MIMAC : A \(\mu\)TPC DETECTOR FOR NON-BARYONIC DARK MATTER SEARCH

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Abstract. The MIMAC project is multi-chamber detector for Dark Matter search, aiming at measuring both track and ionization with a matrix of micromegas \(\mu\)TPC filled with \(^3\)He and CF\(_4\). Recent experimental results on the first measurements of the Helium quenching factor at low energy (1 keV recoil) are presented.

1 Introduction

There is strong evidence in favor of a dark matter dominated Universe : locally, from the rotation curves of spiral galaxies (Rubin et al. 1999) or the Bullet cluster (Clowe et al. 2006) and on the largest scales, from cosmological observations (Komatsu et al. 2008, Tristram et al. 2005, Tegmark et al. 2004). Most of the matter in the Universe consists of cold non-baryonic dark matter (CDM), the leading candidate for this class of yet undiscovered particles (WIMP) being the lightest supersymmetric particle. In various supersymmetric scenarii (SUSY), this neutral and colorless particle is the lightest neutralino \(\tilde{\chi}\).

Tremendous experimental efforts on a host of techniques have been made in the field of direct search of non-baryonic dark matter. Several detectors already reached sufficient sensitivity to begin to test regions of the SUSY parameter space. However, going further required careful choice of radiopurity of materials, underground laboratory, shielding, detector design and data analysis (Moulin et al. 2006).

As the expected event rates are very small \((O(10^{-5} \text{ day}^{-1} \text{kg}^{-1}))\), the challenge is to distinguish a genuine WIMP signal from backgrounds (mainly neutrons and \(\gamma\)-rays). Two main dark matter search strategies may be identified : the detector may be designed to reach an extremely high level of background rejection or to provide an unambiguous positive signal. This can be achieved via :

- a dependence of the differential event rate on the atomic mass of the target nucleus, requiring a good control of detector systematics,
• a correlation of the signal with the motion of the detector with respect to the galactic Dark Matter halo. This can either be an annual modulation, due to the motion of the earth around the sun or a strong direction dependence of the incoming neutralino, toward the Cygnus constellation to which points the sun’s velocity vector (Spergel 1988, Green & Morgan 2007).

Several projects aiming at directional detection of Dark Matter are being developed (Alner et al. 2005, Santos et al. 2009, Collar et al. 2000, Sciola et al. 2008).

2 The MIMAC project

The MIMAC project is multi-chamber detector for Dark Matter search. The idea is to measure both track and ionization with a matrix of micromegas $\mu$TPC filled with $^3$He and CF$_4$. The use of these two gases is motivated by their privileged features for dark matter search. With their odd atomic number, a detector made of such targets will be sensitive to the spin-dependent interaction, leading to a natural complementarity with existing detectors mainly sensitive to scalar interaction, in various SUSY models, e.g. non-universal SUSY (Moulin et al. 2005, Mayet et al. 2002). Moreover, as shown in (Moulin et al. 2005), a 10 kg $^3$He dark matter detector with a 1 keV threshold (MIMAC) would present a sensitivity to SUSY models allowed by present cosmology and accelerator constraints. This study highlights the complementarity of this experiment with most of current spin-dependent experiments: proton based detectors as well as $\nu$ telescopes.

Using both $^3$He and CF$_4$ in a patchy matrix of $\mu$TPC opens the possibility to compare rates for two atomic masses, and to study neutralino interaction separately with neutrons and protons as the spin content of these nuclei is dominated by one kind of nucleon.

Low pressure operation of the MIMAC detector will enable the possibility to discriminate neutralino signal and background on the basis of track shape and incoming direction.

3 Ionization quenching factor measurement

As far as detection of Dark Matter is concerned, the ionization is one of the most important channels; heat, scintillation and tracking being the others. The ionization quenching factor (IQF) is defined as the fraction of energy released through ionization by a recoil in a medium compared with its kinetic energy. Measuring IQF, especially at low energies, is a key point for Dark Matter detectors, since it is needed to evaluate the nucleus recoil energy and hence the WIMP kinematics.

