Design optimization of MACHe3, a project of superfluid $^3$He detector for direct Dark Matter search.

F. Mayet $^a,^1$, D. Santos $^a,^1$, G. Perrin $^a$, Yu. M. Bunkov $^b$, H. Godfrin $^b$

$a$ Institut des Sciences Nucléaires, CNRS/IN2P3 and Université Joseph Fourier, 53, avenue des Martyrs, 38026 Grenoble cedex, France

$b$ Centre de Recherche sur les Très Basses Températures, CNRS, BP166, 38042 Grenoble cedex 9, France

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 paper 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 background rejection, for several configurations, is presented both for neutrons and $\gamma$-rays of various kinetic energies.

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

PACS : 95.35; 67.57; 07.57.K; 11.30.P

$^1$ corresponding authors : Frederic.Mayet@isn.in2p3.fr, santos@isn.in2p3.fr, tel: +33 4-76-28-40-21, fax: +33 4-76-28-40-04
1 Introduction to MACHe3

As previously suggested [1,2], superfluid $^3$He provides a suitable working medium for the detection of low energy recoil interactions. Recent studies [3] have shown the possibility to use a superfluid $^3$He cell at ultra low temperatures ($T\approx 100$ µK). The primary device consisted of a small copper cubic box ($V\approx 0.125\ cm^3$) filled with $^3$He. It is immersed in a larger volume containing liquid $^3$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[3]. A small hole on one of the box walls connects the box to the main $^3$He volume, thus allowing the diffusion of the thermal excitations of the $^3$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 $^3$He quasiparticles. These are detected by their damping effect on the vibrating wire. It must be pointed out that the size of the hole governs the relaxing time (quasiparticles escape time) and the Q factor of the resonator governs the rising time, see figure 2. 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 was still rudimentary, it has allowed to detect signals down to a threshold of 1 keV [3]. Many ideas are under study to improve the sensitivity of such a cell. Recently, the fabrication of micromechanical silicon resonators has been reported [4] and the possibility to use such wires at ultra-low temperatures is under study.

The aim of the present article is to show that, by using a large number of these cells, a high granularity superfluid $^3$He detector could be used for direct Dark Matter (DM) search[5]. For this purpose we have evaluated, by simulation of different kind of background events, the rejection coefficients that may be achieved with such a device.

2 Particle interactions in $^3$He

As other direct DM search detectors (Edelweiss[6], CRESST[7], CUORE[8]), the identification of WIMPs ($\tilde{\chi}$) may be obtained by detecting their elastic scattering on a nucleus of a sensitive medium. In the case of $^3$He, the $\tilde{\chi}$ is expected to transfer [5] up to 6 keV. The maximum $^3$He recoil energy is given

---

2 It should be noticed that such a device need to be placed in an underground site to reduce cosmic rays (mainly muons) background. It should also be surrounded by neutron and $\gamma$-ray shieldings.

3 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.
by:

\[ E_{\text{recoil}}^{\text{max}} = 2 \times \frac{mM^2}{(m+M)^2} \times v^2 \]

where \( m \) is the mass of the \(^3\)He nucleus, \( M \) the mass of the \( \tilde{\chi} \) and \( v \) is the relative speed of the \( \tilde{\chi} \). Assuming that \( M \gg m \), as the accelerator experiments claim, this relation yields to \( E_{\text{recoil}}^{\text{max}} = 2mv^2 \), which gives for \( v \simeq 300 \text{ km.s}^{-1} \), a maximum recoil energy of \( \sim 6 \text{ keV} \).

Hence, in order to evaluate the expected background for such a detection, it is necessary to know the proportion of events releasing less than 6 keV in the \(^3\)He cell. The main background components for direct DM search are: thermal and fast neutrons, muons and gamma rays.

