Xenon bubble chambers for direct dark matter detection

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Abstract: The search for dark matter is one of today’s most exciting fields. As bigger detectors are being built to increase their sensitivity, background reduction is an ever more challenging issue. To this end, a new type of dark matter detector is proposed, a xenon bubble chamber, which would combine the strengths of liquid xenon TPCs, namely event by event energy resolution, with those of a bubble chamber, namely insensitivity to electronic recoils. In addition, it would be the first time ever that a dark matter detector is active on all three detection channels, ionization and scintillation characteristic of xenon detectors, and heat through bubble formation in superheated fluids. Preliminary simulations show that, depending on threshold, a discrimination of 99.99% to 99.9999% can be achieved, which is on par or better than many current experiments. A prototype is being built at the University at Albany, SUNY. The prototype is currently undergoing seals, thermal, and compression testing.

Keywords: dE/dx detectors; Hybrid detectors; Dark Matter detectors (WIMPs, axions, etc.); Time projection chambers

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1 The search for dark matter

According to the ΛCDM model of cosmology, dark matter is thought to make up at least a quarter of the universe, while the 75% remaining is made of dark energy (71%) and baryonic matter (4%) [1]. One of the most popular candidates for a dark matter particle is the WIMP, Weakly Interacting Massive Particle, which should have a very low, yet detectable, cross section with normal matter. Many experiments have thus been devised in order to discover this elusive particle.

While direct detection experiments use different techniques, they all rely on observing, in one way or another, the direct scatter of a WIMP with a target nucleus, thus inducing a recoil of the nucleus. While gammas and electrons interact with the electron cloud of the atom, a process referred to as an electronic recoil (ER), WIMPs and neutrons give nuclear recoils (NR) by either interacting coherently with all nucleons in the nucleus (spin-independent interaction) or via spin coupling to the spin of the nucleus (spin-dependent interaction) [2].

Because the interaction cross-section between a WIMP and a target nucleus is smaller than $4 \times 10^{-46}$ cm$^2$ for example for a 33 GeV/$c^2$ mass WIMP [3], such experiments can only be successful if they have no other background, which means that nothing else but a WIMP can interact in the detector and produce a distinguishable signal. Background control is thus the number one priority of direct dark matter experiments. To avoid background, the detectors are usually located deep underground, either in a mine or under a mountain, where they will be shielded from cosmic rays and muon-induced neutrons. In addition, to limit the background, these detectors are made of highly radiopure materials [5, 6]. However, eliminating backgrounds entirely is nearly impossible and so being able to discriminate between nuclear and electronic recoils is of crucial importance, particularly since the backgrounds consist almost entirely of electronic recoils from gammas and betas.

Amongst the plethora of experiments available, xenon TPCs (Time Projection Chambers) and bubble chambers are maybe the most different detector types. A typical two phase xenon detector...
can measure the deposited energy of the recoil but has a discrimination of about 99.6-8\% , which leads to a $4 - 2 \times 10^{-3}$ misidentification probability \[4, 5, 7\]. A bubble chamber on the other hand has nearly 0\% chance of misidentification (of the order of $10^{-10}$) but has no direct means of measuring the event-by-event energy deposited in the recoil \[8\], although the global energy can be statistically inferred via threshold setting and temperature and pressure sweeping.

Until now, these techniques have been used separately in different experiments, but we are now proposing to combine the strengths of these technologies into one, to build a xenon bubble chamber.

## 2 Bubble chambers

The bubble chamber concept was first invented by D.A. Glaser over 50 years ago \[9\]. It consists of a vessel filled with gas that is compressed to the liquid phase. By having a smooth and clean vessel, and thus preventing nucleation sites, the pressure can then be slowly lowered adiabatically below the vapor pressure without triggering a phase transition. The fluid is still in liquid state, while being at a pressure where it should be gaseous. The fluid is thus superheated. Consequently, bubble chambers only work for certain sets of temperature and pressure depending on the target material. In addition, to avoid nucleation sites in the rough plumbing above the vessel, which would then ruin the stability of the superheated liquid in the vessel, a layer of buffer fluid sits on top of the liquid. It is this buffer fluid that is compressed, and that in turn compresses the liquid \[8\].

As an incident particle interacts with the fluid, it can deposit enough energy, in the form of heat, to warm up the liquid and trigger a phase transition from liquid to gas, therefore creating a bubble. Once a bubble is formed, pressure is quickly applied in order to crush the bubble by reverting the gas back to its liquid state. The process can then be repeated, the fluid put back into a superheated state in order for a bubble to reform should a particle interact in the detector.