The energy released by a particle in a medium produces in an interrelated way three different processes: i) ionization, producing a number of electron - ion pairs, ii) scintillation, producing a number of photons through de-excitation of quasi-molecular states and iii) heat produced essentially by the motion of nuclei and electrons. The fraction of energy given to electrons has been estimated theoretically (Linhard et al. 1963) and parametrized by (Lewin & Smith 1996).
In the last decades an important effort has been made to measure the IQF in different materials: gases (Verbinski & Giovannini 1974), solids (Jones & Krauer 1975, Gerbier et al. 1990), and liquids (Aprile et al. 2006), using different techniques. The use of a monoenergetic neutron beam has been explored in solids with success (Jageman et al. 2005, Simon et al. 2003). However in the low energy range the measurements are rare or absent for many targets (e.g. Helium) due to ionization threshold of detectors and experimental constraints.

We have develop an experimental setup devoted to the measurement of low energy (keV) ionization quenching factor. The purpose is twofold: measuring for the first time the Helium quenching factor and performing very low energy measurements to test the prototype cell (resolution, threshold, ...) in the range of interest for Dark Matter (below 6 keV).

The experimental set-up is the following: an Electron Cyclotron Resonance Ion Source (Geller 1996) with an extraction potential from a fraction of one kV up to 50 kV, is coupled to Micromegas (micromesh gaseous) detector via a 1 µm hole with a differential pumping.

Energy values have been previously checked by a time-of-flight measurements through a 50 nm thick N₄Si₃ foil (Mayet et al. 2008). The ionization produced in the gas has been measured with a Micromegas (micromesh gaseous) detector (Giomataris et al. 1996) adapted to a cathode integrated mechanically to the interface of the ion source. It is a bulk type Micromegas (Giomataris et al. 2006), in which the grid and the anode are built and integrated with a fixed gap, 128 µm for measurements between 350 and 1300 mbar. The electric fields for the drift and the avalanche have been selected to optimize the transparence of the grid and the
gain for each ion energy. Typical applied field were 100 V/cm for the drift and a voltage of 450 V for the avalanche. The drift distance between the cathode and the grid was 3 cm, large enough to include the tracks of $^4\text{He}$ nuclei of energies up to 50 keV. These tracks, of the order of 6 mm for 50 keV, are roughly of the same length than the electrons tracks produced by the X-rays emitted by the $^{55}\text{Fe}$ source used for calibration.

In order to measure the quenching factor of $^4\text{He}$ in a gas mixture of 95% of $^4\text{He}$ and 5% of isobutane ($\text{C}_4\text{H}_{10}$) we proceed as follows: i) the ionization given by the Micromegas was calibrated by the two X-rays (1.486 and 5.97 keV) at each working point of the Micromegas defined by the drift voltage ($V_d$), the gain voltage ($V_g$) and the pressure, ii) the number of ions per second sent was kept lower than 25, to prevent any problem of recombination in primary charge collection or space charge effect.

Two different calibration sources have been used: the 1.486 keV X-rays of $^{27}\text{Al}$ produced by alpha particles emitted by a source of $^{244}\text{Cm}$ under a thin foil of aluminium and a standard $^{55}\text{Fe}$ X-ray source giving the 5.9 keV K$_\alpha$ and the 6.4 keV K$_\beta$ lines. These two lines, as they were not resolved by our detector, have been considered as a single one of 5.97 keV, taking into account their relative intensities. The IQF of a recoil will be the ratio between this energy and the kinetic energy of such recoil. In such a way, the IQF compares the nuclei ionization efficiency with respect to the electrons. The ionization spectra of 1.5 keV $^4\text{He}$ nuclei and of electrons of roughly the same energy (1.486 keV) are shown on Figure 3.

![Spectra of 1.5 keV kinetic energy $^4\text{He}$ (left) and 1.486 keV X-ray of $^{27}\text{Al}$ (right) in $^4\text{He}$ +5% $\text{C}_4\text{H}_{10}$ mixture at 700 mbar.](image)
The measurement reported (Santos et al. 2008) have been focused on the low energy $^4$He IQF. Figure 3 presents the results at 700 mbar compared with the Lindhard theory for $^4$He ions in pure $^4$He and with respect to the SRIM simulation (J. Ziegler) for $^4$He in the same gas mixture used during the measurements. We observe a difference between the SRIM simulation and the experimental points of up to 20% of the kinetic energy of the nuclei, shown in Fig. 3. This difference may be assigned to the scintillation produced by the $^3$He nuclei in $^4$He gas. This difference is reduced at lower pressures due to the fact that the amount of scintillation is reduced when the nuclei mean distance is increased giving a lower production probability of eximer states. More details may be found in (Santos et al. 2008).

