Development of Bubble Chambers with Sensitivity to WIMPs

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Abstract

Bubble nucleation in moderately superheated liquids can be triggered by nuclear recoils from WIMPs. This phenomenon is the basis for superheated droplet detectors. The droplet technique is currently limited by insensitivity to spin-independent interactions, due to lack of heavy elements in the usual target liquids, and sensitivity to contamination of the gel by alpha emitters. As an alternative, we have developed a new type of homogeneous bubble chamber, which can contain heavy liquids, including CF_3Br, CF_3I, and C_3F_8. Detectors of this type may be scalable to large size at modest cost and could have very low backgrounds. We discuss results obtained with a 12 ml prototype and plans for a 1 liter chamber.

1 Detection of Dark Matter By Bubble Nucleation

Detection of WIMP dark matter via bubble nucleation in superheated liquids has previously been proposed by several authors [1] . These proposals are based on the fact that, under certain temperature and pressure conditions, boiling can be initiated by nuclear recoils, but not by gamma ray and electron interactions [2]. The first experiments with superheated liquids, using Superheated Droplet Detectors (SDDs), have demonstrated virtually complete insensitivity to gamma and beta backgrounds, while achieving energy thresholds for nuclear recoils below 10 keV [3]. However, SDD technology suffers from a number of limitations. In particular, the requirement for exact density matching between the droplets and gel in SDD fabrication has so far precluded the use of target liquids incorporating the heavy elements that would have high cross sections for coherent, spin-independent WIMP-nucleus interactions. Moreover, although SDDs are insensitive to gamma and beta rays, they remain sensitive to heavily ionizing background particles, including alpha particles and their recoiling daughters [3]. The superheated liquid and gel need to have extremely high purity to avoid significant backgrounds from this source.

We discuss in this paper the development of high-stability bubble chambers containing heavy liquids as an alternative to SDDs. The use of a stable enough bubble chamber would have many advantages, including the possibility of quick removal and re-purification of the liquid to remove alpha emitters, efficient discrimination of neutron backgrounds by observation of multiple scattering and a relatively simple path towards building detectors with very large sensitive volumes.

The primary obstacle to using conventional bubble chambers for WIMP detection is their instability, due to bubble nucleation on the walls of the chamber. This effect limited the sensitive time of most chambers built from the 1950s to the present to less than 10 msec per decompression, corresponding to a live time fraction of 1% or less. However, when operating at the low degree of superheat required for reduced sensitivity to gamma and beta rays, and with special care taken to avoid the presence of materials such as rough metallic surfaces that contain many nucleation sites, longer-lived superheated periods have been reported [2]. Several recently described techniques that maximize the stability of small bubble chamber prototypes have been identified, for instance, use of an immiscible liquid layer above the active volume, outgassing of surfaces in the presence of a buffer liquid, surface cleaning techniques and wetting improvement via vapor deposition [4].

2 Design of 12 ml Chamber

To further explore this possibility, we built the small bubble chamber shown in Figure 1. The pressure in the chamber is controlled by a piston, which is operated by compressed air. To operate the chamber, gas is introduced from a supply cylinder and liquefied, with the piston fully compressed. When the desired amount of liquid has been condensed into the chamber, the compressed air in the piston is discharged to reduce the internal pressure of the quartz chamber and cause superheating. A -40 to +60 °C range is appropriate for operating with many liquefied halocarbons, including CF_3Br, C_3F_8, and CF_3I. When bubble nucleation occurs, it causes violent boiling, and a rise in pressure. The signal from a pressure sensor is used to trigger recompression, which causes re-liquification of the gas released during boiling.

An unusual feature of our chamber is avoidance of direct contact between the piston and superheated liquid, in order to eliminate the piston as a source of bubble nucleation sites. This is made possible by a layer of propylene glycol separating the liquid and gas phase of the active material. The glycol prevents

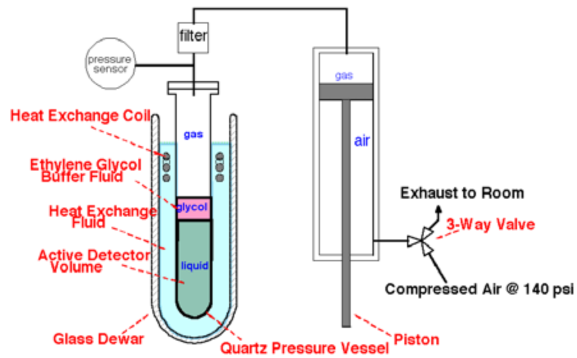

Fig. 1. Small prototype bubble chamber. The superheated liquid is contained in a small quartz pressure vessel, which is surrounded by heat exchange fluid, inside a glass dewar.

