STATUS OF THE DARK MATTER SEARCH PROJECT "ULTIMA"

Yu. M. Bunkov, E. Collin, J. Elbs, H. Godfrin and C. Winkelmann
CRTBT-CNRS, 25 av. des Martyrs, 38042, Grenoble, France

The new project "Ultra Low Temperature Instruments for Measurements in Astrophysics" (ULTIMA) is based on a new target material for bolometric particle detection: superfluid ^{3}He-B at ultra-low temperatures, of the order of 100 μK. At these temperatures the quantum excitations in ^{3}He are nearly frozen and the heat capacity exponentially vanishes. The advantages of a ^{3}He based detector are the direct channels of temperature and ionization measurements, 30% concentration of unpaired neutrons, as well as the virtually absolute ^{3}He purity and giant neutron cross section.

1 Introduction

Superfluid ^{3}He-B at ultra-low temperatures was suggested by G. R. Pickett in 1988 [1] as an appealing target material for bolometric particle detection. The first application of superfluid ^{3}He as a detector was published in 1995 under the title "Potential dark matter detector..." [2]. From that time we considered superfluid ^{3}He as one of the most promising materials for the search for non-baryonic Dark Matter. The main arguments in favor of ^{3}He are first of all its working temperature of about 100 μK, at which thermal fluctuations are extremely small. As a result an extremely high sensitivity of the superfluid ^{3}He bolometer can be achieved [3,4]. It is important also that ^{3}He has a non-zero nuclear magnetic moment (allowing therefore to explore the Spin-Dependent interaction channel) with a high density of non-paired neutrons (33%).

^{3}He is a quantum fluid obeying Fermi statistics, and it remains liquid down to the the absolute zero of temperature. At about 1 mK (depending on the pressure), liquid ^{3}He displays a second order phase transition to its superfluid A- and B-phases. The superfluid A phase has an anisotropic gap structure and an order parameter mixing magnetic and flow properties, while the B phase is characterized by an isotropic gap $\Delta = 1.76\ k_BT_c$ well described at 0 pressure by the weak coupling BCS theory [5]. Experimental temperatures as low as 100 μK are achieved by adiabatic nuclear demagnetization of a copper stage, which then cools down the liquid ^{3}He [6]. At these temperatures far below the transition temperature T_c, the superfluid is in its isotropic B-phase and the density of thermal excitations (quasiparticles) n decreases exponentially with temperature

$$n = \int g(E)dE = \frac{N_A}{V}\sqrt{2\pi\frac{\Delta}{k_BT}}\ \exp(-\Delta/k_BT), \tag{1}$$

where $g(E)$ is the density of states, N_A is Avogadro's number and V the molar volume of the fluid. This density is so low that the liquid can be represented as a renormalized quantum vacuum carrying a dilute quasiparticle gas. In the range of 100 to 200 μK, the heat capacity of the superfluid is dominated by the ballistic quasiparticle gas and reduces to

$$C = C_0 \left(\frac{T_c}{T}\right)^{3/2} \exp(-\Delta/k_B T), \tag{2}$$

with $C_0 \approx 2.1$ mJ K^{-1}cm^{-3}.

A direct and rather rapid method of thermometry of the superfluid is achieved by measuring the density of thermal excitations (quasiparticles) using Vibrating Wire Resonators (VWRs) [7]. A VWR is a fine superconducting wire bent into semi-circular shape and oscillating perpendicularly to its plane. The excitation and the read-out of the VWR are respectively an a.c. current and voltage.

2 Achievements

For the bolometric particle detection we use copper cells of typical dimensions of about 5 mm, filled with superfluid ^{3}He which is in weak thermal contact with the outer bath through a small orifice [2,3]. The interaction of a particle with the ^{3}He in the cell releases energy which results in an increase of temperature, and thus n. The time constants of internal equilibrium of the quasiparticle gas are small (< 1 ms), while the time constant for thermal relaxation of quasiparticles through the orifice after a heating event is tuned to be $\tau_{cell} \approx 5$ s. The heat leak through the container walls can be neglected because of the huge thermal resistance (Kapitza resistance) of the solid-liquid interfaces at very low temperatures. Each bolometric cell contains at least one VWR-thermometer which allows to follow the rapid variations of the temperature.

Neutrons were the first particles studied in superfluid ^{3}He for their large energy release after the capture reaction [2]. Of particular interest was the study of the rapid and inhomogeneous phase transition of a small region around the neutron impact, because of the possibility of topological defects creation in the superfluid in analogy with the Kibble mechanism in cosmology [3,4]. The neutrons, emitted by a moderated AmBe source, produce large signals in the bolometer. A deficit of about 120 keV with respect to the expected 764 keV is observed; part of this deficit is accounted for by ultra-violet (UV) scintillation of the ^{3}He, the rest is interpreted in terms of energy trapped in the form of metastable topological defects of the superfluid (e. g. quantized vortices).

Cosmic muons are expected to deposit about 16 keV/mm in liquid ^{3}He at 0 bar. Muons represent thus bolometric events about an order of magnitude below neutrons. A muon test of the detector and its comparison to a numerical simulation by Geant4 in the frame of the MACHe3 collaboration yielded good agreement, the 20-25 % difference between the experimental and the calculated detection spectra being due to ultra-violet scintillation [8].