The bubbles that are formed in these recoils can be measured by acoustic sensors, by photographing the bubble or by recording the pressure rise using pressure transducers \[8, 10\].

Bubble chambers therefore use only one energy deposition channel, heat, in order to try and detect dark matter. They are threshold detectors, either a bubble forms or it doesn’t. To form a bubble, they require a threshold energy, a highly localized energy deposition $E_C$ within a critical radius $R_C$. If this critical energy is not deposited within the associated critical radius, a bubble will not form.

In addition, different particles have different stopping powers. While minimum ionizing particles could in principle be high energy enough to form a bubble, they deposit their energy over long tracks rather than locally, actually preventing the bubble formation. A bubble chamber is thus blind to particles with low stopping power, as they have for example only 1 in $10^{10}$ or greater chance of depositing enough energy in a small enough radius to trigger a phase transition.

This stopping power dependence on particle type is especially important for gammas, and bubble chambers can be tuned to be insensitive to electronic recoils, a considerable advantage for low background searches like dark matter. A bubble chamber can thus be made sensitive only to nuclear recoils, which have a high stopping power.

Bubble chambers have thus far been very successful in the spin-dependent proton sector where they hold the current best sensitivity \[8\].
3 Scintillation detectors

Scintillation detectors are one of today’s technologies of choice in the search for dark matter. The world leading experiments with the best sensitivity to traditional WIMP masses between 7 and 1000 GeV/c² are both using liquid xenon as scintillator [4, 5] while other competitive experiments using cryogenic crystals also collect scintillation light [11].

The most successful scintillator experiments are dual phase Time Projection Chambers (TPCs). In this type of TPC, a particle interacts in the liquid target material producing a primary scintillation signal (S1) that is detected by two PMT arrays at the bottom and the top of the TPC. At the same time as the scintillation, an ionization signal is produced. The electrons from the ionization are drifted up to the gas phase where they interact with the gas and emit a secondary scintillation signal (S2) also detected by both PMT arrays. This type of liquid xenon detector therefore uses two detection channels, scintillation and ionization, in order to try and detect dark matter. While the combination of the light pattern on the PMT arrays and the drift time of the electrons allows to reconstruct the position of each event in 3D, the recording of both signals provide information about the recoil energy, allowing for event by event energy reconstruction, since the amount of light scales with the recoil energy. Recording both signals also allows for electronic recoil discrimination via the ratio of S2 to S1 [4, 5].

4 New concept: scintillating bubble chamber

The novel idea is to combine the strengths of both bubble chamber and scintillator into a new, more advanced dark matter detector which will have both the energy reconstruction of a scintillator and the electronic recoil rejection of a bubble chamber, as well as use all three detection channels, scintillation, ionization and heat.

4.1 Choice of liquid

For applications in scintillating bubble chambers, only liquid scintillators can be used. Among these, organic scintillators as well as liquid noble gases like xenon or argon can be used.

A bubble chamber with a fluorinated organic scintillator would be advantageous for searching for spin dependent WIMP-proton interactions [8], and would serve as a powerful complement to the spin independent searches, particularly if a discovery is made. However, the advantage of liquid nobles over organic scintillators is that they can definitely be used to measure charge, allowing measurement of heat, scintillation and charge simultaneously.

Amongst liquid nobles, there are several target materials to choose from. Using argon in a bubble chamber for example would have the advantage of using pulse shape discrimination at higher energies, but many photons are needed for this, and so this feature could not be used at the lowest energies where the WIMP signal should be the largest. However, using the discrimination of bubble chambers would allow one to still achieve very low thresholds, which cannot be achieved in current argon detectors [12].

However, xenon is perhaps the best choice, as using it in a bubble chamber would allow an improvement in the electronic recoil discrimination, eliminating the $^{85}Kr$ and neutrino electron
scattering backgrounds, two of the most challenging expected backgrounds with which to deal for the next generation of xenon experiments [13].

Moreover, as shown in figure 1, unlike all other current dark matter experiments which only use one or two detection channels, a xenon bubble chamber would be the first ever detector to attempt to use all three detection channels, by recording heat as a bubble chamber, scintillation as a liquid scintillator, and ionization by applying an electric field to the vessel and drifting the charge through the bubble, like is done in a TPC.

