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Development of bubble chambers with enhanced stability and sensitivity to low-energy nuclear recoils

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Abstract

The viability of using Bubble Chambers as dark matter particle detectors is considered. Techniques leading to the enhanced chamber stability needed for this new application are described in detail. Prototype trials show that sensitivity to the low-energy nuclear recoils induced by Weakly Interacting Massive Particles (WIMP) is possible in conditions of extreme insensitivity to minimum ionizing backgrounds. An understanding of detector response is demonstrated using existing theoretical models. We briefly comment on the prospects for detection of supersymmetric dark matter with large CF_3I chambers.

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The positive identification of sporadic signals from among comparatively frequent backgrounds is common to any experiment at the forefront of particle physics. The challenge faced by direct searches for cold dark matter particles [1] is in this respect extraordinary: signal rates as small as one low-energy nuclear recoil (few keV) per ton of detector mass per year are predicted for the nuclear scattering of supersymmetric Weakly Interacting Massive Particle (WIMP) candidates, even if they comprise the bulk of dark matter halos able to explain galactic evolution and dynamics [2]. A number of detector techniques have been developed for this purpose over the last two decades [1]. Simplicity of design, optimal target materials, rapid scaling to the ton regime and an excellent background rejection are desirable qualities for the next-generation of detectors that should soon explore the vast range of WIMP masses and couplings still allowed.

The use of moderately superheated liquids has been proposed as a possible fast route towards this goal [3,4]. A concentrated energy deposition from certain particles can lead in these to the rupture of metastability and the formation of visible bubbles. Two experiments, SIMPLE [5] and PICASSO [6] exploit this approach, benefiting from an intrinsic insensitivity to most backgrounds, discussed below. Both experiments implement the method using superheated droplet detectors [7] (SDDs, a.k.a. bubble detectors), where small drops ($r\sim10\,\mu$m) of the active liquid are dispersed in an insoluble gel or viscoelastic medium. In a SDD the gel provides a smooth liquid–liquid interface that impedes the continuous triggering (inhomogeneous nucleations) on surface defects, gaskets, motes, etc. that is traditionally observed even in the cleanest bubble chambers. As a result, the lifetime of the superheated state is considerably extended, to the point that a WIMP search can be performed.

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The goal of the present study is to assess the feasibility of employing bulk quantities of superheated liquid instead, i.e., to use a conventional bubble chamber, an alternative for WIMP searches first put forward by Hahn [8]. Large, stable bubble chambers have been previously proposed for other rare-event searches (e.g., nucleon decay, superheavy elements [9]) but no dedicated attempt to extend the superheated times was made. The rapid uncontrollable foaming of a conventional chamber following its decompression was bypassed in accelerator experiments by a precise timing of the pulsed beam injection to coincide with the few ms of usable radiation-sensitive superheated time in each pressure cycle. Our motivation to explore this apparently more problematic approach arises from the difficulty to manufacture SDDs out of the most interesting available industrial refrigerants, e.g., CF_3I and CF_3Br. These liquids constitute ideal supersymmetric WIMP targets [10] due to the presence of both fluorine (optimal for spin-dependent neutralino couplings [11]) and a heavy nucleus (maximally sensitive to coherent spin-independent couplings) [12,13]. Their density is nevertheless severely mismatched with respect to that of a water-based SDD gel matrix, leading to inhomogeneous, unstable emulsions during the fabrication process. Saturation of the matrix with inorganic salts can help alleviate this issue, but leads to exacting requirements on the alpha-emitter radiopurity of the gel [6], exacerbated by the observed tendency of complex actinide salts to migrate to the droplet-gel boundary [12,14], where their ability to create an undesirable alpha-recoil background is the largest. A first attempt to measure the attainable stability of bulk superheated liquid was made within the context of the SIMPLE experiment, using a rudimentary plastic chamber where a single large drop of active fluid was fully encapsulated by a thick sheath of viscoelastic liquid [15] to avoid evaporation and nucleations on chamber walls. The chamber held 30 g of R-115 (C_2ClF_5) superheated for up to 12 h at an underground depth of 1500 m.w.e. [16], with no other precautions against neutron or radon backgrounds. This behavior revealed the possibility to control the sources of instability in a bubble chamber and prompted the further experimentation described here.

