Search for Supersymmetric Dark Matter with Superfluid $^3\text{He}$ (MACHe3)

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Abstract

MACHe3 (MAtrix of Cells of superfluid $^3\text{He}$) is a project of a new detector for direct Dark Matter search, using superfluid $^3\text{He}$ as a sensitive medium. This paper presents a phenomenological study done with the DarkSUSY code, in order to investigate the discovery potential of this project of detector, as well as its complementarity with existing and planned devices.

Key words: Dark Matter, Supersymmetry, Superfluid Helium-3, Bolometer.

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1 Introduction

A substantial body of astrophysical evidence supports the existence of non-baryonic Dark Matter (DM) in the halo of our galaxy, in particular in the form of new, yet undiscovered, weakly interactive massive particles (WIMPs) [1]. One of the leading candidates is the neutralino predicted by the supersymmetric extensions of the Standard Model of particle physics.

Following early experimental works [2], a superfluid $^3\text{He}$ detector has recently been proposed [3] for direct Dark Matter search. Monte Carlo simulations have shown that a high granularity detector, a matrix of superfluid $^3\text{He}$ cells, would allow to reach a high rejection factor against background events, leading to a

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low false event rate. The purpose of this paper is to present a full estimation of the neutralino $(\tilde{\chi})$ event rate, within the framework of the Minimal Supersymmetric Standard Model (MSSM), in order to compare with background event rate obtained by Monte Carlo simulation [3,4]. Finally, the complementarity with existing devices, both for direct and indirect detection, will be shown.

1.1 Experimental device

The elementary component of MACHe3 is the superfluid $^3$He cell [5,6]. It is a small copper cubic box ($V \simeq 125 \text{mm}^3$) filled with superfluid $^3$He in the B-phase. This ultra low temperature device ($T \simeq 100 \mu\text{K}$) presents a low detection threshold ($E_{th} \simeq 1 \text{keV}$). An experimental test of such a prototype cell has been done at CRTBT in June 2001. Preliminary results [7,8] show that a threshold value down to $\sim 1 \text{keV}$ has been achieved, and that a stability of the order of one week, at $T \simeq 100 \mu\text{K}$, has been obtained.

The final version of the detector will be a matrix of 1000 cells of $125 \text{cm}^3$ each. The idea is to take advantage both on the energy loss measurement and the correlation among the cells to discriminate neutralino events from those of background (neutrons, $\gamma$-rays and muons). The design of the matrix has been optimized, with a Monte Carlo simulation [3]. In the preferred configuration, a 10 kg detector, the false event rate has been shown to be as small as $\sim 10^{-1} \text{day}^{-1}$ for neutron events and $\sim 10^{-2} \text{day}^{-1}$ for muon events [3].

Background from $\gamma$-ray events needs to be taken into account. Energy loss measurement and correlation among the cells within a 10 kg detector allows to obtain a rejection up to 99.8% for $\sim 2 \text{MeV}$ $\gamma$-rays [3]. Additionnal internal tag on $\gamma$-rays may be obtained using a new matrix configuration in which two neigbouring cells share a common copper wall, thus greatly improving correlation factor while reducing the amount of copper used. Monte Carlo studies are under way [8]. Furthermore, $\gamma$-ray contamination is to be estimated in the forthcoming months for a multicellular prototype matrix.

In order to compare these false event rates with the expected neutralino rate, only muons and neutrons will be taken into account in the following. We shall recall that neutrons are usually considered as the ultimate background noise for this type of search, as they interact a priori like WIMPs.

1.2 $^3$He as a sensitive medium for direct DM search

Several properties of $^3$He make this nucleus a promising candidate for a sensitive medium for direct DM search.

