COUPP*-500

A Proposal for a Ton Scale Bubble Chamber for Dark Matter Detection

7 October 2010

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We propose to build a ton-scale bubble chamber to search for dark matter. This would be the next in the series of COUPP bubble chambers that have been searching with ever increasing sensitivity over the last five years. This device would be built and commissioned at Fermilab before being deployed deep underground at SNOLAB.

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Executive Summary

The nature of non-baryonic dark matter is one of the most intriguing questions for particle physics at the start of the 21st century. There is ample evidence for its existence, but almost nothing is known of its properties. WIMPs are a very appealing candidate particle and several experimental campaigns are underway around the world to search for these particles via the nuclear recoils that they should induce.

The COUPP series of bubble chambers has played a significant role in the WIMP search. Through a sequence of detectors of increasing size, a number of R&D issues have arisen and been solved, and the technology has now been advanced to the point where the construction of large chambers requires a modest research effort, some development, but mostly just engineering. It is within this context that we propose to build the next COUPP detector – COUPP-500, a ton scale device to be built over the next three years at Fermilab and then deployed deep underground at SNOLAB.

The primary advantages of the COUPP approach over other technologies are

1. The ability to reject electron and gamma backgrounds by arranging the chamber thermodynamics such that these particles do not even trigger the detector.
2. The ability to suppress neutron backgrounds by having the radioactively impure detection elements far from the active volume and by using the self-shielding of a large device and the high granularity to identify multiple bubbles.
3. The ability to build large chambers cheaply and with a choice of target fluids
4. The ability to increase the size of the chambers without changing the size or complexity of the data acquisition.
5. Sensitivity to spin-dependent and spin-independent WIMP couplings

These key advantages should enable the goal of one background event in a ton-year of exposure to be achieved. The conceptual design of COUPP-500 is scaled from the preceding devices. In many cases all that is needed is a simple scaling up of components previously used.

Calibration and R&D are still needed on some aspects of the system. We know we have the ability to distinguish alpha-induced events from nuclear recoils, but we do not yet know whether the combination of material purity and rejection are good enough to run for a year with no alpha background. We also need to have more detailed measurements of the detector threshold and a better understanding of its high gamma rejection. In addition, there are important checks to make on the longevity of the detector components in the hydraulic fluid and on the chemistry of the active fluid.

The 2009 PASAG report explicitly supported the construction of the COUPP-500 device in *all* funding scenarios. The NSF has shown similar enthusiasm. It awarded one of its DUSEL S4 grants to assist in the engineering needed to build COUPP-500. The currently estimated cost of COUPP-500 is $8M, about half the $15M-$20M price tag expected by the PASAG report for a next generation dark matter search experiment.

The COUPP-500 device will have a spin independent WIMP-nucleus cross-section sensitivity of 6×10^{-47} cm^2 after a background-free year of running. This device should then provide the benchmark against which all other WIMP searches are measured.

1 Introduction

The evidence continues to mount that the majority of the matter in the universe is cold, dark, and non-baryonic. A consistent and widely held working hypothesis is that this majority component of matter is the big bang relic density of an as yet undiscovered weakly interacting massive particle or *WIMP*. Although the nature of the *WIMP* and of the *WIMP*-nucleus interaction is unknown, the phenomenology is straightforward and well understood and predicts *WIMP* dark matter should reveal itself to us directly as an excess of nuclear recoil events over those that can be explained by backgrounds from conventional radioactivity.

The essence of direct detection dark matter experiments is the ability to discriminate true nuclear recoil events from the much more frequent electron recoil events, and there is stiff competition among several technologies to push the frontier of direct detection sensitivity. The extraordinary power of the COUPP bubble chamber technology is a discrimination of $\sim 10^{10}$ between electron and nuclear recoil events. Recently it has also been demonstrated that events induced by α decays have a different acoustic signature than those produced by nuclear recoils. With robust α-discrimination, methods exist to reject *all* backgrounds in COUPP.

COUPP is a campaign of detectors, rather than a single experiment. With each successive device the target mass has increased and R&D issues have arisen and been resolved. With the progress made in the series of devices from 2 to 4 to 60kg, the design of a 500kg chamber is largely an engineering task with only a few calibration and R&D questions remaining.

The COUPP-500 chamber meets the definition of a next generation (G2) device laid out in the PASAG report[1], as it will have a cross-section sensitivity exceeding 10^{-46} cm^2. However, it is expected to have a price that is half the $15M-$20M that is expected for other G2 experiments (see Section 8.1 for details). The PASAG report explicitly supported the construction of the COUPP-500 device in *all* funding scenarios. The NSF has shown similar enthusiasm, awarding one of its DUSEL S4 grants to assist in the engineering needed to build COUPP-500.

