A project of a new detector for direct Dark Matter search: MACHe3

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Abstract. MACHe3 (MAtrix of Cells of superfluid $^3$He) is a project of a new detector for direct Dark Matter (DM) search. A cell of superfluid $^3$He has been developed and the idea of using a large number of such cells in a high granularity detector is proposed. This contribution presents, after a brief description of the superfluid $^3$He cell, the simulation of the response of different matrix configurations allowing to define an optimum design as a function of the number of cells and the volume of each cell. The exclusion plot and the predicted interaction cross-section for the neutralino as a photino are presented.

1 Introduction

In the last two decades many experiments on direct detection of DM have been performed. Many of them are running today providing new results which have imposed upper limits for the interaction cross-section of these particles with the stable baryons: neutrons and protons. 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 coming from the natural radioactivity. The cosmogonic activation is in all these experiments an important source of intrinsic contamination.

In general the sensitive medium of an ideal detector of WIMPs should have the following desired properties:

- to be composed of odd nuclei in order to have as well as the scalar interaction (coherent) the axial spin-spin interaction with the hypothetical particles
- to present a high neutron capture cross-section to sign the neutron background
- to be produced with a high purity, mainly free of radioactive isotopes
- to present a Compton interaction cross-section as low as possible in order to minimize the interaction with the natural gamma radioactivity background

In addition, the detection device should allow to get a threshold energy as low as possible. $^3$He in the superfluid phase B at ultra low temperatures ($T \simeq 100 \mu K$) presents in the Lancaster’s configuration \cite{1} a low detection threshold ($\simeq 1$ keV) in a ultra high purity state. The other features are largely fulfilled by the $^3$He nucleus itself.
Nevertheless to further enhance the background rejection we propose a matrix configuration in which the correlations among cells allow to improve the discrimination of background events. This rejection has been confirmed and quantitatively estimated by a Monte Carlo simulation study described below.

2 Description of a cell

The primary device consisted of a small copper cubic box ($V \approx 0.125 \text{ cm}^3$) filled with $^3\text{He}$. It is immersed in a larger volume containing liquid $^3\text{He}$ and thin plates of copper nuclear-cooling refrigerant, see fig. 1. Two vibrating wires are placed inside the cell, forming a Lancaster type bolometer [2]. A small hole on one of the box walls connects the box to the main $^3\text{He}$ volume, thus allowing the diffusion of the thermal excitations of the $^3\text{He}$ generated by the energy deposited in the bolometer by the interacting particle. This high sensitivity device is used as follows: the incoming particle deposits an amount of energy in the cell, which is converted into quasiparticles of the superfluid state. These are detected by their damping effect on the vibrating wire. It must be pointed out that the size of the hole governs the relaxation time (quasiparticles escape time) and the Q factor of the resonator governs the rising time. The present device has a rather high Q factor ($Q \approx 10^4$), giving a rising time of the order of one second. Although the primary experiment [2] was still rudimentary, it has allowed to detect signals down to a threshold of 1 keV. Many ideas are under study to improve the sensitivity of such a cell. Recently, the fabrication of micromechanical silicon resonators has been reported [3] and the possibility to use such wires at ultra-low temperatures is under study.

Fig. 1. Ultra-low temperature nuclear stage and bolometer cell
3 Simulation of a high granularity $^3$He detector.

The performance of a detector for direct DM search is based on the discrimination capability of the different types of background events. The main background components are: thermal and fast neutrons, muons and gamma rays. The aim of the simulation described below was to evaluate the total rejection of different configurations of matrices of $^3$He cells taking into account the correlation among the cells and the energy loss in each cell.

As a typical WIMP is expected to transfer up to 6 keV, it is necessary to evaluate the proportion of background events releasing less than 6 keV in the $^3$He cell. The elastic cross-section between a WIMP and $^3$He being small ($\sigma \lesssim 10^{-3} \text{pb}$), a WIMP event will be characterized by a single-cell event, with equal probability among all the cells of the matrix. Hence, the rejection against background events will be achieved by choosing events having the following characteristics:

- Only one cell fired (single-cell event). The quality parameter related to this selection will be referred to as Correlation Coefficient.
- Energy released in this cell below 6 keV (Energy Rejection).
- The outermost cell layer is considered as a veto (off-line), hence the fired cell has to be in the inner part of the matrix. This will reject neutrons interacting elastically.