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2 Fast neutron contribution, from interaction of muons in the rock, is expected to be negligible as the energy release in the cell will be much greater than 6 keV.
a) Concerning background rejection, and as outlined in [3,9], the neutron capture process offers the possibility to discriminate neutron and $\tilde{\chi}$ event, when considering a 10 kg granular detector. Compton cross-section being small ($\sigma \lesssim 1$ barn), the interactions with $\gamma$-rays will be minimized. Eventually, as explained in [6], superfluid $^3$He is produced with an extremely high purity, the only solute being $^4$He in a negligible fraction. Consequently, no contamination from radioactive materials is expected in the sensitive medium. Of course, natural radioactivity from external materials (Cu, ...) has to be taken into account, by a careful selection of these materials.

b) Concerning neutralino detection the advantage is twofold. First, the maximum recoil energy does only slightly depend on the neutralino mass, due to the fact that the target nucleus ($m = 2.81$ GeV/$c^2$) is much lighter than the incoming $\tilde{\chi}$ ($M_{\tilde{\chi}} \geq 32$ GeV/$c^2$), considering latest results from collider experiments [10]. As a matter of fact, the recoil energy range needs to be studied only below 6 keV, see [3,7]. Second, $^4$He being a 1/2 spin nucleus, an $^3$He detector will be sensitive mainly to axial interaction, making this device complementary to existing ones, as shown below. In fact, the axial interaction is largely dominant (up to three orders of magnitude) in all the SUSY region associated with a substantial elastic cross-section [7].

1.3 Theoretical framework

This phenomenological study has been done with the DarkSUSY code\(^3\) [11], within the framework of the phenomenological Supersymmetric Model, namely with the following free parameters:

$$\mu, M_2, \tan \beta, m_A, m_0 \text{ and } A_{b,t}$$

(1)

with $\mu$ ($M_2$) the Higgsino (Gaugino) mass parameter, $\tan \beta$ the ratio of Higgs vacuum expectation values, $m_A$ the CP-odd Higgs boson mass, $m_0$ the common scalar mass and $A_{b,t}$ the soft trilinear coupling parameters\(^4\).

Apart from $A_{b,t}$ chosen at fixed zero value, as their influence is expected to be negligible, all the parameters have been scanned on a large range, with a variable number of steps (tab. 1). This scan of the free parameters corresponds to a total number of supersymmetric (SUSY) models of the order of $2 \times 10^6$.

We shall suppose all through this work the neutralino ($\tilde{\chi}$), the lightest supersymmetric particle, as the particle making up the bulk of galactic cold DM. Each SUSY model is then checked not to be excluded by collider experiments [10], including $b \to s\gamma$ limit.

\(^3\) The version used is 3.14.01, with correction of some minor bugs.

\(^4\) For a good introduction to MSSM models, we refer the reader to [12].
The next step, the evaluation of the relic density, is the key point of any Dark Matter calculations. Given the number of free parameters (5 in our case), the allowed SUSY parameter space may be extremely large, leading to a $\tilde{\chi}$ relic density ranging on up to five orders of magnitude [7]. In order to exclude SUSY models giving a $\tilde{\chi}$ relic density too far away from the estimated matter density in the Universe [13] ($\Omega_M \simeq 0.3$), only models with $\Omega_\chi$ in the following range are considered:

$$0.025 \leq \Omega_\chi h_0^2 \leq 1$$

(2)

where $h_0 = (0.71 \pm 0.07) \times 1.15$ is the normalized Hubble expansion rate [10]. The lower limit comes from the condition that the neutralino relic density has to be at least greater than the baryonic density, and the upper limit is a conservative limit so that $\tilde{\chi}$ do not give a density greater than the Universe [14]. The SUSY model is thus checked to really provide a good non-baryonic Dark Matter candidate. We follow [14] in the choice of the ”cosmologically interesting” range of $\Omega_\chi$. It should be noticed that this loose selection allows to exclude a large number of models in our SUSY scan. For further details concerning the calculation of the $\tilde{\chi}$ relic density, we refer the reader to [11].