[1] http://www.er.doe.gov/hep/files/pdfs/PASAG_Report.pdf

2 The Technique

2.1 The Physics of Bubble Chambers for Dark Matter Detection

This proposal centers on a detector technology that we believe to be the most promising candidate for a dark matter detector at the ton scale: a *continuously (albeit weakly) superheated* bubble chamber.

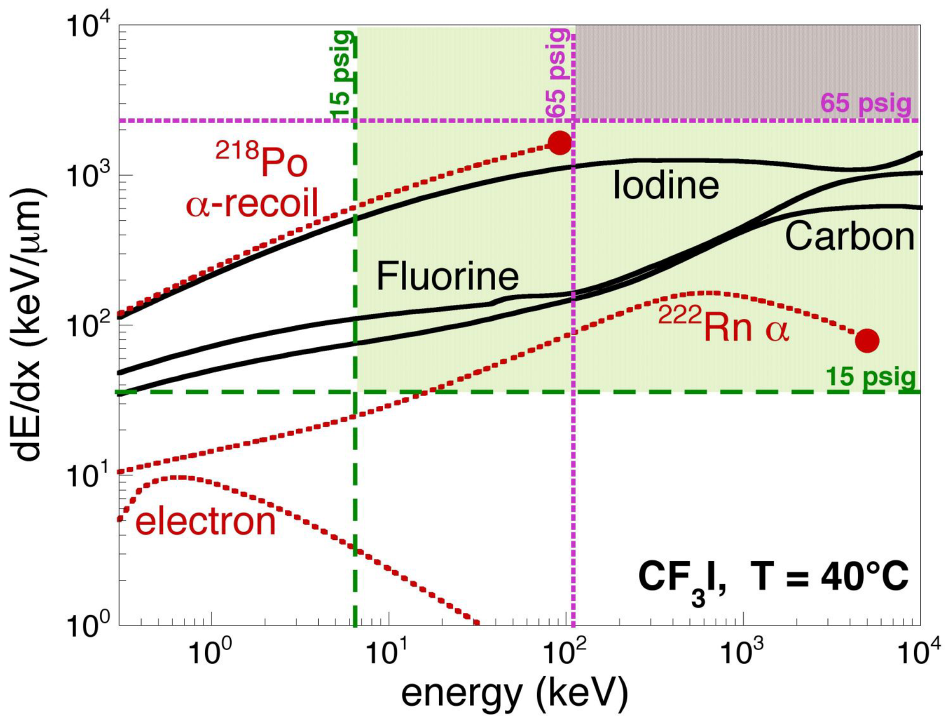

Figure 2-1: Chart illustrating the dependence of bubble nucleation on both of the total deposited energy and dE/dx. The purple (green) shaded regions in the upper right quadrant of the plot indicate the region of efficient bubble nucleation for 65 psig (15 psig). The bubble nucleation physics creates thresholds in both dE/dx and in total energy deposited, The curves on the figure show the relations hip between energy and dE/dx for a variety of particles. The red curves describe backgrounds from electrons, from the alpha particle from ^{222}Rn decay, and from the recoiling 218Po daughter nucleus following ^{222}Rn decay. The black curves describe the signal processes of Iodine, Fluorine, or Carbon nuclear recoil. The insensitivity to electron and gamma backgrounds and the sensitivity to alpha decay backgrounds is apparent.

COUPP bubble chambers have the major virtue of being insensitive to minimum ionizing particles. The threshold for bubble nucleation in a superheated liquid is a strong function of temperature and pressure. A judicious choice of operating parameters results in a bubble chamber that is sensitive to nuclear recoils but blind to minimum ionizing particles such as γ and β interactions. This is shown graphically in Figure 2-1. We have demonstrated that a CF_3I bubble chamber can be operated with a gamma rejection factor of ~10^{10} at a nuclear recoil threshold of 10 keV.[2] This gamma rejection is several orders of magnitude beyond what has been demonstrated by CDMS and the Xenon experiments. With the chamber operated in this weakly superheated mode, a nuclear recoil event will produce a single bubble, as shown on the left hand side of Figure 2-2.