### 2.1 Neutron interaction in \(^3\)He

The total cross-section interaction for a neutron in \(^3\)He ranges from \( \sigma_{\text{tot}} \simeq 1000 \) barns, for low energy neutrons \((E_n \simeq 1 \text{ eV})\), down to \( \sigma_{\text{tot}} \simeq 1 \) 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 \((E_n \leq 10 \text{ keV})\):

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

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 [9] 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 \((E \leq 6 \text{ keV})\). The tritium produced by neutron capture 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 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. From this, it is clear that the worst case will be 8 keV neutrons for which the capture process is less predominant, and the energy left by \((n,n)\) interaction is always less or equal to 6 keV.

In order to reduce contamination from neutron background, the idea is either to have a correlation among the cells, which means a large number of \(^3\)He cells, or to have a cell large enough for the neutron to be slowed down until it is captured.
2.2 \(\gamma\)-ray interaction in \(^3\)He

As \(^3\)He presents the property to have a low photoelectric cross-section, Compton scattering is largely predominant between 100 keV and 10 MeV (for 100 keV \(\gamma\)-rays : \(\sigma_{\text{comp}}/\sigma_{\text{phot}} \approx 10\)). Consequently, the strategy to separate a \(\tilde{\chi}\) event from a \(\gamma\)-ray event is two fold: either the cell is large enough for the \(\gamma\)-ray to undergo multi-Compton scattering within one cell \(\mathbb{1}\), or the number of cells in the matrix is large enough so that there could be an interaction in more than one cell (this will be referred to as a correlated event or a multi-cell event). It will be shown, in the next section, that having a relatively large cell in a large matrix presents the best rejection against \(\gamma\)-ray events.

The copper used to build the cells must be produced by a controlled procedure with respect to the radioactive contaminations. Nevertheless, the interaction of \(\gamma\)-rays with the copper will produce X-rays and scattered electrons by Compton and photo-electric interactions. These kind of interactions have been taken into account in our simulations and they enhance the correlation among the different cells fired by an incoming \(\gamma\)-ray.

3 Simulation of the response of MACHe3 to background events.

The aim of this simulation is to evaluate the capability of a superfluid \(^3\)He matrix to reject background events, by taking advantage both on correlation among the cells (multi-cell events) and energy loss measurement. The simulation has been done with a complete Monte-Carlo simulation using GEANT3.21 [10] package and in particular the GCALOR-MICAP(1.04/10) [11] package for slow neutrons. The simulated detector consists of a cube containing a variable number of cubic \(^3\)He cells, as it can be seen on figure 3. It is immersed in a large volume containing \(^3\)He (\(\rho_{\text{SF}}=0.08\ \text{g.cm}^{-3}\)). Each cell is surrounded by a thin copper layer and it is separated from the others by a gap of 2 mm (filled with \(^3\)He). The events are generated in a direction perpendicular\(^{[3]}\) to one of the matrix faces. The number of events per simulation is of the order of \(200 \times 10^3\). The idea is to find the best matrix design (number of cubic cells and the size of each cell) for which the rejection power, taking into account the correlation among the cells and the energy loss measurement, is the highest.

As said previously, a typical \(\tilde{\chi}\) is expected to release less than 6 keV in the \(^3\)He cell. As the elastic cross-section between a \(\tilde{\chi}\) and \(^3\)He is fairly small (\(\sigma \lesssim 10^{-3}\text{pb}\)), a \(\tilde{\chi}\) event is expected to be characterized by a single-cell event, with

\(^{[3]}\) This will of course be efficient for an energy greater than 10 keV.

\(^{[5]}\) It has been checked that this procedure does not affect the values and general behaviour of the matrix parameters, keeping the calculation time short.
equal probability among all the cells of the matrix. Consequently, the rejection against background events will be achieved by choosing only events having the following characteristics:

- Only one cell fired (single-cell event). The quality parameter related to this selection will be defined below as $C_{geo}$.
- Energy measurement in this cell below 6 keV and above a threshold of 0.5 keV (quality parameter : $R_{ener}$).
- An additional constraint can be imposed : the fired cell is in the inner part of the matrix (quality parameter : $C_{veto}$). This condition, which considers the outermost cell layer as a veto, will allow to reject low energy neutrons interacting elastically, as shown below.