4.2 1956 Xenon bubble chamber

In 1956, Brown, Glaser and Perl attempted to use a xenon bubble chamber [14] to detect high energy gamma rays. At first the experiment was a failure and no bubbles were observed, presumably due to the energy being lost in scintillation rather than in heat. To resolve this issue, the xenon was doped with ethylene to quench the scintillation signal. Bubbles from high energy gammas were then copiously observed as shown in figure 2.

The logical consequence of these results is that, by not adding the quenching material, and using a pure xenon target, a xenon bubble chamber would indeed be blind to gamma rays while still generating scintillation signal, which is exactly the desired goal for WIMP detection. Moreover, because nuclear recoils already lose energy to heat, nuclear recoils should make bubbles and a smaller-than-for-ER scintillation signal at the same time, thus providing an effective means of discrimination. Thus, this earlier measurement is one of the strongest motivations for this new WIMP detector, providing strong evidence that it should be successful.
4.3 Advantages

If both heat and scintillation can be observed in a xenon bubble chamber, the scintillation signal can be used for event by event energy reconstruction just like in TPCs, while the heat signal can be used for electronic recoil discrimination, just like in bubble chambers.

Already, a two channel xenon bubble chamber would combine the strengths of bubble chambers and liquid xenon TPCs, and thus outperform them in theory. If a third detection channel, an S2 signal coming from ionization, could be added to the scintillation and heat, a xenon bubble chamber would be able to go lower in threshold while maintaining its energy reconstruction capacity and blindness to ER, a feat that no other dark matter experiment has thus far achieved. To obtain an S2 signal, electrons would have to be drifted through the bubble itself. This has already been attempted by [15] in non-superheated, stable bubbles with promising first results [16].

In addition, a xenon bubble chamber has one more very important advantage. Xenon detectors perform generally less adequately at low energies due to reduced S1 and S2 signals from nuclear recoils as shown in figure 3 for example. This reduction comes from the efficiency of nuclear recoils to generate more nuclear recoils. As a particle interacts in the liquid, the recoiling nucleus will interact with other nuclei which will in turn also recoil, instead of exciting or ionizing atoms. Thus most of the energy will be going to heat rather than to scintillation and is then lost for typical xenon TPCs.

\[\text{Figure 3. Absolute light yield of liquid xenon (solid blue line) for NR with statistical error band using NEST which is a global fit to the world’s data in all channels [18, 21, 22].}\]

However, in a xenon bubble chamber, this energy would just go from one channel to another; scintillation and ionization would be reduced but the loss of energy would be caught via the heat channel. This means that xenon bubble chambers should not suffer any efficiency loss at low energies and could probe a low energy WIMP mass sector that is unavailable to current experiments.

This also means that with a xenon bubble chamber, all the energy would be accounted for and summing all three energy channels, light yield from S1, charge yield from S2 and the bubble formation probability from heat, would give total quanta independent of energy or electric field. This would be an unprecedented calibration opportunity to inform mainstream liquid xenon dark matter experiments.
4.4 Prototype at University at Albany SUNY

A prototype of a xenon bubble chamber is being developed at UAlbany. Unlike xenon TPCs which operate at -100 °C and typical bubble chambers which operate at close to room temperatures and higher, this prototype will be operated at -40 °C, a temperature at which xenon can be superheated as shown in figure 4 left.

![Phase Diagram of Xenon](image)

**Figure 4.** Left: phase diagram of xenon [Credit: NASA]. Right: improvement of the energy resolution based on density for 662 keV gamma rays in liquid and gas xenon in the charge channel alone [17].

One possible impact of researching the response of liquid xenon detectors at −40°C for xenon bubble chambers is that the energy resolution and therefore S2/S1 discrimination can be very different at this temperature than at −100°C as in typical TPCs. Figure 4 (right) shows how the energy resolution improves at higher temperature for 662 keV gammas.

If this improvement in energy resolution for ER with increasing temperature were to also apply at low energies, and for NR as well, the S2/S1 bands for both NR and ER bands [4, 5] would tighten and the discrimination would consequently improve.

Moreover, if energy resolution and electronic recoil discrimination are found to improve at this higher temperature, current dark matter experiments would profit from this knowledge while future larger dark matter experiments could be tuned, even slightly depending on design constraints, to try and capitalize on this effect and improve their energy resolution, and thus have a better chance of conclusively discovering dark matter.