![Fig. 2. 2-dimensional view of a proposed matrix of 1000 cells (125 cm$^3$ each). The events, generated in a direction perpendicular to the upper face, are 10 keV neutrons. It can be noticed that most of neutrons of this energy are captured in the first layer.](image_url)

A simulation has been done, in order to define an optimum design as a function of the number of cells and the volume of each cell. Then, the rejection capability
has been estimated, for the preferred design, as well as the false WIMP rate. The simulation has been done with a complete Monte-Carlo simulation 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 ($\rho_{SF}=0.08 \text{ g cm}^{-3}$). Each cell is surrounded by a thin copper layer and it is separated from the others by a 2 mm gap (filled with $^3$He).

In contrast to most DM detectors, MACHe3 may be sensitive to rather low energy neutrons, and its response depends strongly on their kinetic energies. The total cross-section interaction for a neutron in $^3$He ranges from $\sigma_{tot} \simeq 1000$ barns, for low energy neutrons ($E_n \simeq 1$ eV), down to $\sigma_{tot} \simeq 1$ barn for 1 MeV neutrons. The main processes are: elastic scattering which starts being predominant above 600 keV, and neutron capture: $^3$He (n,p) $^3$H, which is largely predominant for low energy neutrons ($E_n \leq 10$ keV):

$$n + ^3\text{He} \rightarrow p + ^3\text{H} + 764\text{keV}$$

The energy released by the neutron capture is shared by the recoil ions: the tritium $^3$H with kinetic energy 191 keV and the proton with kinetic energy 573 keV. The range for these two particles is fairly short: typically 12 $\mu$m for tritium and 67 $\mu$m for proton; consequently neutrons undergoing capture in $^3$He are expected to produce 764 keV within the cell, thus being clearly separated from the expected $\tilde{\chi}$ signal ($E \leq 6$keV). The tritium produced by neutron capture

![Fig. 3](image_url)

**Fig. 3.** Correlation Coefficient and Energy Rejection as a function of the size of the $^3$He cell for 1 MeV neutrons. The different curves correspond to different matrix sizes as indicated by the labels.
will eventually decay with a half-life of 12 years by $\beta$-decay with an end-point electron spectrum at 18 keV. It means that the number of neutrons capture per cell must be counted to estimate the contribution of this kind of events on the false $\tilde{\chi}$ rate.

The neutron capture cross-section decreases with increasing neutron kinetic energy, but on the other hand, the energy released in the $^3$He cell by the elastic scattering is getting larger, thus diminishing the probability to leave less than 6 keV.

We present here, the main quality parameters for 1 MeV neutrons (fig. 3) and for 2.6 MeV $\gamma$-rays (fig. 4). This coefficients depend both on the matrix and cell sizes. The full simulation for various kinetic energies has shown that a large cell ($125 \ cm^3$) allows to obtain a large energy rejection ($R \sim 500$ for 1 MeV neutrons), and a large matrix (1000 cells or more) allows to have a good correlation among the cells ($\sim 65\%$ for 1 MeV neutrons), thus rejecting efficiently $\gamma$-rays and neutrons. For background rejection consideration the optimum configuration is a matrix of 1000 cells of 5 cm side (more details may be found in [4]).

![Graph](image_url)

**Fig. 4.** Correlation coefficient as a function of the size of the $^3$He cell for 2.6 MeV $\gamma$-rays. The different curves correspond to different matrix sizes as indicated by the labels.

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With the definition of the quality parameters, the best design is the one for which the correlation coefficient is the lowest (thus minimizing the proportion of single-cell background events) and the energy rejection is the highest (meaning a low proportion of background events with an energy measurement below 6 keV).
A detailed simulation has been done for the matrix of 1000 cells of 5 cm side representing a good compromise between rejection power, volume and feasibility. For neutrons, a large rejection is achieved below 8 keV (mainly thanks to veto and energy rejection) and above 1 MeV (thanks to correlation and energy loss measurement). As expected, 8 keV neutrons represent the worst rejection (see fig. 5), since the capture process is less predominant, and the energy left by (n,n) interaction is always less than 6 keV.

