OPERATION AND CALIBRATION OF LARGE-MASS DROPLET DETECTORS FOR PICASSO

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The PICASSO cold dark matter (CDM) detector is based on the phase transition produced by nuclear recoils in room temperature superheated liquids, induced by CDM particles, such as neutralinos predicted by supersymmetric models. Large-mass superheated droplet detectors have been built for the first time. We review their properties and operation. Simulations performed to understand the detector response are presented, briefly. Signal definition and analysis are described together with possible sources of acoustic background, with their frequency signatures, and eventual elimination. The PICASSO innovative droplet detectors for CDM search will allow the quantitative study of one of the main questions of modern physics.

1 Introduction

Information from the anisotropy measurements of cosmic background radiation and the galactic recession velocities as measured with large red-shift supernovae suggests that Cold Dark Matter (CDM) consists mainly of non-baryonic particles [1]. Weakly interacting massive particles (WIMP) are ideal candidates for CDM. Among them stands the neutralino, predicted by minimal supersymmetric models. The neutralino is stable if R-parity is conserved and has a mass of the order of 100 GeV/c^2. A mass lower limit of 50 GeV/c^2 has been extracted from LEP experiments [2]. In their gravitational motion around the center of the Galaxy, the neutralino velocity distribution is Maxwellian with $v_{rms} \sim 300$ km/s. At the position of the solar system, they are supposed to be the main ingredient of the measured average mass density of 0.3 GeV/cm^3. They interact very weakly with nuclei, which then recoil with typical energies within a range [3] of 0 - 100 keV.

The concept of the PICASSO experiment [4] rests on an approach to detect CDM candidate particles, the neutralino in particular, through the use of large mass superheated droplet modular detectors. The operation of these detectors, similar to that of bubble chambers, is well described by the theory of Seitz [5]. They are threshold detectors, and their sensitivity to various types of radiation is strongly dependent on operation temperature and pressure. Their high efficiency for detecting neutrons, for an adequate gas at room temperature, features a detection process based on the energy deposited by the nuclear recoil produced in the collision of a heavy particle, the neutralino ultimately, with a nucleus of the active medium. This nuclear recoil triggers the liquid-to-vapour phase transition of room-temperature superheated carbo-fluorates, while the droplet detectors are relatively insensitive to minimum ionizing particles and to nearly all sources of background [6]. The very low interaction cross sections between CDM and the detector active medium nuclei requires the use of very massive detectors to achieve a sensitivity level allowing the detection of CDM particles in the galactic environment. This article presents a review of the features of the large mass superheated droplet detectors.

2 The superheated droplet detectors and their operation

The large-mass droplet detectors consist in an emulsion of room temperature meta-stable superheated freon-like (C_4F_8, C_4F_{10}, etc) droplets dispersed in an aqueous solution. This solution is subsequently polymerized after dissolution of an appropriate concentration of a heavy salt (e.g., CsCl, NaBr, sodium acetate) in water. The salt is used to equalize densities of droplets and solution. Bubbles are stationary after formation due to the gel elasticity and can be recompressed to liquid droplets for a new round of measurements by applying pressure with a piston or with compressed gas to the detector container. Bubble formation is triggered by the heat spike deposited when a particle traverses a length of superheated liquid. This formation can be measured either visually (when the loading or detector volume are small enough) or acoustically via piezo-sensors sensitive to the pressure wave produced during the explosive phase transition. A detector is shown in Fig. 1 in a container capable of holding pressures up to 10 bars. Piezo-sensors are glued on the container surface for signal detection. Typical gas loading is in the 10-40 g/litre range. The detectors have been built, according to PICASSO specifications, by BTI (Bubble Technology Industries) [7].

Superheated droplet detectors are threshold detectors. Their response is determined by gas thermodynamic properties and depends on operating temperature and pressure. The detector operation can be understood in the framework of the theory of Seitz [5] which poses that bubble formation is triggered by the heat spike resulting from the energy deposition when a charged particle traverses the superheated medium. The potentiel barrier, E_c, which prevents spontaneous liquid-to-gas transition in a superheated liquid, is given

Figure 1. A 1.5 litre detector module equipped with sensors.