Let $N$ be the number of events giving a signal in the matrix (any energy, any number of cells), $N_1$ the number of single-cell events (any energy) and $N_6$ the number of single-cell events with an energy measurement below 6 keV. $M_1$ and $M_6$ will be referred with the same meaning as $N_1$ and $N_6$, but for events firing a cell in the inner part of the detector (out of the veto).

Then, we may define the following parameters as:

- $C_{geo} = \frac{N_1}{N}$; the correlation coefficient (proportion of single-cell events).
- $R_{ener} = \frac{N_1}{N_6}$; the rejection by energy measurement.
- $C_{veto} = \frac{N_1}{M_1}$; the veto coefficient.
- $R_{int} = \frac{N}{M_6}$; the intrinsic rejection.

### 3.1 Design optimization.

In order to define the optimum matrix design (number of cubic cells and size of the cells), a complete simulation has been done. The results concerning three types of background are presented : 10 keV neutrons, 1 MeV neutrons and 2.6 MeV γ-rays. For each sample, the four parameters defined above are evaluated in various configurations : cell size of 0.5, 1.0, 2.5 and 5.0 cm and matrix containing $3^3$, $5^3$, $7^3$, $10^3$ ($20^3$) cells. The best design will be the one for which $C_{geo}$ is the lowest (thus minimizing the proportion of single-cell background events) and $R_{ener}$ is the highest (meaning a low proportion of background events with an energy measurement below 6 keV).

### 3.2 γ-ray background.

Due to the fact that it is a simulation without any constraint on the detector volume, the correlation coefficient depends strongly on the size of the matrix,
with a small dependence on the cell size, as shown on figure 4. The best correlation is obtained for 8000 cells of size 2.5 cm ($C_{geo} \approx 45\%$). In order to keep a reasonable number of cells, it can be noticed that a matrix of same volume (1000 cells of 5.0 cm side) presents also a good correlation ($C_{geo} \approx 55\%$). A multi-cell event can either be a multi-Compton event, or a single-Compton event for which the electron is escaping the cell and firing a neighbouring cell. This last process depends mainly on the cell size and explains the fact that $C_{geo}$ remains constant for cell sides larger than 1 cm, see fig. 4. It has been found that the energy rejection ($R_{ener}$) depends mainly on the size of the cell. For a large cell (5 cm side), a rejection $R_{ener} \approx 90$ is obtained, allowing to reject 98% of the 2.6 MeV $\gamma$-rays. The total rejection (see fig. 11), which take into account the correlation and energy selection, together with veto selection and interaction probability, is $R \approx 700$ for 1000 cells of size 5.0 cm (for 2.6 MeV $\gamma$-rays).

Consequently, for $\gamma$-ray background rejection purpose, a cell of 5.0 cm side presents the best energy rejection and a matrix of 1000 cells of this size allows to obtain a good correlation coefficient. In section 3.5.1, the rejection of such a matrix as a function of the $\gamma$-ray energy will be presented.

### 3.3 Low energy neutron background.

Figures 5 and 6 present the correlation coefficient ($C_{geo}$) and the energy rejection ($R_{ener}$) as a function of the cell size, for different matrix sizes and an incident neutron energy of 10 keV. The correlation coefficient depends both on the size of the cell and of the matrix, since the neutron capture is the predominant process at this energy. The best correlation is obtained for 8000 cells of size 2.5 cm ($C_{geo} \approx 85\%$), but a larger cell (5 cm side), with only 1000 cells presents also a similar correlation ($C_{geo} \approx 86\%$). The energy rejection ($R_{ener}$) depends not only on the size of the cell, but also on the size of the matrix. The best rejection ($R_{ener} \approx 22$) is achieved for a large cell (5 cm side) and a large matrix (1000 cells). The total rejection, shown on fig.11, is $R \approx 80$ for 1000 cells of 5 cm side, meaning that only 1.25 % of the incoming 10 keV neutrons may simulate a $\tilde{\chi}$ event. It must be pointed out that 10 keV represent the worst case for rejection purpose, as it can be seen on figure 11.

