A SUPERFLUID $^3$He DETECTOR FOR DIRECT DARK MATTER SEARCH

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MACHe3 (MAtrix of Cells of superfluid $^3$He) is a project of a new detector for direct Dark Matter Search. The idea is to use superfluid $^3$He as a sensitive medium. The existing device, the superfluid $^3$He cell, will be briefly introduced. Then a description of the MACHe3 project will be presented, in particular the background rejection and the neutralino event rate that may be achieved with such a device.

1 Introduction

Many existing experiments for direct Dark Matter (DM) search are imposing upper limits on the interaction cross-section of neutralino ($\tilde{\chi}$) on proton, both scalar and axial. They use a great variety of materials and detection techniques. However, the neutrons are still very difficult to discriminate along with a good rejection for $\gamma$-rays. The cosmogonic activation is, in all these experiments, an important source of intrinsic contamination. There are several advantages of using $^3$He as a sensitive medium for direct DM detection. Some of them are:

- It presents a high neutron capture cross-section (up to $\sim 10^3$ barn for $\sim 0.1$ eV thermal neutrons), giving a clear neutron signature and hence a good rejection, as shown in sec 3.2. As neutrons interact a priori like $\tilde{\chi}$, this gives to an $^3$He detector the possibility to discriminate the $\tilde{\chi}$ signal from its ultimate background noise.

- Superfluid $^3$He is produced with a very high purity, making this medium almost free of radioactive contaminations.

- The interaction of a $\tilde{\chi}$ on the $^3$He nucleus (odd spin) is mainly a spin-dependent one, making this medium complementary to other media used in existing DM experiments.

In particular, we shall suppose all through this work a neutralino ($\tilde{\chi}$), the lightest supersymmetric particle, as the particle making up the bulk of galactic cold DM.
In addition a DM detector should present an energy threshold as low as possible. At ultra low temperatures \( T \simeq 100 \mu \text{K} \), \(^3\text{He}\) in the superfluid phase \( \text{B} \) presents in a Lancaster’s cell configuration \(^1\) a low detection threshold \((E_{th} \simeq 1 \text{ keV})\).

In order to enhance the rejection against the background (neutrons, \(\gamma\)-rays and muons), a high granularity superfluid \(^3\text{He}\) detector (fig. \(^1\)) as been proposed \(^2,3\). This matrix configuration would allow to obtain a high background rejection (sec 3.2) along with a reasonable \(\tilde{\chi}\) event rate (sec. 3.1).

2 The superfluid \(^3\text{He}\) cell

The primary device \(^4\) consists of a small copper cubic box \((V \simeq 0.125 \text{ cm}^3)\) filled with superfluid \(^3\text{He}\). It is immersed in a larger volume containing liquid \(^3\text{He}\) and thin plates of copper nuclear-cooling refrigerant. Two vibrating wires are placed inside the cell, forming a Lancaster type bolometer \(^4\). The detection principle is the following: the energy released, in the cell by the incoming particle, creates a cloud of \(^3\text{He}\) quasiparticles. This cloud produces a damping effect on the vibrating wire, allowing the energy released in the cell to be measured. A small hole on one of the box walls connects the box to the main \(^3\text{He}\) volume, allowing the diffusion of the thermal excitations.

Although the primary experiment \(^4\) was still rudimentary, it has allowed to detect signals down to 1 keV.

![Figure 1. 2-dimensional view of a proposed matrix of 1000 cells of \(^3\text{He}\) (125 cm\(^3\) each). The events, generated in a direction perpendicular to the upper face, simulate 10 keV neutrons.](image-url)
3 MACHe3 : MAtrix of Cells of superfluid $^3$He

The performance of a detector for direct DM search is closely related to its $\tilde{\chi}$ event rate and its rejection power against background events (thermal and fast neutrons, muons and $\gamma$-rays). This section describes a $\tilde{\chi}$ rate estimation (sec. 3.1) as well as a Monte Carlo background simulation (sec. 3.2).

3.1 $\tilde{\chi}$ rate estimation

At the tree-level, the spin-dependent elastic scattering of $\tilde{\chi}$ on quark is done via a squark or $Z^0$ exchange. The amplitude on proton (neutron) is calculated by adding the contribution of each quark, weighted by the quark contents of the nucleon. The axial cross-section on $^3$He is given by:

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

where $a_{p/n}$ is the amplitude on proton (neutron), $<S_{p/n}>$ the spin contents of the $^3$He nucleus ($<S_p> = -0.05$ and $<S_n> = 0.49$), $m_r$ is the reduced mass and $J$ the $^3$He spin.