For gamma rays, a high granularity detector provides an intrinsic rejection ranging between 10 and 1000, depending on their kinetic energies. This selection, may be improved by adding a discrimination between recoils and electrons under study. Different experimental approaches should be tested shortly. A complete study of an inner and outer cryostat shielding is also needed, as well as an evaluation of natural radioactivity of materials.

Fig. 5. Total Rejection as a function of the incident particle energy, for a matrix of 1000 cells (125 cm$^3$ each). The different set of points correspond to $\gamma$-rays (squares) and neutrons (circles). It must be pointed out that the evaluated rejection is for a "naked matrix", i.e. without taking into account any lead or paraffin shielding or any separation between electron and ion recoils. It represents the capability of the $^3$He matrix to reject background events by means of energy loss measurements and correlation considerations.

The total rejection is defined as the ratio between the number of incoming particles and the number of false $\bar{\chi}$ events (less than 6 keV in one non-peripheric cell).
As neutrons recoiling off nuclei may easily simulate a $\tilde{\chi}$ event, it is crucial to evaluate the neutron-induced false event rate. For this purpose, a simulation of a paraffin neutron shielding has also been done, in order to evaluate the expected neutron spectrum through this shielding. We have used the measured neutron spectrum in Laboratoire Souterrain de Modane, between 2 and 6 MeV with an integrated flux of $\Phi_n \simeq 4 \times 10^{-6} \text{cm}^{-2}\text{s}^{-1}$.

Using this flux and the expected rejection factor (fig. 5), we evaluated the false $\tilde{\chi}$ rate induced by neutron background, to be $\sim 0.1$ false event per day through the $1.5m^2$ surface of the detector (1000 cells of 125 cm$^3$), which is much lower than the expected $\tilde{\chi}$ rate (of the order of $\sim 1 \text{day}^{-1}$ in a detector of this size, see below and fig. 4).

A study of the muon background has also been done. We estimated the $\mu$-induced false $\tilde{\chi}$ rate to be of the order of 0.01 day$^{-1}m^{-2}$, which is more than two orders of magnitude below the expected $\tilde{\chi}$ rate.

### 4 Cross-section and LSP

The plot showing the accessible cross-section interaction for a rate of 0.1 events per day and per kg as a function of the mass of the WIMP assuming a Maxwellian distribution of the WIMP’s velocities in the galactic halo is shown on fig. 6 for 10 kg of $^3\text{He}$.

![Fig. 6. Accessible total cross-sections $\tilde{\chi} ^{3}\text{He}$, in pb, for 10 kg of $^3\text{He}$ as a function of the neutralino mass. The curve showing the predicted cross-section as a function of the neutralino mass for the special case of a pure photino is also shown](image)

However we have to verify if the available models allowing to estimate the interaction cross-section in the case of the best candidate for the lightest SUSY particle (LSP) as the neutralino give a value accessible by this plot. Doing that

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$^3$ The thermal neutron flux, evaluated in [8] to be $(1.6 \pm 0.1) \times 10^{-6} \text{cm}^{-2}\text{s}^{-1}$, will be highly suppressed by the 30 cm paraffin shielding
for one of the special cases in which the neutralino is a pure photino we get an overlap shown on fig. This special case is one example in which only the axial interaction channel is available to detect the elusive particle.

5 Conclusion

As a conclusion, it can been said that a large matrix (∼ 1000 cells) of large cells (125 cm³) is the preferred design for a multi-cell superfluid $^3$He detector. By means of the correlation among the cells and the energy loss measurement, a high rejection may be obtained for γ-ray, neutron and muon background. For background rejection purpose, the main advantage of a superfluid $^3$He detector is to present a high rejection against neutron background, mainly because of the high capture cross-section at low energy; as neutrons interact $a$ priori like $\tilde{\chi}$, they are the ultimate background noise for DM detectors.

References

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