In addition, xenon bubble chambers can help current bubble chamber experiments such as PICO [8], which have an unknown background possibly due to alphas straggling out of particulates, chemistry effects or micro-droplets of buffer fluid. Adding a scintillation signal to these experiments may help in identifying these backgrounds and by doing so, achieve better results in the spin dependent sector. Indeed, a xenon bubble chamber, having the energy information that typical bubble chambers lack, will be able to identify alphas, whose energy on the order of MeV is orders of magnitude larger than that of dark matter recoils, by the S1 and S2 size and by pulse shape discrimination [24].

To investigate these topics, and to prove the principle of a scintillating xenon bubble chamber, a prototype chamber is being developed at UAlbany. This chamber will hold between 10 and ~ 200 g of xenon, and will record bubble formation and scintillation simultaneously.
The UAlbany chamber itself, shown in figure 5, consists of a small quartz vessel filled with liquid xenon with a buffer fluid resting on top to allow for pressurization. The buffer fluid used is silicone oil and is also the hydraulic and thermal bath fluid of choice. By having a thick (3.25 mm) quartz tube capable of withstanding high pressures and the same fluid as hydraulic, thermal and buffer, there is no need for an external pressure vessel and bellows for pressure equalization. The chamber will be operated at −40°C anywhere below 300 psia at maximum compression. The decompression pressure will actually be varied to study different energy thresholds, for example as low as 0.5 keV at −40°C [25]. The quartz vessel is coated with TPB [23], a transparent wavelength shifter, in order to shift the light from VUV to visible wavelengths. The bubble itself and potentially, the scintillation light itself, will be recorded for the first time ever via a CCD camera. Recording both bubble and scintillation light with the same device will thus make the chamber setup more efficient. In addition, a typical PMT with high QE in blue/violet will be used to record the scintillation light if the CCD fails to record it. In order to reflect scintillation light into the PMT or CCD, the chiller containing the thermal bath will be coated in aluminized mylar.

Figure 5. The UAlbany bubble chamber. Left: GEANT4 simulation. Right: current prototype for pressure/thermal cycling and seal tests with N2 gas. The decompression valve, linked to a gas recuperation system, will be used when tests with LXe will start.

This prototype should address two questions. First, it will allow for a study of what the gamma discrimination is as a function of recoil threshold. This has already been studied in simulations using the Seitz model [25], NEST [18], GEANT4 [19] and PENELLOPE [20]. Figure 6 shows the fraction of bubble formation as a function of critical energy $E_C$ for electronic recoils due to 1 MeV, 100, 50, 10, 5, 2, and 1 keV electrons and gammas in liquid xenon. The steps correspond to the electronic shells of xenon. The plateau at higher energies is due to the resolution limit of the simulation software. This shows that xenon bubble chambers could in principle reach 99.9999% or better discrimination, so up to a factor 4000 better than standard liquid xenon detectors, depending on threshold.

The second question to answer will be whether or not the usage of a buffer fluid will quench the scintillation. Liquid noble detectors are notoriously ultrapure systems to prevent the scintillation light from being absorbed by the impurities in the target material before reaching the PMTs. The buffer fluid thus needs to be completely immiscible and separate perfectly from the liquid xenon,
as even the smallest amount of contamination may jeopardize the light collection. New techniques might need to be devised in order to prevent this from happening.

For now, the UAlbany chamber is undergoing pressure and thermal cycling tests as well as sealing tests. In the meantime, a collaborating group at Rensselaer Polytechnic Institute is investigating new electric field designs to apply to the UAlbany chamber in order to drift electrons through a bubble and acquire an ionization signal in addition to the scintillation and heat signals. A second decompression line will eventually be added in order to decompress below 1 atm in order to reach low thresholds.

5 Conclusion

A new type of dark matter detector is proposed, a scintillating xenon bubble chamber which would have the potential for high discrimination against electronic recoils at low thresholds like a typical bubble chamber while also recording all the energy information like a typical xenon TPC. Preliminary simulations give a conservative estimate on the predicted discrimination from xenon bubble chambers of 99.99% to 99.9999+%. In addition, scintillating xenon bubble chambers may be the first detectors to ever use all three discovery channels, heat, scintillation and ionization, making it the most versatile and powerful dark matter detector. In theory, provided a change in temperature and pressure, such a detector could potentially be expanded beyond the initial use with xenon, and several scintillating bubble chambers with different target materials could be used to help diagnose problems and improve other types of dark matter experiments, as well as confirm the expected $A^2$ dependence of any potential WIMP signal. A first prototype at University at Albany SUNY is currently under construction.
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