Final evidence for the muonic nature of the observed energy peak at about 50~60 keV at ground level was brought by the recent experiment with a 3-cell prototype. The simultaneous detection in 3 adjacent cells allowed to discriminate with large efficiency the muons, who are, depending on their trajectory, generally detected coincidently in two or more cells. This setup therefore allowed to demonstrate the large muon rejection efficiency of a future underground multicell detector. Since the energy range of a neutralino scattering is expected to be in the keV range, the proof that a 1 keV detection resolution and threshold could be attained had to be brought using a known particle source. A low activity ^{57}Co source was therefore implemented directly in one cell. Such a source emits γ-rays mainly at about 120 keV, which have a weak Compton scattering cross-section with the ^{3}He, but also low energy electrons (from internal conversion and the Auger effect) which thermalize completely in the liquid of the cell. Such low energy electron events are expected mainly at about 7 and 14 keV, and only in one cell [8,9]. Measurements on the 3-cell prototype indeed allowed to identify such bolometric events, again an order of magnitude below typical muons. The low energy detection spectrum from the cell with source and its comparison to another cell (without source) allows to clearly identify these events as produced by the ^{57}Co source.

Bolometric calibration of the detector cells is achieved by an extra VWR present in the cell that can produce a short mechanical pulse at its resonant frequency and thus deposit a well-controlled amount of energy (heat) to the liquid through mechanical friction [4]. The results of the calibration are compared to measured heat depositions by the nuclear neutron capture reactions as well as muon impacts and low energy electron irradiation. A deficit of about 15 % is found in the case of neutrons, in good agreement with previous measurements at 0 bar [3]. In the case of high energy muons, as well as electrons in the 10 keV range, a deficit of about 25 % is found which can be entirely attributed to UV scintillation emission. It is not surprising to find the scintillation rates resulting from these two types of irradiation to be of the same order since the much larger incident energy of cosmic muons is compensated by their larger mass.

3 Recent development

Recently quartz forks have been tested as ^{3}He thermometers [10]. To be applied to our experimental cell, the quartz oscillators signal to noise ratio should be improved by about one order of magnitude. We are working now on the design of quartz forks adapted for bolometric conditions. Another new development is the use of Silicon structures as vibrating sensors [11]. We are also developing these devices for bolometric applications.

Parallel methods of discrimination of ionizing events are in study. The fraction of energy released by a particle going into the ionization of ^{3}He can provide a fine criterium of discrimination. Ion dynamics in ^{3}He have been studied for a long time already, for positive ions as well as for negative ^{3}He ions. Ions create a ball of solid ^{3}He with a mass of about 100 atoms due to the van der Waals interaction. The main problem is the small velocity of ions in an applied electric field, which can move without friction only with a velocity below a critical one, which is of the order of 10 cm/s. Consequently, the time constant of the ionization channel in ^{3}He is of the order of seconds. However there is a possibility to create an ion amplification for thermal signal. At a high electric field the accelerated ions deposit more thermal energy to the ^{3}He liquid, than is deposited by the scattering of particles. An amplification by a factor of 10 is possible for our experimental conditions.

Last year we have studied carefully the heat capacity of superflid ^{3}He at different pressures, magnetic fields and temperatures. Some unexpected phenomena have been found and will be published in condensed matter journals.

Finally, we are working on the design of a new nuclear demagnetization cryostat for underground environment. In which particular underground laboratory this experiment will be conducted is still open.

4 Axial interaction with ^{3}He

In the non-relativistic limit, which is appropriate for WIMPs in our Galaxy, the variety of possible forms of WIMP-nucleus interactions is reduced to two cases, namely, to a spin-spin interaction and to a scalar one. The fundamental constants of the WIMP interaction with nucleon constituents, specified by each concrete particle model, determine the effective coupling of WIMPs to nucleons, which, in turn, define constants of the WIMP-nucleus interaction (for a more detailed review see [12]). The essential difference between spin-spin and scalar interactions is in the following. In the scalar case, the WIMP-nucleus interaction amplitude (A_{XA}) is given by the WIMP-nucleon ($A_{Xp,n}$) one, multiplied by the number of respective nucleons, while in the spin-spin case A_{XA} is proportional to the nucleon spin averaged over the nucleus state $S_{p,n}$, which for heavy non-zero spin nuclei is, as a rule, even smaller than that for a single nucleon

($S_p = S_n = 1/2$). It leads to a loss of advantage in using heavy target-nuclei in the exploration of WIMPs with spin dependent interaction. The ^{3}He nucleus having a non-zero magnetic moment and a huge density of non-paired neutrons (33%), a ^{3}He detector will be mainly sensitive to the axial interaction [13,14], making this device complementary to existing ones, mainly sensitive to the scalar interaction. The axial interaction is largely dominant in most of the SUSY region associated with a substantial elastic cross-section.

5 Conclusion

While the use of ^{3}He imposes challenging technological - namely cryogenical - constraints, this material has nevertheless extremely appealing features for Dark Matter detection. Since the original proposal of the use of ^{3}He for particle detection, the detection threshold and sensitivity have been improved by 2 orders of magnitude, reaching nowadays 1 keV, which covers already most of the expected energy range for a neutralino impact. The use of a ^{57}Co source producing a well known γ-ray and low energy electron spectrum directly in one bolometric cell allowed to illustrate both our understanding of the detector at keV level and the high transparency of the target material to γ-rays. In addition, the simultaneous detection in 3 adjacent cells demonstrated the future rejection efficiency versus ionizing events of a large multicell detector.

On the basis of the last several years of investigations on superfluid ^{3}He, the new direct Dark Matter search project "Ultra Low Temperature Instruments for Measurements in Astrophysics" (ULTIMA) has started in December 2005 at the CRTBT-CNRS, Grenoble. We are thankful to the French National Research Funding Agency ANR for financial support of the new project.

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