The mechanism leading to the nucleation of the gaseous phase and possible ensuing phase transition in the bulk of a superheated liquid is described by the classical theory of homogeneous nucleation [17], where the probability of *spontaneously* generating a protobubble of radius larger than r_c is computed as a function of pressure, temperature and thermophysical properties of the liquid. If this critical radius is reached or surpassed, the vapor nucleus grows unchecked and metastability is lost. Protobubbles smaller than r_c collapse back onto themselves, producing no phase transition. In the case of a radiation-induced nucleation, the local heating (“hot spike” [18]) from the energy deposition can be responsible for the formation of a critically sized nucleus, but only if this energy is concentrated over a small enough region, comparable to r_c. This last condition leads to the mentioned insensitivity to most backgrounds by imposing a threshold in stopping power, amply surpassed by nuclear recoils but not by minimum-ionizing particles (MIPs) [3,4]. For moderate degrees of superheat like those necessary to sensitize the liquid to low-energy nuclear recoils, r_c is typically few tens of nm, and the rate of homogeneous nucleation is entirely negligible as a source of instability ($\ll 10^{-20}$ bubbles/kg/day [17]).

Nucleations can nevertheless also occur on microcavities, scratches or imperfections naturally present even in the smoothest surfaces (e.g., glass) or in motes, partially or totally wetted by the liquid. The (inhomogeneous) nucleation rate on these cavities is only marginally increased with respect to the extremely small (homogeneous) bulk rate if the fluid has a zero contact angle with the surface, i.e., if the cavity is well wetted [17,19]. The actual source of the inhomogeneous nucleations known to limit a bubble chamber’s stability is instead any entrapped gas in these cavities [20], which can act as a vaporization initiator, allowing mass transfer from the fluid to the unwetted cavity volume [19,21]. Once nucleation is initiated in such a cavity, the superheat required to sustain boiling on it drops to a much lower value than what is required for homogeneous nucleation [19,21], i.e., destabilization occurs. It is however important to distinguish between cavities filled by vapor from the superheated fluid and those filled by noncondensable gas or a binary. In the first case, cooling or pressurization leads to deactivation of the nucleation site by recondensing the trapped vapor. In the second, and in particular for reentrant cavities, deactivation can be arduous, albeit continued boiling leads to an eventual depletion of the entrapped volume [19].

Once the nature of the problem was understood, precautions were taken that led to an enhanced bubble chamber stability: (i) only smooth quartz surfaces are allowed to be wetted by the superheated liquid, thereby reducing the number of available cavities (quartz is also very low in alpha-emitters, leading to a very small surface event rate from this source). (ii) a layer of a low-density buffer liquid is allowed to form a “lid” above the (immiscible) active liquid [22], with all rough metallic parts (bellows, diaphragms, gaskets) coming in contact with the buffer only. (iii) this same buffer liquid is used to create a layer that fills cavities, previously evacuated to remove noncondensable gases (Fig. 1, left) [21]. Cavity filling can be improved by transferring the buffer (a step prior to the addition of the denser active liquid) by slow condensation of its vapor into the chamber rather than pouring. This ensures maximum wetting of even reentrant cavities [19,25] (Fig. 1, right). In the particular case of CF_3I, the shape of the meniscus at the interface with the buffer “lid” reveals a highly preferential wetting of quartz by the (water) buffer, a positive indication of its effectiveness. To some extent, these methods reproduce the advantages of the smooth liquid–liquid interfaces in SDDs. (iv) Exhaustive cleaning of glass surfaces [23] in clean-room conditions and ultrafiltration of all gases and fluids leads to a reduction