The second major virtue of bubble chamber technology is its mechanical simplicity, which lends itself to clean construction and scalability to larger devices. The detector consists only of a quartz bell jar, a stainless steel diaphragm/bellows, seals, and highly purified fluids. All of these materials are amenable to purification or cleaning, and we are confident that we will be able to attain the degree of radio-purity necessary to advance dark matter limits. Furthermore, as the size of the chamber increases we suffer no signal loss, and the number of DAQ channels remains essentially constant as the event information comes from video images and acoustics traces. We have successfully operated CF_3I bubble chambers in continuously sensitive mode for nine months, and we see no technical obstacles to building considerably larger and cleaner devices.

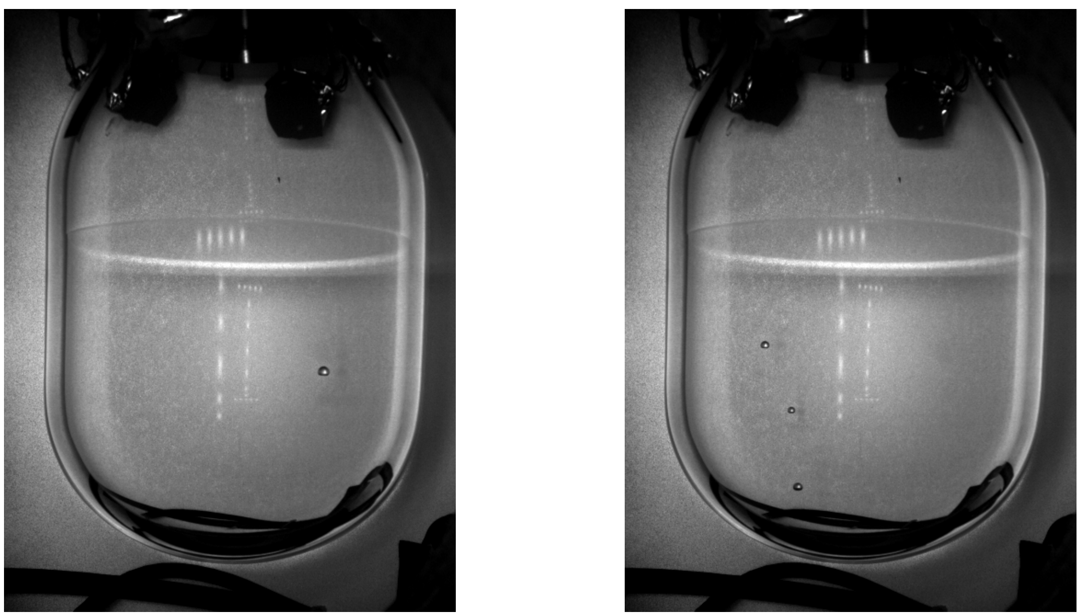

Figure 2-2: On the left is a single-bubble event in the 4kg chamber. On the right is a three-bubble event caused by a neutron.

A third important consideration is the ability of the bubble chamber to easily identify neutron background by a multiple scattering analysis. Because the mean-free-paths are typically of order 15 cm for the most troublesome background neutrons in most candidate fluids, neutron induced events will frequently appear as multiple bubbles. Inexpensive

[2] E. Behnke et al., *Science* Vol. 319. no. 5865, pp. 933 – 936 (www.sciencemag.org/cgi/content/full/319/5865/933/DC1)

cameras can easily resolve bubbles at the millimeter level and so effective segmentation is attainable as seen on the right of Figure 2-2. For large bubble chambers, neutron induced events will occur preferentially near the vessel walls and significant self-shielding is possible.

A fourth crucial consideration favoring the bubble chamber is the ease with which we can explore a variety of different target nuclei. Our initial target fluid of choice is trifluoroiodomethane (CF_3I) that has a density of 2.1 g/cc. Because of its modest boiling point, it is possible to operate a CF_3I bubble chamber very near atmospheric pressure and room temperature. In addition, CF_3I provides excellent sensitivity to spin-independent couplings because of the large A^2 enhancement for scattering on iodine. It also provides excellent sensitivity to spin-dependent couplings through fluorine, which has ~100% isotopic abundance of spin ½ ^{19}F and a favorable nuclear form factor[3]. It will be straightforward to increase confidence in the WIMP interpretation of putative signal by operating the chamber with CF_3Br, C_4F_{10}, or a variety of other possible target fluids.

The weakness of the bubble chamber technique arises from the lack of event-by-event energy information. For nuclear recoil events, the bubble chamber behaves like a calorimeter with a discriminator, where the discriminator threshold is determined by the operating temperature and pressure. The weakness is addressed by scanning the threshold by slowing ramping the chamber pressure. Effectively this recovers energy spectrum information at the expense of livetime. Note that this loss of livetime from scanning is only relevant once dark matter has been discovered. Prior to that the typical mode of operation of a chamber is to have it searching for events above expected background by integrating all interactions above a low threshold.

