easily explorable, expand toward gaugino–dominated compositions since spin–dependent cross sections (with exchange of light squarks) are important in the capture of neutralinos by the Sun.
From these results it can be concluded that neutrino telescopes with an area above $10^5 \text{m}^2$ are very powerful tools for investigating neutralino dark matter in large regions of the parameter space. It also emerges from the previous results that the signals from the Earth and from the Sun somewhat complement each other to allow an exploration about DM neutralino over a wide range of $m_\chi$. In Ref. 12 has been derived the relation between the exposure $At$ of a neutrino telescope ($A$ being the telescope area, $t$ the live time) and the explorable range in the neutralino parameter space, when the signal–to–background ratio is optimized by appropriate angular selections.

4. Direct Detection

Another way to search for dark matter neutralinos is the direct detection which relies on the measurement of the recoil energy of nuclei of a detector, due to elastic scattering of $\chi$'s. The relevant quantities to calculate are the differential rate (in the nuclear recoil energy $E_r$):

$$\frac{dR}{dE_r} = N_T \frac{\rho_\chi}{m_\chi} \int_{v_{\text{min}}(E_r)}^{v_{\text{max}}(E_r)} dv f(v) v \frac{d\sigma_{\text{el}}}{dE_r}(v, E_r)$$

and the integrated rate $R_{\text{int}}$, which is the integral of Eq. (7) from the threshold energy $E_r^{\text{th}}$, which is a characteristic feature of the detector, up to a maximal energy $E_r^{\text{max}}$. In Eq.(7) $N_T$ denotes the number of target nuclei, $d\sigma_{\text{el}}/dE_r$ is the differential elastic cross section and $f(v)$ is the distribution of $\chi$ velocities in the Galaxy. It is important to note again that the local density $\rho_\chi$ is evaluated here according to the procedure discussed in Sect.2. In general, the $\chi$–nucleus cross section has two contributions: a coherent contribution, depending on $A^2$ ($A$ is the mass number of the nucleus) which is due to Higgs and $\tilde{q}$ exchange diagrams; a spin–dependent contribution, arising from $Z$ and $\bar{q}$ exchange, proportional to $\lambda^2 J(J+1)$.

By way of example, let us remind the expression of the coherent cross section due to the Higgs–exchange:

$$\sigma_{\text{el},H} = \frac{8G_F^2}{\pi} \alpha_H^2 A^2 \frac{m_Z^2}{m_h^2} \frac{m_\chi^2 m_i^2}{(m_i + m_\chi)^2}$$

where $\alpha_H$ is a quantity depending on the neutralino–Higgs and the Higgs–quarks couplings. It is worth mentioning that $\alpha_H$ depends rather sensitively on the $\chi$–composition and on a number of parameters, such as $\tan \beta$ and the Higgs masses.

Except for very special points in the parameter space, the coherent contribution to elastic cross section strongly dominates over the spin–dependent one. For a detailed analysis on the calculation of the direct event rates see Ref. 19 and references quoted therein. For an experimental overview about dark matter detectors see Ref. 20.

Here, as an example, we simply report in Fig.7 the event rates $R_{\text{int}}$ for a Germanium detector as a function of $m_\chi$ for neutralino compositions $P = 0.1, 0.5, 0.9$. Rates are calculated by integrating the differential rate of Eq.(7) over the electron–equivalent energy range (2–4) KeV. In Fig.8 we show the regions of the $M_2$–$\mu$ parameter space
which can be explored with an improvement of one and two orders of magnitude in the sensitivity of the detector.

As for the shape of these regions we refer to the comments presented above, in Sect.3, in connection with Fig.4. Again, the signals are higher along the iso–mass line with an \( m_\chi \) close to the mass of the nuclei composing the detector. Thus, using detectors of different compositions allows explorations of the \( M_2-\mu \) plane over a wide range in \( m_\chi \). For instance, investigation of regions with small \( m_\chi \) values (of order of 10 GeV) with very low threshold detectors would be very interesting. In fact this \( m_\chi \) range (which is excluded by accelerator data only under a number of assumptions) is out of reach for the indirect detection discussed in the previous Section.