by the Gibbs equation

$$E_c = \frac{16\pi}{3} \frac{\sigma(T)^3}{(p_i - p_0)^2} \tag{1}$$

where p_0, p_i (functions of temperature, T) are the applied and internal pressures, respectively. The surface tension is given by $\sigma(T) = \sigma_0$ (T_c - T)/(T_c - T_0) where T_c is the critical temperature of the gas, σ_0 is the surface tension at a reference temperature T_0. Bubble formation will occur when the energy deposited exceeds the threshold value E_c over a critical length $R_c = 2\sigma(T)/(p_i - p_0)$. The actual energy threshold for recoil detection $E_{R,th}$, is related to E_c by an efficiency factor $\eta = E_c/E_{R,th}$ ($2 < \eta < 6\%$) [8,?]. The threshold value being dependent on temperature and pressure of operation, the detector can be set into a regime where it responds only to nuclear recoils and discrimination is achieved against background radiations such as $mip's$ and gamma rays.

Different freon-like gases can be employed to obtain adequate response in a specific temperature and pressure range. The detector responses to α-particles, γ-rays and AcBe source neutrons have been measured. Several different gases have been studied with mono-energetic neutrons to define the optimal choice of detection medium for a large-scale CDM detector. The droplet detector operation can be understood using monoenergetic incident neutrons which allow precise measurements of energy thresholds and response functions for various temperatures and pressures of operation. From these neutron measurements, one can deduce the detector efficiency as a function of the nuclear recoil energy. The dependence of the neutron threshold energy on temperature and pressure of operation is shown in Fig. 2.

The detector response to mono-energetic neutrons of 200 and 400 keV as a function of temperature and pressure of operation is shown in Fig. 3 and 4, respectively.

The explosive droplet-bubble transition generates an acoustic signal which

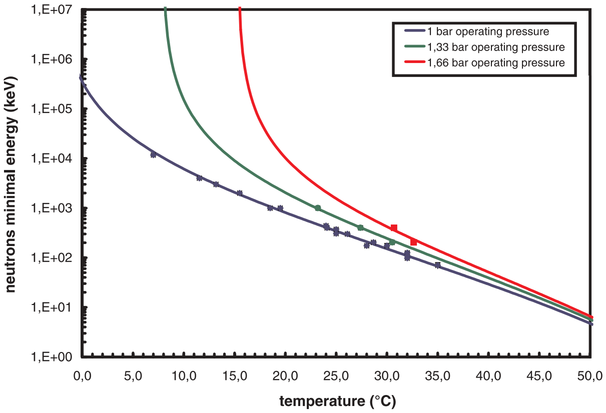

Figure 2. Neutron threshold energies as a function of temperature and pressure.

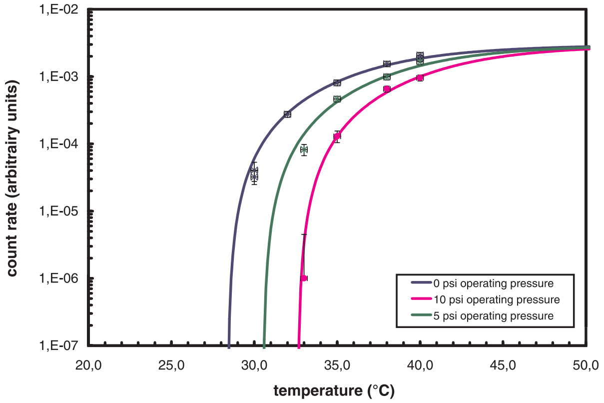

Figure 3. Detector response to 200 keV neutrons as a function of temperature and pressure.

can be detected by PZT-piezoelectric sensors adapted to the acoustic emission spectrum. These sensors, two or more, are glued to the surface of the detector container and coupled to high gain, low noise preamplifiers whose frequency response is optimized to suppress lower frequency acoustic noise. Examples of acoustic signals transformed into electronic signals are shown in Fig. 5. A Control and Data Acquisition system (CDAQ) has been developed and

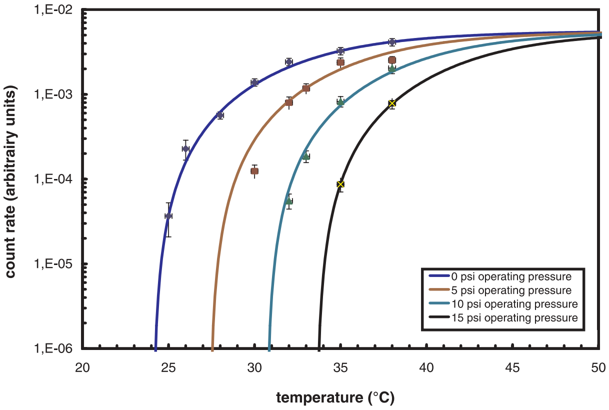

Figure 4. Detector response to 400 keV neutrons as a function of temperature and pressure.

optimized to enhance the operation of the detectors, it is described in details elsewhere [10].