A second effect of the threshold nature of the detection is to make the bubble chamber method prone to backgrounds from alpha decays. Other technologies can eliminate alpha induced events by making a simple energy cut. We have recently shown, however, that the acoustic 'plink'[4] emitted when a bubble is formed is louder from alpha decays than for nuclear recoils[5]. It is suspected that this effect stems from having multiple proto-bubbles created along a relatively long alpha track, but only one initiated by a nuclear recoil. The level at which alphas can be rejected by this technique is currently being explored by our 4kg chamber running at the SNOLAB deep underground site. It is important to note that methods exist to reject all known sources of backgrounds in a COUPP bubble chamber.

2.2 The Basics of a COUPP Chamber

Figure 2-3 illustrates the general features of the design for a generic COUPP bubble chamber. The superheated liquid is contained in a quartz bell jar, with a layer of water floating on top. The water isolates the superheated liquid from contact with a metal pressure-transmitting diaphragm or bellows. The diaphragm/bellows equalizes the

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[3] G.Bertone et al., Phys.Rev.Lett.99:151301,2007
[4] Donald A. Glaser and David C. Rahm, Phys. Rev. 97, 474–479 (1955)
[5] E.Behnke et al., arXiv:1008.3518, accepted by Phys. Rev. Lett.

pressure inside the quartz with the pressure of a surrounding hydraulic fluid that might be propylene glycol, water, or mineral oil. The pressure difference across the quartz wall is maintained near zero, and the stress in the quartz is therefore very low. The hydraulic fluid and inner vessel are inside a conventional stainless steel pressure vessel. The active volume of the detector may be viewed by video cameras through small glass viewports.

We have already explored several variations of the design. The essential design feature enabling the near-continuous sensitivity of all of these devices is the use of a water blanket to isolate the pressure control mechanism from the active, superheated liquid. The water isolates the superheated liquid from the bubble nucleation sites that are present on rough metal surfaces. The water also serves, together with the external hydraulic fluid, as a neutron shield and heat-exchange medium.

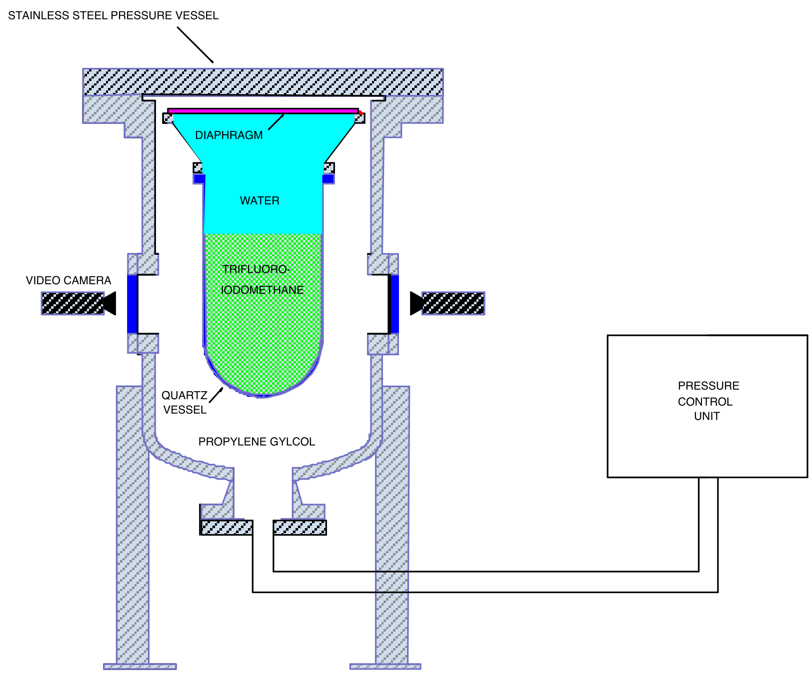

Figure 2-3: Cartoon of a generic bubble chamber showing the inner quartz vessel, the pressure balancing diaphragm (could also be a bellows), the outer pressure vessel, and the external cameras and hydraulic control unit.