### 3.4 Fast neutron background.

Figures 7 and 8 show the correlation coefficient ($C_{geo}$) and the energy rejection ($R_{ener}$) as a function of the cell size, for different matrix sizes and an incident neutron energy of 1 MeV. As well as for low energy neutrons, the correlation coefficient depends on the matrix and cell sizes. A correlation of $\sim 65\%$ is
achieved for a large $^3\text{He}$ volume (1000 cells of 5 cm or 8000 cells of 2.5 cm). A large matrix of big cells (1000 cells of 5 cm) allows to obtain a rather large energy rejection ($R_{\text{ener}} \simeq 500$), leading to a total rejection of the order of 1000 (see fig.11), meaning that 99.9% of 1 MeV neutrons arriving on the $^3\text{He}$ matrix may be discriminated from a $\tilde{\chi}$ event.

For these three particle samples, the simulation has shown that a large cell (125 cm$^3$) allows to obtain a large energy rejection, and a large matrix (1000 cells or more) allows to have a good correlation among cells, thus rejecting efficiently $\gamma$-rays and neutrons of kinetic energy $E \simeq 1$ MeV. Hence, for background rejection consideration the optimum configuration is a matrix of 1000 cells of 5 cm side.

### 3.5 Rejection power of a superfluid $^3\text{He}$ matrix.

As shown previously, a matrix of $10^3$ large cells (125 cm$^3$ each) presents the best rejection power, both for neutrons and $\gamma$-rays. This section presents the various coefficients, as defined in section 2.1, as a function of the energy of the incoming particle.

#### 3.5.1 Rejection against $\gamma$-ray background.

Figure 10 shows the correlation coefficient, the veto coefficient, the energy rejection and the total rejection as a function of the $\gamma$-ray energy. A good correlation is achieved for high energy $\gamma$-rays ($E_{\gamma} \geq 1$ MeV), whereas low energy $\gamma$-rays are mainly rejected by the veto. In fact, 80 keV X-rays undergo photoelectric effect in the copper layer ($\sigma_{\text{phot}} \simeq 10^4$ barn) surrounding the cell; the scattered electrons may escape the copper layer and leave a few keV in the cell. This will mainly happen in the outermost cells.

Figure 11 presents the total rejection as a function of the $\gamma$-ray energy. It can be concluded that an $^3\text{He}$ matrix provides a rejection ranging between 10 and 1000, depending on the $\gamma$-ray energy. It must be pointed out that this is the rejection power of the matrix itself. For instance, 90% of X-rays will be rejected by the matrix, but the flux of such particles will be reduced substantially by an inner and outer copper shielding.

#### 3.5.2 Rejection against neutron background.

Figure 9 presents the four matrix parameters as a function of the neutron energy. A correlation better than 70 % is achieved for neutrons of energy greater than 100 keV (fig. 9, upper left), while low energy neutrons are mainly rejected by the veto. Indeed, 60 % of 10 keV neutrons are captured in the first layer (fig. 9, upper right). The energy measurement constitute an efficient...
selection for low energy neutron ($R_{\text{ener}} \approx 100$ for 1 keV neutrons) and for fast neutrons ($R_{\text{ener}} \approx 1000$ for 1 MeV neutrons). As expected 10 keV neutrons have the worst energy rejection ($R_{\text{ener}} \approx 15$).

