Available online at www.sciencedirect.com
SCIENCE DIRECT®

Nuclear Physics B (Proc. Suppl.) 138 (2005) 68–71

NUCLEAR PHYSICS B
PROCEEDINGS
SUPPLEMENTS

www.elsevierphysics.com

Development of bubble chambers with sensitivity to WIMPs

L. Bond[a], J. I. Collar[b*‡], J. Ely[a], M. Flake[a], J. Hall[b], D. Jordan[a], D. Nakazawa[a], A. Raskin[a], A. Sonnenschein[a] and K. O'Sullivan[b]

[a]Pacific Northwest National Laboratory, Richland, WA 99352, USA
[b]Department of Physics and Center for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA
[‡]Corresponding author email: collar@uchicago.edu

We constructed a small bubble chamber, with special features needed to search for WIMPs: long sensitive time periods, intrinsic insensitivity to minimum ionizing particles and target liquids with high sensitivity to both spin-dependent and -independent couplings. Stereo photography of bubbles allows rejection of events occuring at the chamber walls and discrimination of neutron backgrounds. The chamber can be operated with a variety of liquids, including CF_3Br, CF_3I, C_3F_8 and liquid xenon. A >60% live time fraction has been achieved and sensitivity to nuclear recoils demonstrated. Detectors of this type may be scalable to very large size at modest cost.

1. DETECTING DARK MATTER VIA 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

*This research is supported by the NSF Center for Cosmological Physics at the University of Chicago and NSF CAREER award 0239812.

0920-5632/$ – see front matter
doi:10.1016/j.nuclphysbps.2004.11.016

chamber. This is in contrast with SDDs, where smooth liquid-liquid interfaces circumvent the issue. This effect limited the sensitive time of most chambers built from the 1950's to the present to ~10 msec per decompression. In these chambers the superheated liquid was in contact with the metal walls of the pressure vessel and other materials that contain nucleation sites. However, a few "clean chambers", with glass walls were built, beginning with Glaser's first prototype [4], in which the superheated state was maintained for ~1 minute. When operating at the low degrees of superheat required for reduced sensitivity to gamma and beta rays, long-lived superheated periods have been reported. It would appear that chambers where special attention has been paid to deactivation of nucleation sites on surfaces could achieve nearly continuous sensitivity to WIMP-nucleus scattering, provided that the average total event rate (signal plus background) remains much less than the time required to recompress the chamber. A first test of this approach in the framework of the SIMPLE experiment [3] used a rudimentary gel-lined plastic chamber containing 30 g of R-115 (C_2ClF_5). The device displayed a promising stability (up to several hours) when operated at a depth of 500 m.w.e. [5]. It must be noted that since the demise of bubble chambers in particle physics, large progress has been made in site deactivation techniques for suppression of nucleations on surfaces [6].

2. DESIGN OF 12 ML CHAMBER

To further explore this possibility, we built the small bubble chamber shown in Fig. 1. The superheated liquid is contained in a small quartz pressure vessel, which is surrounded by heat exchange fluid, inside a glass dewar. The heat exchange fluid is cooled with a chiller. A –40 to +60 °C range is appropriate for operating with many liquefied halocarbons, including CF_3Br, C_3F_8, and CF_3I. Most

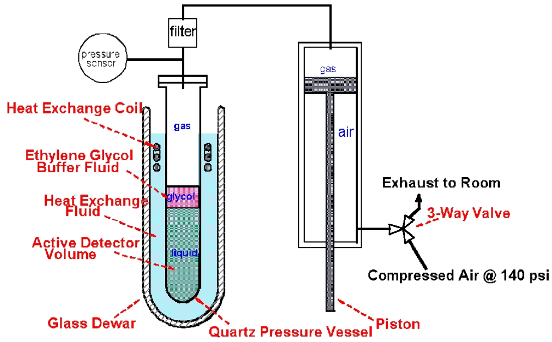

Figure 1. Small Prototype Bubble Chamber.

measurements so far, including those below, have been made with CF_3Br. The chamber has also been operated with liquid xenon, using HFE-7100 heat exchange liquid and cooling with cold nitrogen vapor.

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 (typically 12 ml), the compressed air in the piston is slowly discharged to reduce the internal pressure of the quartz chamber and cause superheating. 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 [6]. This is made possible by a layer of propylene glycol separating the liquid and gas phase of the active material (Fig. 1). The glycol prevents evaporation of the superheated liquid.

Photographs of bubbles are made with two Basler A600 CCD cameras, using a timing signal provided by amplification of the output from a small piezoelectric sensor glued to the bottom of the quartz vessel. The sensor registers an acoustic pulse with ~100 μsec rise time, coincident with the start of bubble growth in the chamber. Bubbles grow at a rate of ~1 mm/msec, depending on the temperature and pressure at which nucleation occurs, and are usually photographed after 2 ms of growth to obtain images of the most useful size. Example images are shown in Fig. 2.