As the detection on earth is concerned, a galactic halo model has to be considered. In the following, standard parameters have been used, in a spherical isothermal halo distribution, with a local density ($\rho_0$) and an average velocity ($v_0$), with the following values:

$$\rho_0 = 0.3 \text{GeV}/c^2 \text{cm}^{-3} \text{ and } v_0 = 220 \text{ km s}^{-1}$$

(3)

These parameters are widely used for dark matter detection computations, see [15] for instance. No clumpy galactic dark matter structures [16] are considered hereafter, since the effect is expected to be small both for direct detection and neutrino telescopes, in which the signal depends on the local halo density, as emphasized in [17].

2 Spin dependent cross-section and event rate

As early recognized by Goodman and Witten [18], the interaction between neutralino and quarks may be either spin dependent or spin independent, involving different Feynman diagrams [1]. In the general WIMP case, the allowed interactions are : vectorial, axial and scalar. The neutralino being a Majorana fermion, the vectorial interaction vanishes, leaving two classes of interaction : scalar and axial, the first one being spin independent, the second spin dependent and obviously requiring a non-zero spin nucleus. $^3$He being a light 1/2

$^5$ It can be noticed that selecting on $\Omega_\chi h_0^2$ allows for a slightly looser selection.
spin nucleus, a medium made of such nuclei will be sensitive only to axial interaction, as shown in [7].

Using the DarkSUSY code, the $\tilde{\chi}^3\text{He}$ spin dependent cross-section has been evaluated. The calculation of the $\tilde{\chi}$-quark elastic scattering amplitude is done at the tree-level, via an exchange of squark or $Z^0$. The amplitude on nucleon ($a_{p/n}$) is then evaluated by adding the contribution of each quark ($a_{q_i}$), weighted by the quark contents of the nucleon:

$$a_{p/n} = \sum_i \frac{\Delta_i^{(p/n)} a_{q_i}}{\sqrt{2} G_F}$$

where $\Delta_i^{(p/n)}$ is the quark contents of the nucleon [19].

The axial cross-section on $^3\text{He}$ is then given by:

$$\sigma_{\text{spin}}(^3\text{He}) = \frac{32}{\pi} G_F^2 m_r^2 \frac{(J + 1)}{J} (a_p < S_p > + a_n < S_n >)^2$$

where $< S_{p/n} >$ is the spin contents of the $^3\text{He}$ nucleus ($< S_p >$ = -0.05 and $< S_n >$ = 0.49), $m_r$ is the reduced mass and $J$ the ground state angular momentum of the $^3\text{He}$ nucleus.

Figure 1 presents the cross-section on $^3\text{He}$ as a function of the $\tilde{\chi}$ mass. It can be seen that, for SUSY models not excluded by collider experiments and giving a relic density within the range of interest, a cross-section as high as $\sim 10^{-2}$ pb can be obtained for $\sim 60$ GeV/c$^2$ neutralino.

Using the cross-section, the $\tilde{\chi}$ event rate (R) has been evaluated for a 10 kg $^3\text{He}$ matrix, for comparison with the background rate previously evaluated [3].

$$R = \frac{\sigma(^3\text{He})}{M_{\chi}} \times \rho_0 \times v_0 \times \frac{M_{\text{det}}}{M_{\text{He}}}$$

with $\rho_0$ the local halo density and $v_0$ the average neutralino velocity (eq. 3).

A large number of models are giving a rate higher than the estimated false event rate induced by neutrons ($\sim 0.1$ day$^{-1}$), or above the estimated muon background ($\sim 10^{-2}$ day$^{-1}$). It could thus be concluded that a high granularity $^3\text{He}$ detector would present a sensitivity to a large part of the SUSY region.

In the following, the $\mu$ background level ($10^{-2}$ day$^{-1}$) is considered to be the lowest reachable limit for MACHHe3 and it is thus taken as the reference value. Any model giving a rate greater than this value is considered hereafter to be visible. This will be used for the comparison with other DM search strategies.
3 Complementarity with existing devices

We present a study of the discovery potential of various detection strategies that may be correlated with MACHe3. It is indeed worth understanding whether planned projects would be sensitive to different SUSY regions. In each case, we will take into account background estimations, or projected limits, in order to investigate the different discovery potentials. Choosing conservative values will allow to study the phenomenology of various searches without bias. It should be noticed that the results are model-dependent, both SUSY and galactic halo ones. However, standard galactic parameters have been considered and the large SUSY scan allows for an exhaustive study within phenomenological MSSM model.