The total rejection $R_{\text{total}}$ (ratio between number of incoming particles and number of false $\tilde{\chi}$ events), shown on figure 11, indicates that only one 1 keV neutron out of 2000 may simulate a $\tilde{\chi}$ event. The rejection falls down to 75 for 10 keV neutrons (mainly rejected by the veto) and is of the order of 1000 for 1 MeV neutrons.

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. As a conclusion, it can be said that the $^3$He matrix presents a rejection power ranging between 75 and 2000 for neutrons, and between 10 and 800 for $\gamma$-rays, depending on their kinetic energies.

3.6 An evaluation of the neutron-induced false event rate.

As neutrons recoiling off nuclei may easily simulate a $\tilde{\chi}$ event, it is crucial to evaluate the neutron-induced false event rate.

In contrast to most DM detectors, MACHe3 may be sensitive to rather low energy neutrons, and its response depends strongly on their kinetic energies. For this purpose, a simulation of a paraffin neutron shielding has been done, in order to evaluate the expected neutron spectrum through this shielding.

The simulated device is a large ($1m \times 1m$) paraffin block ($\rho=0.95 \text{ g.cm}^{-3}$) with a width of 30 cm. In order to be conservative, as well as keeping the calculation times short, we choose to generate the events in a direction perpendicular to the face of the paraffin block and considering that all neutrons crossing the block are supposed to enter the matrix volume.

A benchmark study has been done, to compare MCNP calculation code[12] and GEANT3.21. We found that these two codes give similar results, except for thermal neutrons (below 1 eV) for which GEANT underevaluate the flux. Again, to be conservative, we choose the one giving the highest flux (MCNP$^\blacklozenge$). We have used the measured neutron spectrum [13] in Laboratoire Souterrain de Modane (LSM), between 2 and 6 MeV $\square$ with an integrated flux of $\Phi_n \approx 4 \times 10^{-6} \text{cm}^{-2}\text{s}^{-1}$. We found an overall neutron flux through the shielding of

---

6 This coefficient takes into account the interaction probability and will be used to evaluate the false event rate.

7 MCNP is much faster than GEANT, in this case, allowing shorter calculation times.

8 The thermal neutron flux, evaluated in [13] to be $1.6\pm0.1 \times 10^{-6} \text{cm}^{-2}\text{s}^{-1}$, will be highly suppressed by the 30 cm paraffin shielding.
5.1 \times 10^{-8} \text{cm}^{-2}\text{s}^{-1}, with the neutron kinetic energy ranging between 10^{-2} \text{eV} and 6 \text{MeV} (see the upper curve on fig. 12).

Using this flux and the expected rejection factor (fig. 11), we evaluated the false $\tilde{\chi}$ rate induced by neutron background, see fig. 12. We found a rate of $\sim 0.1$ false event per day through the 1.5 m$^2$ surface detector (1000 cells of 125 cm$^3$). Even with such a conservative approach, this contamination is much lower than the expected $\tilde{\chi}$ rate (of the order of $\sim 1$ day$^{-1}$ in a detector of this size [5]).

3.7 An evaluation of the muon-induced false event rate.

The muon background flux in an underground laboratory (Gran Sasso) has been measured by [14]. They found a mean flux of $\Phi_\mu = 2.3 \times 10^{-4} \text{m}^{-2}\text{s}^{-1}$ for an average kinetic energy $\langle E \rangle = 200 \text{GeV}$.

An evaluation of the $\mu$-induced event rate has been done. The same procedure as above (see section 3) has been used, without paraffin shielding; i.e. the events are generated in a direction perpendicular to one of the matrix faces. This is a conservative approach because the worst case is in which muons are passing in between 2 cell layers. As expected, most of the $\mu$-events interact in all the crossed cells (75% interact in 10 cells, with an average energy left of $\sim 1 \text{MeV}$). The correlation coefficient is $C_{\text{geo}} \simeq 2.1\%$ (meaning 97.9\% of $\mu$-events are rejected), with an energy rejection $R_{\text{ener}} \simeq 40$, leading to an overall rejection of $R \simeq 2100$. This lead to a $\mu$-induced false $\tilde{\chi}$ rate of the order of $0.0095 \text{day}^{-1}\text{m}^{-2}$, which is more than two orders of magnitude below the expected $\tilde{\chi}$ rate. The layers may be shifted, thus allowing a much higher rejection against muon background events.