As shown in (Trichet et al. 2008) energy resolution of Micromegas $\mu$TPC has been measured down to 1 keV. At 6 keV, it is of the order of 10%. Moreover, it does not depend on pressure and it does not affect the number of expected events for Dark Matter, even at low energy. Threshold as low as 300 eV (ionization) has been reached.

As presented in (Santos et al. 2008), measurements have been done in various experimental conditions, showing a clear increase at lower gas pressure and also at lower isobutane percentage (the quencher). Hence, the ionization signal is expected to increase with Helium purity, which is needed for Dark Matter search, and also at the lowest pressures, which is compulsory for directional detection.

4 Conclusion

In summary, this first measurement of Helium ionization in Helium down to energies of 1 keV recoil opens the possibility to develop a Helium $\mu$TPC for Dark Matter. For the next step, measurements of CF$_4$ quenching and recoil tracks at low pressure are being investigated.

References

G. J. Alner et al., Nucl. Instr. Meth. A 555 (2005) 173
E. Aprile et al., Phys. Rev. Lett. 97 (2006) 081302
D. Clowe et al., Astrophys. J., 648 (2006) L109
J. I. Collar and Y. Giomataris, Nucl. Instrum. Meth. A 471 (2000) 254
R. Geller, Electron Cyclotron Resonance Ion Sources and ECR plasmas, Bristol and Philadelphia: Institute of Physics Publishing, 1996
G. Gerbier et al., Phys. Rev. D42 (1990) 3211
I. Giomataris et al., Nucl. Instr. and Meth. A376 (1996) 29
I. Giomataris et al., Nucl. Instr. and Meth. A560 (2006) 405
A. M. Green and B. Morgan, Astropart. Phys. 27, 142 (2007)
Th. Jageman et al., Nucl. Instr. and Meth. A551 (2005) 245
K. W. Jones & H. W. Kraner, Phys. Rev. A11 (1975) 1347
E. Komatsu et al., arXiv:0803.0547 [astro-ph]
Fig. 3. Helium ionization quenching factor as a function of $^4\text{He}$ kinetic energy (keV). Lindhard theory prediction ($^4\text{He}$ in pure $^4\text{He}$ and $^3\text{He}$ in pure $^3\text{He}$), parametrized as in [Lewin & Smith 1996] is presented and compared with SRIM simulation results (solid line and points) in the case of $^4\text{He}$ in $^4\text{He} + 5\% \text{C}_4\text{H}_{10}$ mixture. Measured quenching factor are presented at 700 mbar with error bars included mainly dominated by systematic errors. The differences between data and SRIM simulation are shown by triangles.

J. D. Lewin & P. F. Smith, Astropart. Physics 6 (1996) 87-112
J. Lindhard et al., Mat. Fys. Medd. K. Dan. Vidensk. Selsk. 33 (1963) 1-42.
F. Mayet et al., Phys. Lett. B 538 (2002) 257
F. Mayet et al., to appear
E. Moulin et al., Phys. Lett. B 614 (2005) 143
E. Moulin et al., Astron. Astrophys. 453 (2006) 761
V. C. Rubin et al., arXiv:9904050
D. Santos, F. Mayet, O. Guillaudin et al., arXiv:0810.1137
D. Santos et al., to appear
G. Sciolla et al., arXiv:0806.2673
E. Simon et al., Nucl. Instr. and Meth. A507 (2003) 643
D. N. Spergel, Phys. Rev. D 37 (1988) 1353
M. Tegmark et al., Astrophys. J. 606 (2004) 702
A. Trichet, F. Mayet et al., Proc. of the Dark Energy and Dark Matter conference, Lyon (2008), arXiv:0904.1642 [astro-ph.CO]
M. Tristram et al., Astron. Astrophys. 436 (2005) 785
F. Mayet et al.: $\mu$TPC detector for non-baryonic dark matter search

V. V. Verbinski & R. Giovannini, Nucl. Instr. and Meth. 114 (1974) 205

J. Ziegler et al., http://www.srim.org