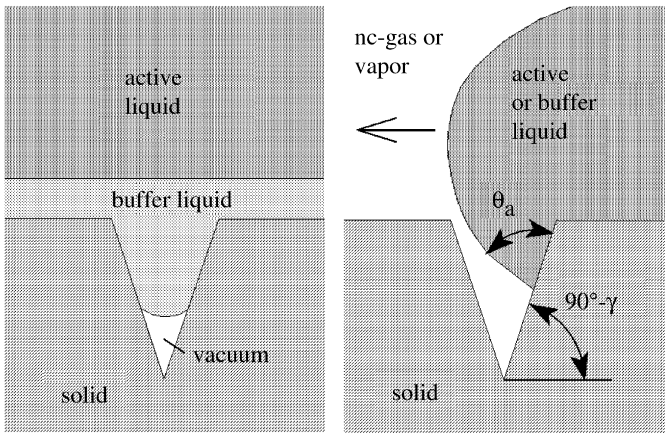

Fig. 1. *Left*: Use of a buffer liquid to isolate microscopic surface cavities able to act as inhomogeneous nucleation centers in a bubble chamber [21]. Mass transfer into the cavity can still lead to boiling, but deactivation is possible in the absence of noncondensable (nc) gas (see text). *Right*: Direct pouring of a liquid during chamber filling can lead to vapor entrapment in cavities when the advancing contact angle θ_a is larger than the groove angle 2γ [19]. Filling by slow vapor condensation after evacuation leads instead to efficient wetting of cavities, including those reentrant.

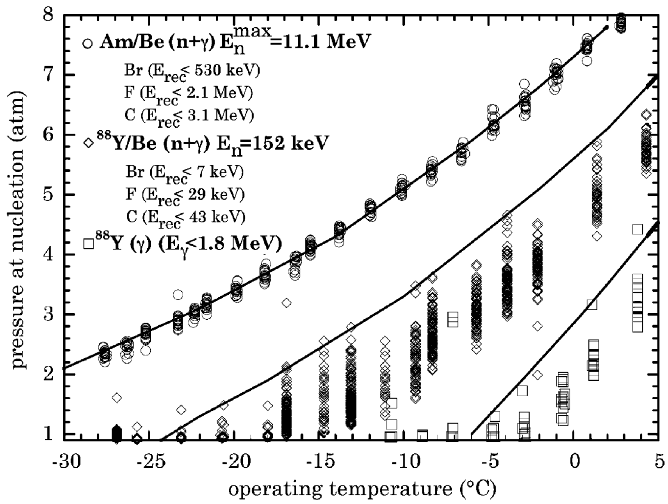

Fig. 2. Response of a CF_3Br chamber to radiation sources and comparison with theoretical predictions. Lines indicate the pressure below which full sensitivity to the source is expected according to the Seitz model [18,28] (the experimental points represent the appearance of the first bubble upon decompression, see text). Insensitivity to gamma interactions in conditions that nevertheless afford good sensitivity to low-energy nuclear recoils has been demonstrated (see text).

in the number of large motes present (cavities smaller than $\sim r_c$ in principle cannot act as nucleation centers). Some known cleaning techniques also have the desirable effect of improving surface wetting by the buffer [24]. (v) After application of these techniques in the chambers and operating conditions described below, a periodic long recompression ($\sim$200 s) is seen to effectively deactivate the few boiling centers that can still sporadically appear due to mass transfer through the buffer layers, or from cavity exposure to vapor during radiation-induced boiling.

Small bubble chamber prototypes up to 50 c.c. in active volume can be built for moderately superheated refrigerants, using commercially available pressure-resistant quartz vials [26]. Pressure cycling is achieved with a three-way valve or its equivalent and temperature control by means of a double-bath [27]. Fast triggering (<10 ms) of data storage and recompression is performed by use of a piezoelectric microphone sensitive to the acoustic emission that accompanies nucleations [12], by monitoring the sudden pressure increase caused by bubble growth, or by real-time analysis of camera images (leading to motion detection). These simple devices have been used to study chamber stability and response to radiation sources.