The "Pressure Control Unit" shown in the drawing is responsible for cycling the pressure of the inner and outer vessel. The chamber is ultimately controlled by compressed air via solenoid valves. The compressed air drives a pneumatic cylinder that actuates a hydraulic cylinder that in turn transmits the pressure to the compression fluid. The fluid in the inner vessel is maintained in equilibrium with the hydraulic fluid through a flexible diaphragm or bellows. Starting with a compressed chamber, we initiate an expansion cycle by releasing the compressed air and allowing the pressure to bleed down to the set point. With the pressure relieved, the active fluid expands to its sensitive superheated state to await a bubble. We sense the appearance of a bubble via a pressure pulse, an acoustic signal, or an analysis of the streaming video images. When a bubble is detected, the solenoid valve is actuated and the chamber is rapidly re-pressurized. Typically the chamber remains pressurized for 30 seconds to ensure all the fluid is re-condensed before the chamber is expanded and live again.

3 Historical Development

This chapter presents an abridged history of the COUPP campaign of bubble chambers, focusing on what issues were uncovered and how they were subsequently handled. The proposed COUPP-500 device is the next step in this campaign.

Our first clear technical demonstration of the stable bubble chamber technology was accomplished with a 12-ml "test-tube" chamber filled with CF_3Br. With this device, operated during 2002-2003 at the University of Chicago, we were able to demonstrate sensitivity to neutron-induced nuclear recoils and threshold behavior that were both consistent with theoretical expectations and promising for dark matter searches[6]. We were also able to demonstrate excellent immunity to electron recoils. This laid the platform for the next stage – a 2kg chamber.

3.1 COUPP-2 (T945)

The 2kg COUPP-2 chamber was designed, built, and commissioned at the University of Chicago in 2004. The COUPP-2 bubble chamber introduced the use of a standard, ASME code-rated stainless steel vessel for pressure containment. The safety of the operators and environment was the single most important consideration in implementing this design, which guarantees gas and fluid containment in event of a rupture of the quartz inner vessel. The design also greatly reduces the probability of failure by minimizing the stress on the quartz and permits easy scalability, since even very large steel pressure vessels are relatively simple to design and procure.

Because the superheated liquid is insensitive to gamma rays from radioactive impurities in the steel and other construction materials, this chamber did not require any special screening process or assembly in clean room conditions. Therefore, we were free to construct the bulk of the apparatus using commercially available components and industry standard materials and construction techniques that allowed us to bring the detector on-line very quickly and at low cost. The 2kg chamber was designed, built and commissioned in 14 months with an M&S cost of approximately $40k.

Following a successful evaluation test at the University of Chicago, the COUPP-2 bubble chamber came to Fermilab in March of 2005 and was operated 300 feet underground in the NuMI near detector tunnel at Fermilab. While not sufficiently deep for most competitive dark matter searches, the NuMI site proved to be a very convenient location for the development of the bubble chamber technology. In the first successful NuMI run in 2006, we were able to demonstrate reliable, stable operations with superheat times of 180 sec or more. We developed temperature and pressure controls and optical triggering using the video camera data.

[6] W.J. Bolte et al, Nucl.Instrum.Meth.A577:569,2007

In the 2006 NuMI run, we observed a significant count rate from the decay of radon and radon daughters in the active fluid. Radon was injected into the system during the chamber filling process, and we also observed a continuous injection of radon into the vessel throughout the run that was ultimately attributed to a Viton rubber O-ring used in the quartz-to-metal seal between the bellows and the quartz inner vessel. We observed a significant count rate of ~1 event/cm^2/day of bubbles nucleating on the walls of the quartz vessel. While not a background per se, these events were of concern because their rate would limit our ability to scale the detector up to a larger volume. The wall nucleation rate was ultimately understood to arise from the intrinsic Uranium and Thorium contamination of natural quartz. Decays of these nuclei and their daughters result in the emission of alpha particles into the fluid providing a source of bubble nucleation. Despite the rather significant wall event and radon decay rate, we were still able to establish significant new limits on spin-dependent WIMP nucleon scattering[7].

3.2 COUPP-4 (T945-A2)

To address the technical and background issues seen in the 2kg chamber, we initiated an upgrade in 2007, labeling it COUPP-4. The goals were:

a) To construct an improved muon veto/neutron shielding system.
b) To test improved DAQ and controls hardware and software.
c) To test the use of a synthetic silica vessel to address the "wall event" issue.
d) To test improved materials choices for fluid handling and seals.
e) To test the use of acoustic transducers for the rejection of alpha-decay events.

The upgrades to the 2kg bubble chamber were completed over a two-year period and the apparatus was re-commissioned in the fall of 2009. The new apparatus used a liquid scintillator tank to provide neutron shielding and tagging of cosmic ray muons. The new inner vessel was fabricated from a 6" diameter sample of synthetic silica replacing the original 4" diameter vessel and allowing us to increase the target mass to 4kg. The data acquisition was based on a National Instruments PXI system with an embedded processor. Controls improvements included a microprocessor-based pressure control system and a closed loop temperature regulation system. Improvements in material selection included replacement of the Viton rubber seals with Teflon coated nickel-inconel seals and replacement of polyethylene tubing with Teflon in our CF_3I handling equipment.