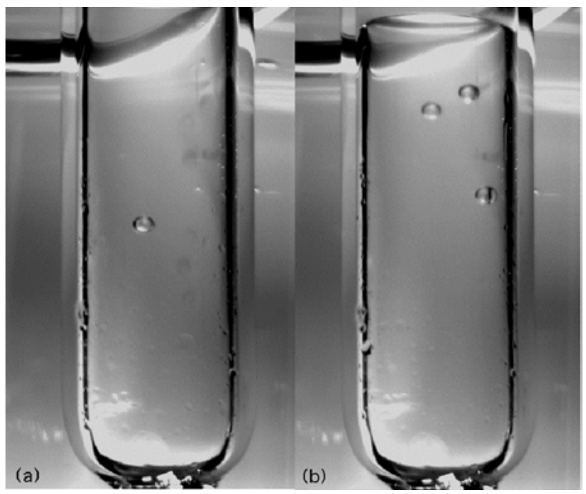

Fig. 2. Photographs from the prototype chamber: (a) a single bubble produced by exposure to neutrons from an Am-Be source, (b) a triplet of bubbles produced by multiple scattering by an environmental neutron.

evaporation of the superheated liquid.

Photographs of bubbles are made with two CCD cameras, using a timing signal provided by amplification of the output from a piezoelectric sensor glued to the bottom of the quartz vessel. The sensor registers an acoustic pulse coincident with the start of bubble growth. Example images are shown in Figure 2.

3 Neutron Calibrations

The response of the detector to nuclear recoils from neutron scattering has been studied, using sources with a well-defined endpoint energy (Am/Be and ^{88}Y/Be) and CF_3Br as the target liquid. The Am/Be source produces neutrons with a maximum energy of 11 MeV, yielding nuclear recoils on C, F,

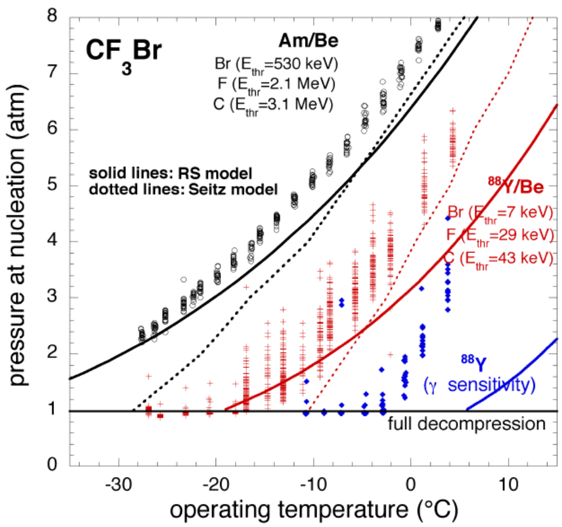

Fig. 3. Measurement of bubble nucleation pressure threshold, as a function of temperature, with Am/Be and ^{88}Y/Be neutron sources. Lines show predictions calculated using the Seitz and reduced Superheat bubble nucleation theories.

and Br with energies up to 3.1 MeV, 2.1 MeV, and 530 keV respectively. The bubble nucleation pressure threshold at a given temperature can be predicted from the Seitz bubble nucleation theory [5] and Reduced Superheat theory [6]. As shown in Fig. 3, we obtained fairly good agreement between calculations and data even prior to any optimization of free theoretical parameters [7]. The theories can also be used to predict the recoil energy thresholds during the normal operation of the chamber at a fixed pressure and temperature. At -10 °C and ambient pressure, these recoil thresholds on Br, F, and C are calculated to be 7 keV, 50 keV and 110 keV. The photonuclear $^{88}Y/Be$ source emits a mixed field of $\sim 10^8$ high-energy gammas and 3×10^3 monochromatic (152 keV) neutrons per second. This allows for a dramatic demonstration of insensitivity to photoelectrons in operating conditions that nevertheless ensure optimal response to WIMP interactions. The insensitivity (rejection factor) to photoelectrons in operating conditions at which the threshold for nuclear recoils is in the few keV has been measured to be $> 10^9$. This guarantees the ability to build much larger prototypes in the tonne or multi-tonne regime with essentially no concern for minimum ionizing particles.