A large scan of the supersymmetric (SUSY) parameter space has been done using the DARK SUSY code, in a constrained MSSM model. Each point have been checked to satisfy the following conditions: i) not to be excluded by the latest collider constraints ii) to give a $\tilde{\chi}$ relic density in the range : $0.025 \leq \Omega_{\chi} h^2 \leq 1$. Fig. 2 presents the cross-section on $^3$He as a function of the $\tilde{\chi}$ mass, for all points satisfying the two conditions. The event rate is evaluated as follows:

$$R = \frac{\sigma_{\text{tot}}(^3\text{He})}{M_{\chi}} \times \rho_{\text{halo}} \times v_0 \times \frac{M_{\text{det}}}{M_{\text{He}}}$$

with $\rho_{\text{halo}} = 0.3 \text{GeV}^{-2}\text{cm}^{-3}$ and $v_0 = 270 \text{km.s}^{-1}$. The mass of the detector is $M_{\text{det}} = 10 \text{kg}$, as obtained by the optimization of the background rejection (see sec. 3.2).

This leads to a maximum rate $R \simeq 0.5 \text{day}^{-1}$. A rate higher than $\sim 0.1 \text{day}^{-1}$ is achieved for a large number of SUSY models with a mass of $\tilde{\chi}$ in the 50-100 GeV/c$^2$ range.

In addition, a $\tilde{\chi}$ event in MACHe3 would release a maximum energy of:

$$E_{\text{recoil}}^{\text{max}} = 2 \times \frac{M_{\text{He}} M_{\chi}^2}{(M_{\text{He}} + M_{\chi})^2} \times v_0^2 \simeq 2 M_{\text{He}} v_0^2 \simeq 6 \text{ keV}$$

It has been checked that, for the $^3$He nucleus, the scalar cross-section is always negligible compared to the axial cross-section, at least in the MSSM parameter space giving a reasonable event rate. Consequently, the value used for $R$ is : $\sigma_{\text{tot}} = \sigma_{\text{spin}}$. 

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Consequently a $\tilde{\chi}$ event in MACHe3 will have the following characteristics: only one cell fired (single-cell event), due to the low cross-section ($\approx 10^{-2}$ pb), and less than 6 keV in this cell.

![Cross-section on $^3$He (pb) as a function of the $\tilde{\chi}$ mass (GeV/$c^2$). All points have been checked to give a $\tilde{\chi}$ cosmological relic density in the range of interest and not to be excluded by collider experiments.](image)

3.2 Background rejection simulation

In order to estimate the background rejection, one has to evaluate the number of background events giving a $\tilde{\chi}$ false event (less than 6 keV in one cell). For this purpose a complete Monte-Carlo simulation has been done, using GEANT3.21 package and in particular the GCALOR-MICAP(1.04/10) package for slow neutrons. The simulated detector (fig. 3) consists of a cube containing a variable number of cubic $^3$He cells, immersed in a large volume...
containing $^3$He. Each cell is surrounded by a thin copper layer (0.1 mm) and separated from the others by a 2 mm gap (filled with $^3$He).

It has been shown that the best design for MACHe3, as far as background rejection is considered, would be a matrix of 1000 cells of 5 cm side each.

The rejection against background events is achieved by choosing only events having the following characteristics: 

i) Only one cell fired (single-cell event)

ii) Energy measurement in the cell below 6 keV

iii) The fired cell in the inner part of the matrix (veto selection), thus improving the rejection for low energy neutrons interacting elastically. For the preferred design the background rejection has been obtained for neutrons and γ-rays for several values of kinetic energies (fig. 3).

For γ-rays, the rejection ranges between 20 and 800, depending on the γ-...
ray energy. This indicates that a good intrinsic rejection can be obtained with the proposed matrix configuration.

At low energy, the neutron rejection is dominated by the capture process, whereas high energy neutrons (1 MeV) are mainly rejected due to the fact that the probability to leave less than 6 keV in the cell is decreasing with increasing neutron energy.

Using the measured neutron flux in the Laboratoire Souterrain de Modane (LSM) in the 2-6 MeV range ($\Phi_n \approx 4 \times 10^{-6} cm^{-2}s^{-1}$), and the simulated rejection, it is possible to evaluate the false event rate induced by neutrons. For this purpose a simulation of a 30 cm wide paraffin shielding has also been done. We found an overall neutron flux through the shielding of $5.1 \times 10^{-8} cm^{-2}s^{-1}$, with the neutron kinetic energy ranging between $10^{-2}$ eV and 6 MeV. Using this flux and the expected rejection factor (fig. 3), the false event rate induced by neutron background is estimated to $\sim 0.1$ day$^{-1}$ through the 10 kg matrix (1000 cells of 125 cm$^3$). The same simulation has been done for muons (200 GeV). Most of them are interacting in all crossed cells. We found a false event rate of the order of 0.014 day$^{-1}$ in the proposed matrix configuration.

4 Conclusion

MACHe3 would allow to obtain a high intrinsic rejection against $\gamma$-ray, neutron and muon background, by means of correlation among the cells and energy loss measurement. The contamination is evaluated, for $\mu$ and neutrons, as well below the maximum expected $\chi$ rate. The results of the simulation are encouraging, both for signal and background rejection.

References

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