The 2009 run of the COUPP-4 chamber was successful in all of its goals. The DAQ and controls system operated without operator intervention for months at a time. Temperature and pressure regulation performance exceeded our requirements. From the beginning, it was clear that the overall count rates were significantly improved. The "wall event" bubble nucleation was entirely eliminated by the use of high radiopurity synthetic silica for the vessel. With the old, natural quartz jars the wall rate in a very large chamber would cause it to have intolerable deadtime. This breakthrough opened the way to building ton scale chambers. The initial radon rate observed in the chamber was consistent with less than 100 radon atoms injected at the fill, significantly better than our past efforts. After decay of the initial radon injection, the observed rate of alpha decay

[7] E. Behnke et al., *Science* Vol. 319. no. 5865, pp. 933 – 936

events in the chamber was less than 1 event/kg/day. The most significant result was a clear confirmation of the difference in acoustic signature between alpha decay events and nuclear recoils. Using the new acoustic alpha discrimination, we were able to set new, improved limits on spin-dependent WIMP couplings[8]. Ironically, the lack of radon contamination in the chamber limited our ability to evaluate the power of the alpha recoil discrimination.

The 2009 NuMI run of the 4kg chamber was cut short by a failure of the hydraulic controls system that led to an over extension of the inner vessel bellows. The replacement of the damaged bellows required only a modest effort, but because of the exceptional performance we had already seen and because the physics reach of the detector in the NuMI site was already limited by cosmic ray induced events, we decided to re-deploy the 4kg chamber at a deep site. In the summer of 2010, we refurbished the bellows assembly, made improvements in the controls hardware and software and installed the COUPP-4 bubble chamber in SNOLAB. As of September 2010, the installation was complete and commissioning is in progress. It is our expectation that new physics results from the 4kg chamber will be available early in 2011.

3.3 COUPP-60 (E961)

Based on the successful early runs of the COUPP-2 detector, a 60kg device was proposed and approved at Fermilab in fall, 2006. The detector was designed and built in the period 2007-2010 and is currently undergoing commissioning in the NuMI tunnel. In 2009, proposals to Fermilab and SNOLAB were approved to move this detector to the deep underground SNOLAB site after the initial testing is complete at Fermilab. Drawings and photographs of the detector are shown in Figure 3-1 and Figure 3-2.

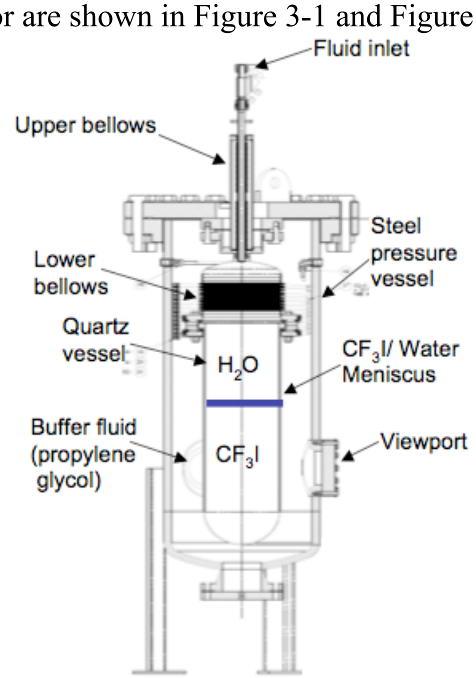

Figure 3-1: Drawing of the COUPP-60 bubble chamber. Like the smaller COUPP devices, the chamber consists of an inner vessel full of the superheated CF_3I liquid, surrounded by a stainless-

[8] E.Behnke et al., arXiv:1008.3518, accepted by Phys. Rev. Lett.

steel outer vessel. The space between the two vessels is filled with propylene glycol hydraulic fluid and motion of a bellows equalizes the pressure between the two volumes.