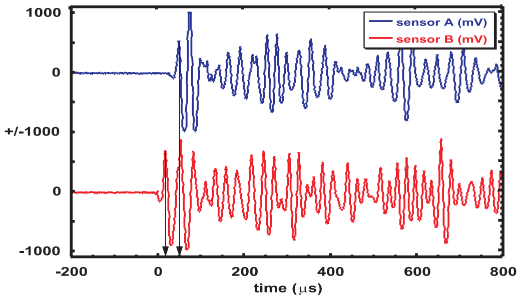

Figure 5. Electrical signal produced by the passage of droplet-to-bubble transition sound wave through two (A and B) piezo-electric sensors.

3 Signal analysis

The signal produced by the droplet-to-bubble transition is transmitted through the gel as a pressure front, then through the container wall to the piezo-sensor. The sound velocity in the gel has been measured to be 1600

± 100 m/s, close to the sound velocity in the plastic materials used in the container fabrication [10]. The detectors have been exposed to a variety of radiations. The signal shapes and frequency responses are dependent on the energy released in the liquid-to-vapour phase transition, on the distance travelled by the pressure wave in the gel leading to signal attenuation as a function of event-sensor distance. It also depends on the temperature and pressure of operation, and on the recording history of the detector, i.e. on the number of events that have occurred before the measured signal since the last compression of the detector. The dependence of the signal amplitude as a function on the number of events counted after a recompression and pressure release cycle has been investigated, for various temperatures of operation [10]. The trend of the data, obtained by dispersing an alpha-emitting activity in the detector gel, shows a decrease of counting and mean maximum amplitude which reflects the detector depletion, starting with the largest droplets, fewer in number but containing a larger fraction of the active volume. The amplitude attenuation for various sensor-event distances indicates that signals can be obtained with adequate efficiency up to 20 cm from the source.

In ref. [10], the signal amplitude is observed to increase with increasing temperature and decreasing pressure of operation. That follows the expectation that the energy released in a droplet explosion increases with temperature and decreases with pressure. It allows one to set well-defined limits on the temperature and pressure ranges of operation.

The piezo-sensors have been selected to discriminate against low frequency noise, typical of acoustic noise, while favoring higher frequencies useful for timing purpose [10]. Fast Fourier transform analysis of pulses within specific frequency windows selected according to the known sensor response allows acoustic noise rejection, yielding a clean radiation-induced signal at a cost of low efficiency loss ($< 10\%$).

The sources of background are γ-rays, mip's, and α-particles due to U/Th contamination of the detector. Another source of background are neutrons, with energy above threshold. There are two sources of neutrons: from radioactivity in the environment or from spallation induced by cosmic ray muons. Spontaneous nucleation is possible, although rapidly decreasing with decreasing temperature and shown to be completely negligible in the temperature range of interest for neutralino-induced recoils measurements [6]. The sensitivity to gamma-ray background becomes also negligible at the same temperatures, as is the sensitivity to cosmic-ray muons. Figure 6 shows the response of a 1.5 litre detector to α-particles emitted from the gel doped with a known α-actvity of ^{232}U (20 Bq). The detector becomes sensitive to background gamma-rays for temperatures above ~ 38 C.

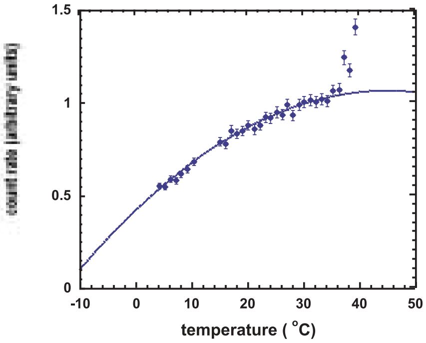

Figure 6. Response of a 1.5 litre detector to α-particles emitted from gel doped with 20 Bq ^{232}U. Above ~ 38 C the detector becomes sensitive to background gamma-rays.