3.1 Complementarity with scalar detection

Firstly, we studied the possible correlation between the two types of direct detection: axial and scalar. In the latter case, many detectors are already running, or planned to start measurements in the near future. At first sight, these two direct searches should be largely independent as they involve different processes, in particular the Feynman diagrams at the tree level are different.

Within the framework of the study described above, the proton scalar cross-section has been evaluated at the tree level. Figure 2 presents the scalar cross-section on proton as a function of the $\tilde{\chi}$ mass, for all models of the scan not excluded by collider experiments and associated with a relic density within the range of interest (eq. 2). It can be seen that many SUSY models lie below the projected limits of future scalar detectors (CDMS [21], CRESST [23]), while giving an event rate above the value taken as the lowest reachable limit for MACHe3.

As an illustration of this complementarity, we present on fig. 3 the regions potentially covered by direct scalar search and by MACHe3, in a given part of the SUSY parameter space (see fig. 3 for details). The reference limits have be chosen as : the CDMS projected limit [15] in one case and the $10^{-2}$ day$^{-1}$ limit for MACHe3, previously discussed.

It can be noticed that only axial direct search may be sensitive to the $\mu < 0$ region, in this given part of the SUSY parameter space, due to the fact that scalar interaction vanishes. The cancellation arises in the $t$ channel (Higgs exchange) which is dominant, with u and d quark contributions of opposite sign and absolute values of the same order [24]. Similar cancellation does arise

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6 Higher order diagrams, involving gluon loops [1], are not taken into account in the current version of DarkSUSY.
for different value of \( \tan \beta \), in the case of axial interaction. It can be concluded that these two detection strategies are sensitive, as expected, to different SUSY regions, thus highlighting their complementarity.

### 3.2 Complementarity with indirect detection

Amongst various kind of indirect searches \( (\bar{p}, \bar{D}, e^+, \gamma, \nu) \), the detection expected in neutrino telescopes is the only one likely to be correlated with direct detection, as it involves both elastic scattering and annihilation. The neutralino capture may occur either in the Sun or in the Earth, through successive elastic scatterings. As far as comparison with direct detection is concerned, the key point is that the composition of the Sun and the Earth are different. While the Earth is mainly made of even-even nuclei (O, Si, Mg, Fe), the Sun is mainly made of H and He. So one expects the signal coming from annihilation in the centre of the Earth to be only correlated with the signal expected from scalar direct detection. On the contrary, the Sun being made of both even and odd nuclei, a very light correlation is expected with direct detection, both scalar and axial.

Within the framework of the study described above, we tried to find out whether the MACHe3 project would present a complementarity with the project of \( \nu \) telescopes, such as IceCube [26] or Antares [27]. These projects aimed at building a very large detector, of size of the order of 1 km\(^3\). The instrumentation will thus be loose, giving a rather high detection threshold. We follow [25] in choosing a reference threshold of 25 GeV.

Figure 4 shows the result of the calculation for \( \nu \) telescopes and MACHe3. The expected \( \mu \) flux (km\(^{-2}\) year\(^{-1}\)) is shown against the rate in MACHe3 (day\(^{-1}\)). The background usually taken as ultimate for \( \nu \) telescopes, coming from the interaction of cosmic rays in the sun’s corona [28], is indicated at a level of \( \sim 10 \) km\(^{-2}\) year\(^{-1}\). We consider this value as the most favourable limit for these projects of km\(^3\) detectors. In the same way, the background noise from \( \mu \) in MACHe3 is taken as the lowest reachable level, as discussed above (sec. 2). Any model above these limits are said hereafter to be visible for this type of detection. It can be concluded from fig. 4 that there is a complementarity between indirect \( \nu \) detection and axial direct detection, and in particular in the case of the MACHe3 detector. Many models may be visible in only one kind of detection strategy, high mass neutralinos being seen, for instance, only in \( \nu \) telescopes.