Calibrations using neutron sources having a well-defined maximum energy (11.1 MeV for ^{241}Am/Be) or monochromatic neutron emission (152 keV for ^{88}Y/Be) have allowed to measure the response of the liquids to nuclear recoils down to 4 keV in the case of CF_3I and to establish agreement with theoretical models of this response. Data points in Fig. 2 represent the appearance of the first bubble upon decompression while in the presence of each source (i.e., as the energy threshold for radiation-induced nucleation is lowered), each point corresponding to a compression/decompression cycle. For sufficiently high source intensities and/or slow decompression rates this bubble is the result of a recoil with an energy close to the well-defined maximum that these sources can produce. These maximum recoil energies are indicated by labels in the figure, for each recoiling species. Solid lines represent the theoretical expectations (Seitz model [18,28]) for the onset of sensitivity to these maximum-energy recoils, i.e., should trace the top boundary of the data points. The data point dispersion towards lower pressures is expected from a progressive onset of sensitivity, which is not perfectly described by a step-function [6] as is naively assumed in the Seitz model. The effect of Moliere electron straggling [29] on stopping power was included in the calculation of ^{88}Y (gamma) response. A review of the theoretical background leading to these predictions can be found in Ref. [12]. A good agreement with the data is observed by best-fitting the single free parameter in this model. The best value obtained ($a\sim4$ in the notation of Ref. [12]) is compatible with previous [28] and most recent [30] studies. Since the predicted onset of response to the source is not exactly the same for each recoiling species (differing by just a fraction of an atm), the lines represent the first species expected to react to the source (Br and F, closely matched, for CF_3Br). A calibration is planned where tagging of gamma rays emitted in 2.8 MeV neutron inelastic scattering will allow to identify the separate contributions from each species.

The photonuclear ^{88}Y/Be source employed emitted a mixed field of $\sim10^8$ high-energy gammas and just 3.5×10^3 monochromatic neutrons per second: Fig. 2 illustrates the much higher degree of superheat (lower pressure at a given temperature) necessary to become sensitive to the gamma component once the Be sheath, the actual neutron emitter, is removed from the source. This allows for a dramatic demonstration of insensitivity to photoelectrons in operating conditions that nevertheless would ensure an optimal response to WIMP interactions. For instance, following Fig. 2, at $-10\,^{\circ}$C and 1 atm no response to gammas is observed nor expected, while sensitivity to WIMP-induced recoils more energetic than the indicated maximum recoil energies produced by ^{88}Y/Be is guaranteed.

Prototypes containing a few tens of c.c. of active liquid remain superheated for periods of several minutes on the average in a shallow-depth laboratory (6 m.w.e.). The reduced ambient neutron flux in this site was characterized using a ^{3}He detector surrounded by several configurations of neutron moderator and absorber (Bonner spheres) calibrated using known neutron sources, and deconvolved following an approach similar to Ref. [31]. Taking the measured fast neutron spectrum as input to a MCNP-POLIMI simulation [32] of the energy depositions in the chamber, the observed spontaneous nucleation rate is found to be in agreement with the expected neutron-induced recoils at this depth (Fig. 3). For superheated times t_{SH} longer than a few seconds, no observable excess of nucleations on walls can be inferred from bubble photography using two orthogonal cameras, which allows for 3-D reconstruction of nucleation sites with ~1 mm precision. For shorter t_{SH} a small excess of wall events, evident in the figure, is observed (sporadic boiling sites can be deactivated as previously described). The duty (live) time was ~65% during these runs. The insensitivity (rejection factor) to MIPs at $-10\,^{\circ}$C and 1 atm is $\gtrsim 10^{9}$ from the absence of any observable reaction to the $\sim 10^{6}$ gamma interactions per second induced within the active volume by the ^{88}Y source (Fig. 3). As discussed above, good sensitivity to WIMP-recoils is nevertheless expected in these same running conditions. This *intrinsic* rejection factor (a lower limit) can be compared with the best ($\sim 10^{4}$)