3.8 $\gamma$-ray background.

As shown in section 3.5.1, a high granularity superfluid $^3\text{He}$ detector provides an intrinsic rejection ranging between 10 and 800 for $\gamma$-rays, depending on their kinetic energies. This selection, based on the correlation among the cells and energy loss measurement, may be improved by adding a discrimination between recoils and electrons. Different experimental approaches should be tested. A complete study of an inner and outer cryostat shielding is also needed, as well as an evaluation of natural radioactivity of materials. Nevertheless, this simulation indicates that an important intrinsic rejection can be achieved.
In this prospective paper, we have demonstrated that a large matrix (∼ 1000 cells) of large cells (125 cm$^3$) is the preferred design for a superfluid $^3$He detector searching for DM, as far as background rejection is concerned. An experimental work needs to be done to demonstrate the possibility to use such a large volume of superfluid $^3$He-B at ultra-low temperatures. This work has evaluated the background rejection of a high granularity superfluid $^3$He detector for a large range of kinetic energies, both for neutrons and γ-rays. It has been shown that, by means of correlation among the cells and energy loss measurement, a high rejection may be obtained for γ-ray, neutron and muon background. Using the measured muon and neutron flux in an underground laboratory, we have evaluated the contamination to be one order of magnitude (two orders for muons) less than the expected $\bar{\chi}$ rate. 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 $\bar{\chi}$, they are the ultimate background noise for DM detectors.

Acknowledgements
The authors are grateful to D. Kerdraon and L. Perrot for the help concerning the use of MCNP calculation code, and also F. Ohlsson-Malek for the fruitful discussions on the GEANT code.

References

[1] G. R. Pickett, in Proc. of the European Workshop on Low Temperature Devices for the Detection of Low Energy Neutrinos and Dark Matter (1988 Annecy, France), edited by L. Gonzales-Mestres and D. Perret-Gallix (Ed. Frontieres).

[2] Yu. M. Bunkov et al., in Proc. of the International Workshop on Superconductivity and Particle Detection (1994 Toledo, Spain) eds. T.A. Girard, A. Morales and G. Waysand, World Scientific, p.21 (1995)

[3] D. I. Bradley et al., Phys. Rev. Lett. 75 (1995) 1887.
C. Bäuerle et al., Phys. Rev. B57 (1998) 22.

[4] S. Triqueneaux et al., in Proc. of the 22nd International Conf. on Low Temperature Physics, August 1999, Physica B (in print).

[5] D. Santos, F. Mayet, G. Perrin et al., to be submitted to Phys. Rev. D.

[6] L. Berge et al., astro-ph/9801199

[7] M. Bravin et al., hep-ex/9904005
[8] A. Alessandrello et al., in Proc. Dark matter in astrophysics and particle physics 1998.

[9] J. S. Meyer and T. Sloan, J. of Low Temp. Phys. (108) 1997.

[10] R. Brun, F. Carminati, GEANT Detector Description and Simulation Tool, CERN Progam Library Long Writeup W5013, September 1993.

[11] J. O. Johnson, T. A. Gabriel, A user’s guide to MICAP, ORNL/TM-10340, January 1988
C. Zeitniz and T. A. Gabriel, Nucl. Instr. and Meth. 349 (1994) 106.

[12] J. F. Briesmeister, MCNP\textsuperscript{TM}, A general Monte Carlo N-particle transport code, LANL Report LA-12625-M(93)

[13] V. Chazal et al., Astropart. Phys. 9, 163 (1998).