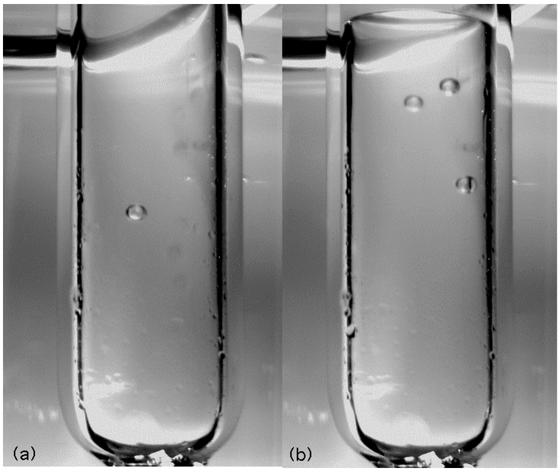

Figure 2. (a) a single bubble produced by exposure to neutrons from an Am-Be source, (b) a triplet of bubbles produced by multiple scattering by an environmental neutron.

3. NEUTRON CALIBRATION

The response of the detector to nuclear recoils from neutron scattering was studied, using an Am-Be (α,n) source. This source produces neutrons with a maximum energy of 11 MeV, yielding nuclear recoils on C, F, 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 [7]. As shown in Fig. 3, we obtained good agreement between calculations and data. The theory 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.

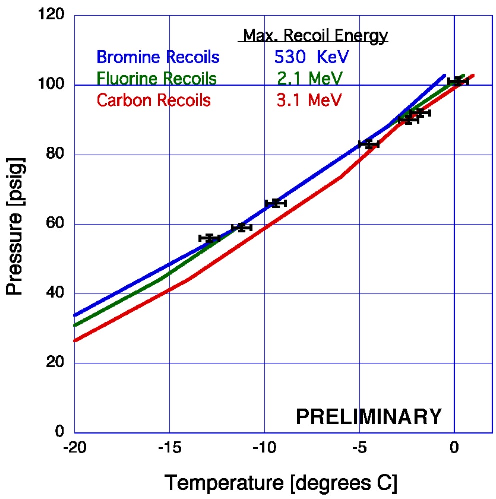

Figure 3. Measurement of bubble nucleation pressure threshold, as a function of temperature, with a Am-Be neutron source. Solid lines show predictions calculated using the Seitz bubble nucleation theory.

4. MEASUREMENT OF NEUTRON BACKGROUND

With no neutron source present, the mean time between events was 14.8 minutes with 18g of CF_3Br at 5 m.w.e. and -10 °C. As illustrated in Fig. 4, 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. 2b) in 1.7 live days (163 events total), together with measurements of fast neutron flux in the laboratory, suggests that the observed events are due to ambient neutrons. Currently, preparations are underway to operate the detector in a ~60 m.w.e. shaft located at the University of Chicago. The additional depth and use of neutron shielding can reduce the neutron flux by a factor >100.

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. This limits the application of this chamber design to situations in which the counting rate is very small.

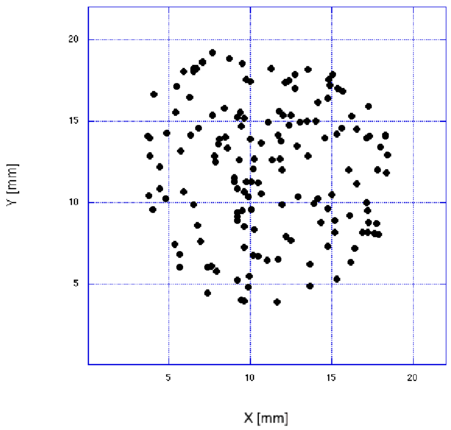

Figure 4. Spatial distribution of background events, projected into the plane perpendicular to the axis of the chamber.

5. CONCLUSIONS AND FUTURE PLANS

We believe that devices of this type are promising for next-generation dark matter search experiments. In principle, they can be scaled to large size at very modest cost, while remaining insensitive to the most vexing sources of background radiation. Many challenges remain, including demonstration of scalability and obtaining low levels of contamination by alpha-emitting isotopes. Currently, we are constructing a 1-liter chamber, which will be operated at a deep underground site with extensive neutron shielding.

REFERENCES

1. B. Hahn, Nuc. Phys. B (Proc. Suppl.) 36 (1994) 459; V. Zacek, Nuovo Cimento 107 (1994) 291; J. I. Collar, Phys. Rev. D 54 (1996) 1247.
2. G. Brautti, M. Ceschia, P. Bassi, Nuovo Cimento Vol. X, 6 (1958) 1148; J.R. Waters, C. Petroff, and W.S. Koski, IEEE Trans. Nuc. Sci. 16(1) (1969) 398.
3. R.E. Apfel, Nucl. Instr. Meth. 162 (1979) 603; J. I. Collar *et al.*, Phys. Rev. Lett. 85 (2000) 3083; N. Boukhira *et al.*, Astroparticle Physics 14 (2000) 227.
4. D.A. Glaser, Phys. Rev. 87 (1952) 665.
5. J. Puibasset, Ph.D. thesis (U. of Paris VI, 2001).
6. M.A. Grolmes and H.K. Fauske, Proc. 5th Intl. Heat Transfer Conf., Tokyo 1974; M.G. Buivid and M.V. Sussman, Nature 275 (1978) 203; P. Reinke, Exp. Heat Transfer 10 (1997) 133.
7. F. Seitz, Phys. Fluids 1 (1958) 2; See C.D. West, ORNL/TM-13683 for a recent review.