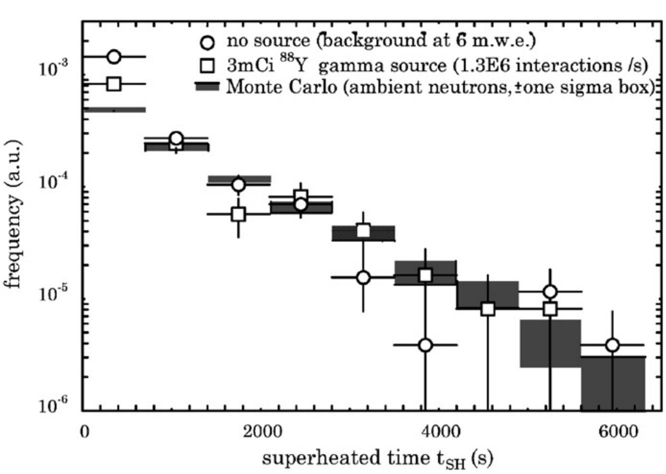

Fig. 3. Distribution of duration of the superheated state t_{SH} in a 12 ml CF_3Br bubble chamber operated at 6 m.w.e., $-10\,^{\circ}$C and atmospheric pressure. When fitted by a form $\propto e^{-t_{SH}/\tau}$ and after rejection of inhomogeneous nucleations during decompression, all cases depicted yield $\tau \sim 1220$ s.

achieved using complex cryogenic WIMP detectors [1]. It should permit construction of much larger chambers in the ton or multiton regime essentially without any concern for MIPs, including beta emissions from elevated concentrations of ^{14}C.

The encouraging outcome from these tests led to the construction of a steel recompression chamber housing 2 kg of CF_3I in an inner quartz vessel [33]. A bellows mechanism prevents any pressure differential across the quartz vessel, the interior of which is sealed against Rn penetration and sees materials relatively low in its emanations. These are measures against alpha-recoil backgrounds [5]. Provisions to ensure the long-term stability of this fire-extinguishing compound at the optimal running temperature of $\sim 40\,^{\circ}$C are in place [34]. The behavior of this chamber at 6 m.w.e. ($<t_{SH}> \sim 60$ s) remained in agreement with the predicted contribution from ambient neutrons. Tests of CF_3I neutron and gamma response yield results similar to those discussed here. To further assess the prospects of this new approach to WIMP detection, this chamber has been operated during part of 2005 and 2006 within a neutron shield at the 300 m.w.e. depth of the NuMI injector gallery on Fermilab grounds (COUPP, the Chicagoland Observatory for Underground Particle Physics). More than 250 kg-day of data have been acquired during these runs, demonstrating the ability to operate large, stable bubble chambers in the unattended fashion required for a WIMP search. Residual radon-induced backgrounds from known sources have been identified as the origin of most nucleations in these conditions and are presently being addressed. However, the existing data already provide an excellent sensitivity to spin-dependent WIMP couplings. The sensitivity that can be achieved in the present site after installation of an efficient muon veto would also be competitive with the best present searches in the spin-independent plane [35]. Details on this chamber's operation, calibration, present sensitivity and prospects will be given elsewhere [35]. Besides those mentioned here, there are unique advantages (neutron rejection ability, multiple target availability, room temperature operation and low cost [33,35]) that distinguish ton-sized bubble chambers from their competitors in this exciting endeavor of WIMP detection. Two prototypes, designed to contain 20 and 60 kg of CF_3I, are under construction.

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References

[1] R.J. Gaitskell, Annu. Rev. Nucl. Part. Sci. 54 (2004) 315.
[2] G. Bertone, et al., Phys. Rep. 405 (2005) 279.
[3] V. Zacek, Nuovo Cimento A 107 (1994) 291.
[4] J.I. Collar, Phys. Rev. D 54 (1996) R1247.