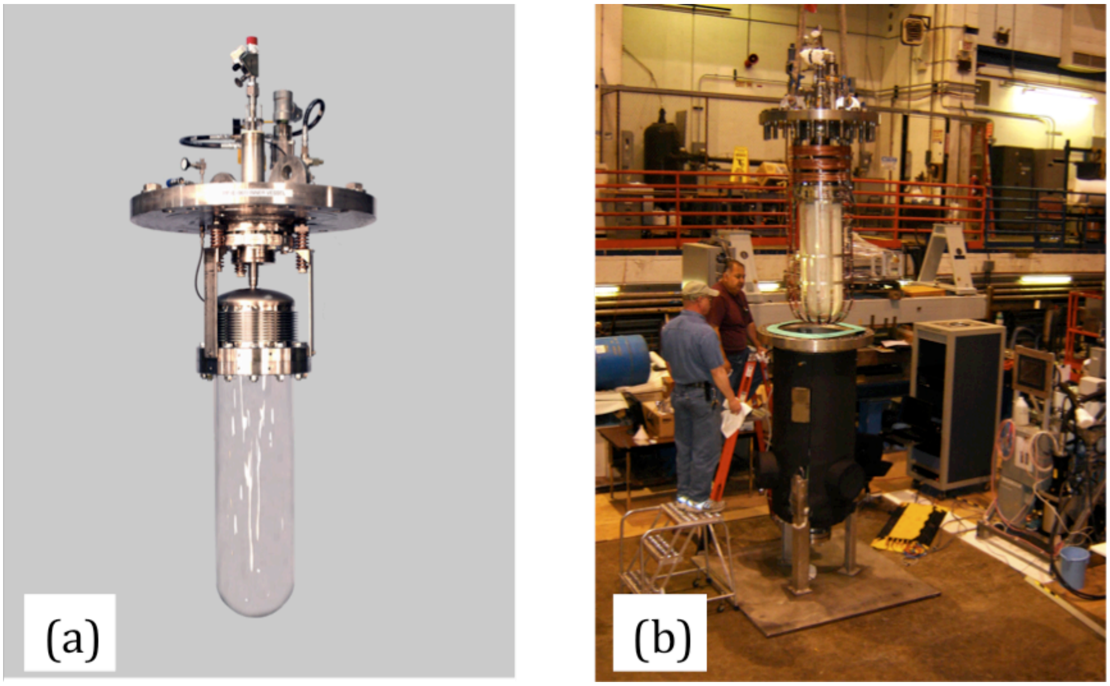

Figure 3-2: Photos of the COUPP-60 chamber: (a) The inner vessel assembly and (b) the inner vessel assembly being inserted into the pressure vessel.

The detector was installed inside a water shield tank in the NuMI tunnel and filled with 44kg CF_3I in July 2010. Initial running of the detector demonstrated that the temperature and pressure control systems functioned well and that the liquid could be superheated for long periods of time. High signal-to-noise acoustic traces were recorded from 8 sensors attached to the inner vessel. The video data acquisition system operated successfully, with one of the early events shown in Figure 3-3. The cosmic ray muon system, based on observation of Cerenkov light in the surrounding water shield tank, produced robust signals that could be time correlated with neutron-induced events recorded in the chamber. Several live-weeks of data were recorded in July and August and are currently being analyzed. While a complete analysis of these events is not available yet, early indications are that the level of alpha-induced background activity in this detector is low.

Several problems were identified in this commissioning run that will need to be corrected before moving the detector to SNOLAB. The most significant problem is an observed darkening of the CF_3I, most likely due to a small light leak into the inner vessel[9]. Additionally, a much higher rate of bubble nucleation at the CF_3I-water interface

[9] CF_3I is unstable when exposed to short-wavelength light (ultraviolet through blue), but has proven to be stable for indefinite periods when illuminated by the red LEDs used for photography of the COUPP chambers. Exposure to shorter wavelengths causes reddening of the normally transparent CF_3I via the production of free iodine.

was observed compared to expectations from operation of the smaller chambers. It is possible that demonstrating a robust solution to these problems will require at least one additional run at NuMI, before the move to SNOLAB can be carried out.

