Cold Dark Matter and Neutralinos
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Neutralinos are natural candidates for cold dark matter in many realizations of supersymmetry. We briefly review our recent results in the evaluation of neutralino relic abundance and direct detection rates in a class of supergravity models.

1. Introduction

The fact that most of the Universe is dark and composed of new, exotic components has been established over the years by means of various sets of observations, which recently have converged into a consistent picture where the Universe is about critical and dominated by an exotic form of matter and by an unexpected type of dark energy. In terms of the density parameter \( \Omega \), the current view can be summarized as follows: the total amount of matter/energy of the Universe is \( \Omega_{\text{tot}} \simeq 1 \) at the 10\% level and this is composed of a matter component \( \Omega_M \simeq 0.3 \) and a vacuum–energy component \( \Omega_\Lambda \simeq 0.7 \) \cite{1}. The existence of both dark exotic matter and dark energy asks for extension of the standard model of fundamental interactions, since no known particle or field can represent either of these components. In this paper, we will deal with the problem of explaining the observed amount of dark matter, which we can summarize as: \( 0.05 \lesssim \Omega_M h^2 \lesssim 0.3 \), and with the studies related to the searches for dark matter particles. For an updated review on these subjects, see Ref. \cite{2}.

2. Neutralino dark matter in Supergravity

Supersymmetric models with \( R \)-parity conservation naturally predict the existence of a stable relic particle. The nature and the properties of this particle depend on the way supersymmetry is broken. In particular, the neutralino happens to be the dark matter candidate in models where supersymmetry is broken through gravity–(or anomaly–) mediated mechanisms. The actual implementation of a specific susy scheme depends on a number of assumptions on the structure of the model and on the relations among its parameters. This induces a large variability on the phenomenology of neutralino dark matter.

The simplest and most direct implementation of supersymmetry is represented by the \textit{minimal supergravity} (mSUGRA) scheme, where gauge coupling constants are unified at the GUT scale and at the same scale also the susy–breaking mass parameters are universal. The low–energy sector is obtained through renormalization group evolution of all the parameters of the model, and this also induces the breaking of the electroweak symmetry in a radiative way. This model is very predictive, since it relies only on four free parameters. However, neutralino phenomenology is quite constrained \cite{2,4} and also quite sensitive to some Standard Model parameters, like the mass of the top and bottom quarks (\( m_t \) and \( m_b \)) and the strong coupling constant \( \alpha_s \) \cite{5}. Less con-
Neutralino relic abundance in mSUGRA models is shown in Figs. 1 and 2. All the mSUGRA parameters are varied except for $\tan \beta$ (the ratio of the two Higgs vev’s) which has been fixed at two representative values. Here and hereafter, $m_b, m_t$ and $\alpha_s$ are varied inside their 95% C.L. allowed ranges. We notice that for $\tan \beta \lesssim 40$ the requirement that the neutralino relic abundance does not conflict with the cosmological observation on the amount of dark matter in the Universe poses severe constraints on the mSUGRA parameter space. This is not the case for large values of $\tan \beta$.

The results shown in Figs. 1 and 2 are valid in a standard cosmological model for the evolution of the Universe. The results may be quite different in models of the early Universe where the temperature at the end of the reheating phase is low. In this low–reheating models, the strong constraints which are induced on the mSUGRA parameter space at $\tan \beta \lesssim 40$ are strongly relaxed, depending on the actual value of the reheating temperature. The requirement that neutralinos provide a sizable contribution to dark matter, i.e. that the neutralino relic abundance lies in the range $0.05 < \Omega_M h^2 < 0.3$, implies that the reheating temperature of the Universe cannot be smaller than about 1 GeV in mSUGRA models.

Direct detection relies on the scattering of dark matter particles off the nuclei in a low–background detector. The detection rate depends on the neutralino–nucleus scattering cross section, which is usually dominated by the coherent interaction, and is sensitive to the local properties of the neutralinos in the halo, i.e. its local abundance $\rho_\chi$ and its local velocity distribution (for a recent and exhaustive analysis on this topic, see Ref. 7). The current sensitivity of direct

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**Figure 1.** $m_{1/2} - m_0$ plane at $\tan \beta = 30$ in mSUGRA. The dotted (red) region denotes where the neutralino relic abundance lies in the cosmologically relevant range $0.05 \leq \Omega_M h^2 \leq 0.3$. The light–dotted (yellow) area is excluded by experimental and theoretical constraints.

**Figure 2.** The same as in Fig. 1, for $\tan \beta = 50$. The dotted (red) light regions denote where the neutralino relic abundance lies in the cosmologically relevant range. The hatched (blue) region refers to a cosmologically sub–dominant neutralino, i.e. $\Omega_\chi h^2 < 0.05$. 

strained susy implementations are obtained by relaxing the universality conditions (non–universal SUGRA models) or by defining the relevant susy framework directly at the electro–weak scale as an effective low–energy theory (low–energy minimal supersymmetric standard model).
Figure 3. Scatter plot of the values of the product $\xi \sigma^{(\text{nucleon})}_{\text{scalar}}$ between the scaling parameter $\xi$ and the neutralino–nucleon scalar cross section, vs. the neutralino mass $m_\chi$, for a generic scan of the mSUGRA parameter space. (Red) crosses refer to $0.05 \leq \Omega_\chi h^2 \leq 0.3$, while (blue) dots denote configurations with $\Omega_\chi h^2 < 0.05$. $m_t$, $m_b$, and $\alpha_s$ are varied inside their 95% C.L. allowed ranges. The shaded (green) area shows the region which, for a relic particle with pure coherent interactions, is compatible with the annual modulation effect observed by the DAMA/NaI experiment.