[5] J.I. Collar, et al., Phys. Rev. Lett. 85 (2000) 3083.
[6] N. Boukhira, et al., Astro. Phys. 14 (2000) 227;
N. Boukhira, et al., Nucl. Phys. B (Proc. Suppl.) 143 (2005) 537.
[7] R.E. Apfel, Nucl. Instr. and Meth. 162 (1979) 603.
[8] B. Hahn, Nucl. Phys. B (Proc. Suppl.) 36 (1994) 459.
[9] G. Harigel, et al., Nucl. Instr. and Meth. A 216 (1983) 355;
K. Behringer, et al., Phys. Rev. C 9 (1974) 48.
[10] J.I. Collar, et al., Proc. First Workshop on the Identification of Dark Matter, Sheffield, World Scientific, 1996.
[11] J. Ellis, R.A. Flores, Phys. Lett. B263 (1991) 259.
[12] J.I. Collar, et al., New J. Phys. 2 (2000) 14.1.
[13] F. Mayet, et al., Phys. Lett. B538 (2002) 257;
V.A. Bednyakov, et al., Phys. Rev. D 63 (2001) 095005.
[14] L.K. Pan, et al., Nucl. Instr. and Meth. A 420 (1999) 345.
[15] Aquasonic, Parker Laboratories, Fairfield, NJ.
[16] J. Puibasset, Ph.D. Thesis, Université Paris VI, 2000.
[17] M. Blander, J.L. Katz, AIChE J. 21 (1975) 833.
[18] F. Seitz, Phys. Fluids 1 (1958) 1.
[19] V.P. Carey, Liquid-Vapor Phase-Change Phenomena, Hemisphere, Washington, DC, 1992.
[20] M.G. Buivid, M.V. Sussman, Nature 275 (1978) 203.
[21] P. Reinke, Exp. Heat Transfer 10 (1997) 133;
P. Reinke, Ph.D. Thesis, Swiss Federal Institute of Technology, 1996.
[22] B. Hahn, H.W. Reist, Helv. Phys. Acta 45 (1972) 949;
M.A. Grolmes, H.K. Fauske, in Proceedings of the Fifth International Heat Transfer Conference, Tokyo, 1974.
[23] J. Bardina, in: K.L. Mittal (Ed.), Particles on Surfaces, Plenum Press, NY, 1988, and references therein
[24] M.D. Lelah, et al., Ceram. Bull. 58 (1979) 1121.
[25] D. Quéré, private communication.
[26] Griffin-Worden vessel, Kontes Glass Co., Vineland NJ.
[27] L. Bond, et al., Nucl. Phys. B (Proc. Suppl.) 138 (2005) 68.
[28] M. Harper, Ph.D. Thesis (U. of Maryland, 1991), Nucl. Sci. Eng. 114 (1993) 118, Nucl. Instr. and Meth. A 336 (1993) 220;
Ch. Peyrou in: R.P. Shutt (Ed.), Bubble and Spark Chambers, Academic Press, NY, 1967;
S.C. Roy, et al., Nucl. Instrum. and Meth. A 255 (1987) 199.
[29] H. Niedrig, J. Appl. Phys. 53 (1982) R15.
[30] M. Das, et al., Nucl. Instr. and Meth. A 531 (2004) 577.
[31] P. Belli, et al., Nuovo Cimento A101 (1989) 959.
[32] S.A. Pozzi, et al., Nucl. Instr. and Meth. A 513 (2003) 550.
[33] J. Bolte et al., Proceedings of the Fifth Workshop on the Identification of Dark Matter, Edinburgh, World Scientific, 2004.
[34] M.K. Donnelly, et al., NIST Technical Note 1452.
[35] COUPP collaboration, in preparation. http://www-coupp.fnal.gov/.