5. Comparison between Direct and Indirect Signals

Fig.s 3,5,7 provide a comparison between the capabilities of the direct detection versus the detection by neutrino telescopes. It has to be noted that these figures refer to an arbitrary representative point of the parameter space. However, since both (direct and indirect) signals depend mainly on a common quantity, i.e. the \( \chi \)–nucleus elastic scattering, the relative size is approximately independent of the variation of the model parameters. The main departures from this feature occur in the case of the signal from the Earth in regions where the factor \( \tanh^2(t/\tau_A) \) is small and for the signal from the Sun in regions where spin–dependent effects in the capture rate are dominant. Fig.s 3,5,7 also display how the the theoretical predictions compare with the present sensitivity for each individual method. A comparison of the relative power of the two detection methods for exploring the \( M_2-\mu \) plane is provided by Fig.s 4,6,8.

6. Conclusions

In the previous sections we have examined two types of detection methods for relic neutralinos, one based on direct measurement and one on the detection of indirect signals due to \( \chi-\chi \) annihilation in celestial bodies. As we have seen by the explicit expressions given in Sect.s 3–4, in both cases the detection rates are proportional to the neutralino local density and to the elastic neutralino–nucleus cross section: \( R \propto \rho_\chi \sigma_{el} \) (for simplicity, here and in the following, we consider the neutralino mass fixed at some arbitrary value \( m_\chi \); the other free parameters may vary in the parameter space along iso–mass curves).

Because of the properties discussed in Sect.2, once the neutralino relic abundance is evaluated, one has to distinguish between two cases:

a) \( \Omega_\chi \geq \Omega_{min} \) which entails \( R \propto \sigma_{el} \)

b) \( \Omega_\chi < \Omega_{min} \) which entails \( R \propto \sigma_{el}/<\sigma_{ann}v>_{int} \)

Now, if the strength of the couplings increases, and hence \( \sigma_{el} \) and \( \sigma_{ann} \) increase, it turns out that also in case b) the rates \( R \) usually increase even if at a much less extent than in case a). It then happens that for the two detection methods discussed
so far, the largest values of the detection rates for relic neutralinos occur for models where $\tan \beta$ is large and neutralino is largely mixed (this last condition has to be somewhat relaxed for the signal from the Sun, as discussed above). For these models, because of the large value of the annihilation cross section, the neutralino relic density is small. This is a scenario where the detection methods under discussion have good chances to detect relic neutralinos, even if these particles cannot provide a substantial contribution to the total $\Omega$ of the Universe. Regions of the parameter space where this situation occurs are defined by some authors as cosmologically uninteresting and consequently disregarded. On the contrary, we believe that they deserve a careful investigation, since much interesting physics could occur there. The relevance of this point is further confirmed by some recent results derived from SUGRA theories where some of the universality properties, usually required at the GUT scale, are relaxed. In fact it turns out that, in this case, very interesting schemes with large neutralino mixing, large $\tan \beta$ and small relic abundance naturally emerge.

As we have seen, when $\Omega_\chi$ is large the two detection techniques previously discussed have less chances to succeed (except for the signal from the Sun, which however requires neutrino telescopes of very large area). In order to cover this case adequately, one may resort to different detection methods. These are based on the measurements of indirect signals due to neutralino–neutralino annihilation in the Galactic halo. These have been widely discussed in the literature; we refer to Ref. 23 for previous references and for a new analysis aimed at the evaluation of the antiproton to proton ratio $(\bar{p}/p)$ in cosmic rays. A common feature of this class of measurements is that the event rates are typically proportional to the square of the local neutralino density times the annihilation cross section: $R \propto \rho_\chi^2 \sigma_{\text{ann}} v >_0$. This implies that, in this case, detection rates are high in regions of the parameter space where the neutralino relic abundance is large. By way of example, we give in Fig.9 the regions of $M_2 – \mu$ plane that can be explored by measuring the $(\bar{p}/p)$ ratio.

In conclusion we may state that complementarity among various detection methods may potentially offer a good coverage of the neutralino parameter space.

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