α-emitters in the detector materials can be removed through purification treatment as used by very low background experiments, such as SNO. Shielding against neutrons is provided by using moderators such as paraffin or water to bring their energies below threshold (<50 keV at room temperature, for a given choice of active medium) or by going underground to eliminate muon-induced neutrons in the environment or in the shielding material as envisaged for the installation of PICASSO in the SNO mine. Details about these backgrounds measurements are reported in reference [6]. Present in the detector environment, radon is another source of background. Radon can diffuse into the detector and induce an α-background (Fig. 7). Flushing the detector container with pure nitrogen eliminates radon. Radon must be eliminated during the detector fabrication and storage and also from the gas used for recompression of the detector to avoid α-contamination buildup.

4 Simulations

To understand the droplet detector response to α-emitting contamination of the gel due to U and Th and to radon absorption, we are considering various processes involving α-particles recoiling in droplets: energy loss by ionization, elastic and inelastic collisions with C and F nuclei, in order to develop detailed Monte-Carlo simulation calculations. Experimental results, such as energy thresholds, as measured with mono-energetic neutron beams, and threshold functions, are included in the calculations. The results are expressed as a function of the reduced superheat parameter $s = (T - T_b)/(T_c - T_b)$ (T_b is

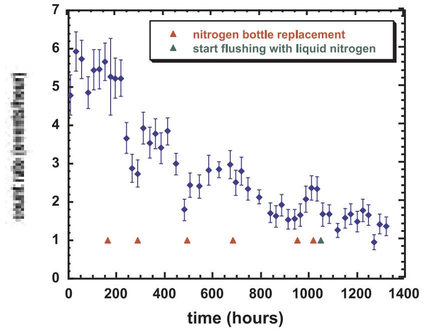

Figure 7. Background counting rate of a 1.5 litre detector as a function of time. The background count rate depends on quality of nitrogen used for flushing. Fluctuation stabilized and minimized with liquid nitrogen boil off.

the boiling or saturation temperature of the droplets), with effective critical temperature (T_{ceff}) values obtained from measured spontaneous nucleation threshold [6]. The T- or s-dependence of neutron energy thresholds is obtained from eq. 1, as shown in Fig. 8. Critical ranges of C and F nuclei are then extracted (Fig. 9) using dE/dX values as calculated with TRIM [11]. The reduced superheat parameter allows a unified description of various active gas detector response as shown in Fig. 8 and Fig. 10.

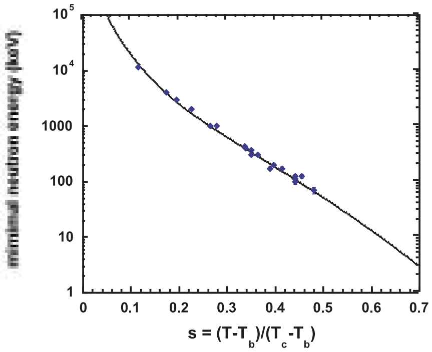

Figure 8. Minimal neutron energy as a function of the reduced superheat parameter s.

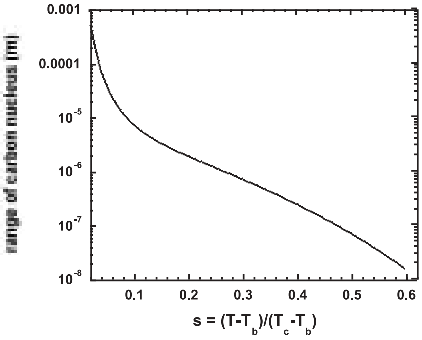

Figure 9. Calculated "effective" critical range as a function of the reduced superheat parameter s for the carbon nucleus.

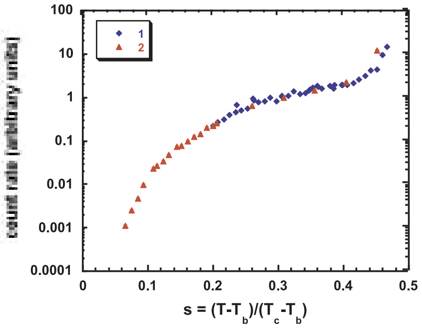

Figure 10. The response of two detectors (1 and 2 with different neutron energy thresholds) to neutrons from a AcBe source as a function of temperature. The use of the parameter s allows the unification of the response of the two detectors. With parameter s, the response for different gases is computed with $T_{ceff} = 0.9\ T_c$.

5 Conclusions

Large mass superheated droplet detectors have been fabricated and tested. Their active mass of 10-40 g/litre allows the assembly of a very large detector array capable of achieving quantitative study of CDM. The on-going program of signal processing and analysis, of background understanding and elimination, is leading to a significant signal sensitivity for such a large mass detector array.

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