As for the comparison between scalar and axial detection, we present on fig. 5 the SUSY regions potentially observable for these two types of detection strategies. As expected, neutrino telescopes are sensitive to higher values of \( M_2 \). For this given region of the SUSY parameter space, it can be concluded that the combination of these two signals may close the gap between collider excluded
region and cosmological bounded regions, up to high $M_2$ values.

4 Conclusion

It has been shown that a 10 kg high granularity $^3$He detector (MACHe3) would allow to obtain, in many SUSY models, a $\tilde{\chi}$ event rate higher than the estimated (neutrons and muons) background. MACHe3 would thus potentially allow to reach a large part of the SUSY region, not excluded by current collider limits and for which the neutralino relic density lies within the range of interest. Furthermore, it has been shown that this project of new detector would be sensitive to SUSY regions not covered by future or ongoing DM search detectors, both for direct and indirect detection, thus highlighting the complementarity of MACHe3 with existing or planned devices.

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Scalar cross-section (on proton) as a function of the $\tilde{\chi}$ mass, for all models of the scan not excluded neither by colliders nor by cosmological constraints. Exclusion limits from the Edelweiss [20] and CDMS [21] experiments are shown, as well as the 3 $\sigma$ “DAMA region” [22]. Dotted lines indicate projected limits [15] from CRESST [23] and CDMS. Dark points indicate SUSY models giving a $\chi$ rate in MACHe3 lower than the estimated background level, while light points are giving a rate higher than $10^{-2}$ day$^{-1}$. The two regions are overlapping as the signal in MACHe3 is not correlated with scalar cross-section.

Sensitivity regions for scalar search and MACHe3, in the $(M_2, \mu)$ plane. The three figures have been obtained with $\tan \beta = 10$, $m_0 \simeq 1.6$ TeV/$c^2$ and three values of $M_A$. The central white region is excluded by collider limits, while the two other white regions are associated with a relic density outside the preferred range. The color code indicates the region potentially covered by MACHe3 (with a $10^{-2}$ day$^{-1}$ background value), by scalar detection (for which CDMS projected limit is taken as ultimate limit), by both strategies, or none of them.

Muon flux in neutrino telescopes (with a 25 GeV threshold) against event rate in MACHe3. For references, the estimated backgrounds are shown, in one case from energetic neutrinos created in the sun’s corona [28], and in the other case the background from muon and neutrino events in MACHe3.

See fig 3. In this case the color code indicates the region potentially covered by MACHe3 (with a $10^{-2}$ day$^{-1}$ background value), by neutrino telescopes detection (for which a 10 km$^{-2}$ year$^{-1}$ background value [28] is considered), by both strategies, or none of them.

| Parameter     | Minimum | Maximum | Number of steps |
|--------------|---------|---------|-----------------|
| $|\mu|$ (GeV)  | 50      | 1000    | 100 (+/-)       |
| $M_2$ (GeV)   | 50      | 1000    | 100             |
| $m_0$ (GeV)   | 100     | $10^4$  | 11              |
| $M_A$ (GeV)   | 100     | 1000    | 3               |
| $\tan \beta$ | 3, 10 and 60 |        |                 |

Table 1
Scan of the SUSY parameters used for the study. The total number of models is of the order of $\sim 2 \times 10^6$. 
Fig. 1. Axial cross-section on $^{3}$He (pb) as a function of the neutralino mass (GeV/c$^{2}$), for all models of the scan not excluded neither by colliders nor by cosmological constraints (eq. 2). The rates corresponding to the Monte Carlo evaluation [3] of neutron and muon background are indicated for reference.
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Fig. 5. See fig 3. In this case the color code indicates the region potentially covered by MACHe3 (with a $10^{-2}\ \text{day}^{-1}$ background value), by neutrino telescopes detection (for which a $10 \ \text{km}^{-2}\ \text{year}^{-1}$ background value [28] is considered), by both strategies, or none of them.