[14] C. Arpesella, LNGS-92-28 Contribution to TAUP ’91 Workshop, Toledo, Spain, Sep 9-13, 1991.
H. V. Klapdor-Kleingrothaus et al., hep-ph/9910205.
List of Figures

1. Ultra-low temperature nuclear stage and bolometer cell.

2. Temperature recorded inside the bolometer as a function of time.

3. 2-dimensionnal 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.

4. Correlation coefficient ($C_{geo}$) 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.

5. Correlation coefficient ($C_{geo}$) as a function of the size of the $^3$He cell for 10 keV neutrons. The different curves correspond to different matrix sizes as indicated by the labels.

6. Energy Rejection ($R_{ener}$) as a function of the size of the $^3$He cell for 10 keV neutrons. The different curves correspond to different matrix sizes as indicated by the labels.

7. Correlation coefficient ($C_{geo}$) 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.

8. Energy Rejection ($R_{ener}$) 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.

9. Neutrons interacting in MACHe3 : The four matrix parameters defined in sec. 3, as a function of the neutron energy, for a matrix of 1000 cells (125 cm$^3$ each).

10. $\gamma$-rays interacting in MACHe3 : The four matrix parameters defined in sec. 3, as a function of the $\gamma$-ray energy, for a matrix of 1000 cells (125 cm$^3$ each).
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). The total rejection is defined as the ratio between the number of incoming particles and the number of false $\chi$ events (less than 6 keV in one non-peripheric cell).

The upper curve is the simulated neutron spectrum through a 30 cm wide paraffin shielding, the measured spectrum at LSM being the input. Comparing with the measured neutron flux, this shielding allows an overall reduction factor of $\sim 50$. The lowest curve represents the neutron induced false $\chi$ rate in MACHe3. This spectrum has been obtained by combining the upper curve with the total rejection (fig. 11), with a threshold of 500 eV. The overall counting rate, due to neutron background, is evaluated to be $\sim 0.1$ day$^{-1}$ in a 1000 cells detector.
Fig. 1. Ultra-low temperature nuclear stage and bolometer cell.

Fig. 2. Temperature recorded inside the bolometer as a function of time.
Fig. 3. 2-dimensionnal 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.

Fig. 4. Correlation coefficient ($C_{geo}$) 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.
Fig. 5. Correlation coefficient ($C_{\text{geo}}$) as a function of the size of the $^3\text{He}$ cell for 10 keV neutrons. The different curves correspond to different matrix sizes as indicated by the labels.

Fig. 6. Energy Rejection ($R_{\text{ener}}$) as a function of the size of the $^3\text{He}$ cell for 10 keV neutrons. The different curves correspond to different matrix sizes as indicated by the labels.
Fig. 7. Correlation coefficient ($C_{geo}$) 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.

Fig. 8. Energy Rejection ($R_{ener}$) 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.
Fig. 9. Neutrons interacting in MACHe3: The four matrix parameters, defined in sec. 3, as a function of the neutron energy, for a matrix of 1000 cells (125 cm$^3$ each).

Fig. 10. $\gamma$-rays interacting in MACHe3: The four matrix parameters, defined in sec. 3, as a function of the $\gamma$-ray energy, for a matrix of 1000 cells (125 cm$^3$ each).
Fig. 11. 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). The total rejection is defined as the ratio between the number of incoming particles and the number of false $\tilde{\chi}$ events (less than 6 keV in one non-peripheric cell).
Fig. 12. The upper curve is the simulated neutron spectrum through a 30 cm wide paraffin shielding, the measured spectrum at LSM being the input. Comparing with the measured neutron flux, this shielding allows an overall reduction factor of $\sim 50$. The lowest curve represents the neutron induced false $\tilde{\chi}$ rate in MACHe3. This spectrum has been obtained by combining the upper curve with the total rejection (fig. 11), with a threshold of 500 eV. The overall counting rate, due to neutron background, is evaluated to be $\sim 0.1 \text{ day}^{-1}$ in a 1000 cells detector.