Detection experiments on the neutralino–nucleon cross section is: few $\cdot 10^{-10}$ nbarn $\lesssim \xi \sigma^{(\text{nucleon})}_{\text{scalar}}$ $\lesssim$ few $\cdot 10^{-8}$ nbarn for neutralino masses in the range: 30 GeV $\lesssim m_\chi \lesssim 300$ GeV. These ranges take into account a large variability of galactic halo models. The quantity $\xi \leq 1$ measures the fraction of local dark matter to be ascribed to the neutralino $\rho_\chi = \xi \rho_l$, where $0.18 \lesssim \rho_l/(\text{GeV cm}^{-3}) \lesssim 1.68$ denotes the local value of the total halo dark matter.

Fig. 3 shows the results of our theoretical calculations in the mSUGRA scheme. The quantity $\xi$, which determines whether the neutralino is a dominant or sub–dominant dark matter component, is calculated according to its relic abundance as: $\xi = \min(1, \Omega_\chi h^2/0.05)$. The closed shaded area represents the DAMA/NaI region which is obtained when the annual modulation effect observed by the DAMA Collaboration is interpreted as due to a dark matter particle whose interactions with nuclei are dominated by coherent scattering. A careful and exhaustive modeling of the galactic halo properties has been performed in obtaining the region showed in Fig. 3.

The question whether current direct detection sensitivities are probing dominant or subdominant relic neutralinos may be answered in terms of the plot shown if Fig. 4, which translates di-
rectly in terms of astrophysical and cosmological quantities the direct detection results. By considering the current interval of sensitivities on the quantity \([\rho_\chi \times n_{\text{scalar}}(\text{nucleon})]\), the calculation of \(n_{\text{scalar}}(\text{nucleon})\) allows us to determine the values of \(\rho_\chi\) which are required, for each susy configuration, in order to provide a detectable signal. Fig.4 shows the calculated values of \(\rho_\chi\) vs. the neutralino relic abundance, for the mSUGRA scheme. We see that a fraction of susy models overlap with the region of main cosmological and astrophysical interest: \(0.05 < \Omega_\chi h^2 < 0.3\) and \(0.18 < \rho_\chi/(\text{GeVcm}^{-3}) < 1.68\). For points in this region, the neutralino is the dominant component of dark matter both in the Universe and at the galactic level. For points which fall inside the band delimited by the slant dot–dashed lines, the neutralino would provide only a fraction of the cold dark matter density both at the level of local density and at the level of the average \(\Omega\), a situation which would be possible if the neutralino is not the unique cold dark matter particle component. On the other hand, configurations above the upper dot–dashed line and below the upper horizontal dashed line would imply the somewhat more unlikely situation of a stronger clustering of neutralinos in our halo as compared to their average distribution in the Universe. Finally, configurations above the upper horizontal line are incompatible with the upper limit on the local density of dark matter in our Galaxy.

3. Conclusions

We can certainly define the following items as the current main issues and open problems in particle dark matter studies: \(i\)) to explain the observed amount of dark matter in the Universe (\(0.05 < \Omega_\chi h^2 < 0.3\)) by finding suitable particle candidates; \(ii\)) to detect a relic particle. We have shown that for both of these issues, there appear to be good prospects of success, especially for the most studied candidate which is the neutralino. In particular, there are many susy schemes where relic neutralinos can provide enough cosmological abundance to explain the observed amount of dark matter, and at the same time they can have detection rates large enough to be accessible to detection. Clearly the occurrence of this particularly interesting situation depends on the actual realization of supersymmetry. The observation of a signal from dark matter, like for instance in the case of the annual modulation effect observed by the DAMA/NaI Collaboration or of signals which could hopefully come in future experiments, can be very important not only for astrophysics and cosmology but also for particle physics, since the need to explain such effects can help in deriving properties of particle physics models and possibly discriminate among different realizations, for instance of supersymmetry.

REFERENCES

1. For a recent updated review on the subjects concerning dark matter and dark energy, see the Proceedings of TAUP 2001, Nucl. Phys. (Proc. Suppl.) B 110 (2002).
2. N. Fornengo, invited review talk at TAUP 2001, Nucl. Phys. (Proc. Suppl.) B 110 (2002) 26 [arXiv:hep-ph/0201154].
3. A. Bottino, F. Domato, N. Fornengo and S. Scopel, Phys. Lett. B423 (1998) 109 [arXiv:hep-ph/9709292]; Phys. Rev. D 59 (1999) 095003 [arXiv:hep-ph/9808456]; Phys. Rev. D 59 (1999) 095004 [arXiv:hep-ph/9808455]; Phys. Rev. D 62 (2000) 056006 [arXiv:hep-ph/0001300]; Phys. Rev. D 63 (2001) 125003 [arXiv:hep-ph/0010203].
4. For an updated list of references to theoretical papers on direct detection, see Ref. 3.
5. G.F. Giudice, E.W. Kolb and A. Riotto, Phys. Rev. D64 (2001) 023508.
6. N. Fornengo, A. Riotto and S. Scopel, in preparation.
7. P. Belli, R. Cerulli, N. Fornengo and S. Scopel, [arXiv:hep-ph/0203242] to appear in Phys. Rev. D.
8. R. Bernabei et al. (DAMA/NaI Collaboration), Phys. Lett. B424 (1998) 195; Phys. Lett. B450 (1999) 448; Phys. Lett. B480 (2000) 23.