4 Measurement of Neutron Background at 5 m.w.e.

With no neutron source present, the mean time between events was 14.8 minutes with 18g of CF3Br at 5 m.w.e. and -10 °C. These events are distributed uniformly in the volume of the detector, indicating that they are not caused by alpha particle emission or spontaneous boiling at the quartz surfaces. The observation of 6 double scattering events and 1 triple scattering event (Fig.

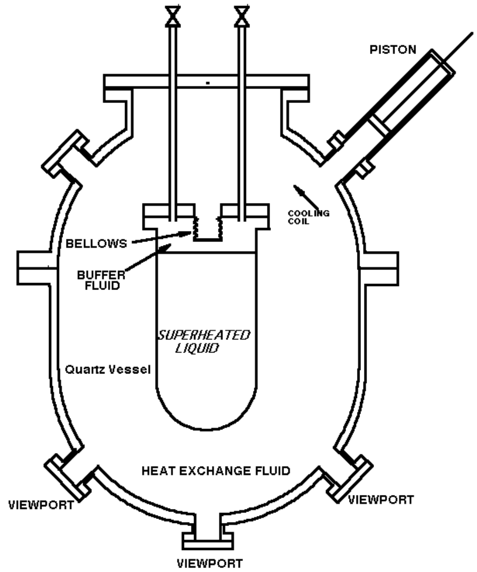

Fig. 4. Design concept for large quartz chambers. A bellows is used to eliminate the pressure across the quartz vessel.

2b) in 1.7 live days (163 events total), together with Bonner sphere measurements of fast neutron flux in the laboratory (roughly one tenth of sea-level), suggests that the observed events are due to ambient neutrons. Recent Monte Carlo simulations using the measured neutron flux as input have confirmed this [8].

For the background measurement, we were able to keep the chamber sensitive 64% of the time, with the remaining time used for the long recompression period that was found to be necessary after each event. Attempts to decompress the chamber more quickly than 5 minutes after each event often resulted in spontaneous boiling on the quartz walls.

5 Development of 1 Liter Chamber

The next step in evaluating the suitability of bubble chamber technology for a WIMP search will be to build an apparatus with enough target liquid to obtain meaningful estimates of backgrounds. It is anticipated that the dominant backgrounds will be due to contamination of the superheated liquid by environmental alpha emitters, including ^{222}Rn and ^{210}Po. Backgrounds of this type have been extensively investigated in the context of solar neutrino experiments, such as Borexino and SNO, and techniques have been developed to reduce alpha contamination of liquids to very low levels (e.g. $\sim$ 1/ton-day in liquid scintillator [9]). Achieving similar rates in a bubble chamber would result in sensitivity to WIMPs approximately 2 orders of magnitude greater than in the best current experiments.

A central design issue in scaling up to large detector masses is how to avoid contact between the superheated liquid and rough metal surfaces. Large, thick-walled quartz or glass pressure vessels are impractical, due to safety reasons. However, low-pressure vessels can be produced with volumes up to several m^3. To build large bubble chambers, we propose the novel design sketched in Figure 4, which incorporates a pressure-balancing mechanism to allow the use of a thin- walled quartz vessel inside a standard steel pressure vessel. A 1 liter chamber based on this concept is currently under construction. This chamber is intended to be operated at the Soudan underground laboratory, where event rates as low as to ~ 0.01/kg-day could be probed [8], resulting in sensitivity to WIMPs competitive with other experiments under development, even at this early stage.

ACKNOWLEDGEMENTS This research is supported by the NSF through the Kavli Institute for Cosmological Physics at the University of Chicago and CAREER award 0239812.

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