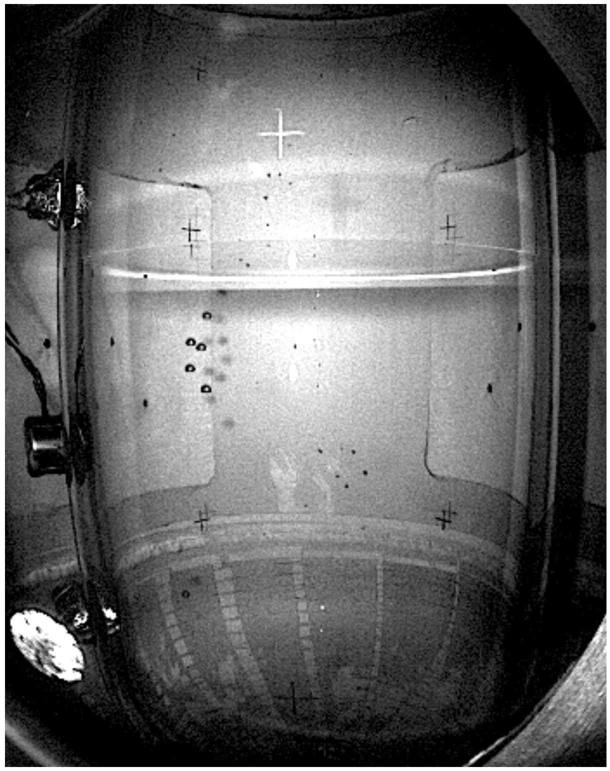

Figure 3-3: Sample image from COUPP-60 showing an event with 5 bubbles from neutron scattering.

4 Potential Backgrounds

Radioactivity and cosmic rays can produce bubbles in a superheated liquid that are indistinguishable from those due to WIMP scattering on an event-by-event basis. Here we consider separately the backgrounds that might be expected from photons and electrons, neutrons and alpha particles.

The total background rate is the critical limiting factor in dark matter searches. It makes little sense to take several years to build a new detector only to be background limited in a few months of data taking. With realistic estimates for dead time, fiducial volume and other analysis losses, COUPP-500 will have a sensitivity of 0.3 ton-years = $1x10^5$ kg-days in one year of data taking. Therefore we must limit the total rate for all expected backgrounds to $<1x10^{-5}$ /kg/day.

4.1 Photons and Electrons

Gamma and beta decays are the most abundant sources of natural radioactivity. Gamma rays from internal and external sources interact in the bubble chamber by Compton and photoelectric scattering and by pair production. In each case, the result is an energetic recoil electron that loses energy primarily by ionization. These events are indistinguishable from events resulting from β-decays internal to the chamber. Despite the large natural abundance, this class of events is dramatically reduced, and possibly eliminated entirely, by the $\sim10^{10}$ rejection factor that is intrinsic to the weakly superheated, continuously sensitive bubble chamber.

This very high level of discrimination between electron recoils and nuclear recoils can be predicted from the Seitz model of bubble nucleation in superheated liquids[10]. This prediction was verified in early bubble chamber experiments[11] and in experiments with superheated droplets[12]. We have directly measured the probability of bubble nucleation from 662 keV gamma rays from ^{137}Cs in our 2kg chamber and find that it is $\sim10^{-10}$ under conditions of temperature and pressure where the nuclear recoil threshold is calculated to be 10 keV.[13]

This extraordinary level of rejection means that even an *unshielded* detector confronting a typical external gamma and beta rate of $\sim10^7$/kg-day would only see a rate of at most ~0.001/kg-day from these sources. With a modest degree of shielding, this rate would be reduced by 2 to 3 orders of magnitude. As outlined in Section 6.2 we plan further studies

[10] F. Seitz, The Physics of Fluids, Volume 1, Number 1 (2-13) 1958

[11] 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

[12] R.E. Apfel, Nucl. Instr. Meth.162 (1979), J.I. Collar et al., Phys. Rev. Lett. 85 (2000) 3083; N. Boukhira et al., Astroparticle Physics 14 (2000) 227

[13] E. Behnke et al., *Science* Vol. 319. no. 5865, pp. 933 – 936 (www.sciencemag.org/cgi/content/full/319/5865/933/DC1)

of the electron and gamma rejection to determine what level of external shielding (if any) would be required by the COUPP-500 device.

The background due to *internal* beta sources is also expected to be very low. The dominant source of internal beta activity is expected to be ^{14}C. If we assume, for the purposes of estimating an upper bound, that the ^{14}C content in our CF_3I target fluid is at the 10^{-12} level characteristic of organic material on the earth's surface, we would expect a rate of 0.0003 events/kg-day form this source. Fortunately, the carbon in the CF_3I is of fossil origin, so this rate will be heavily suppressed by the 5730 year ^{14}C half-life.

We anticipate that γ and β induced backgrounds are unlikely to limit sensitivity of a bubble chamber dark matter search at recoil thresholds ~10 keV until we are well beyond the one ton scale.

4.2 Neutrons

Elastic scattering by neutrons produces nuclear recoil events that are individually indistinguishable from the nuclear recoil events that would be produced by WIMP interactions. The general features of neutron backgrounds are common to all dark matter experiments and have been studied extensively over the past decade[14]. The sources of these are well understood, as are the techniques for mitigating them. Mitigation generally relies first on a deep underground site to minimize the flux of energetic cosmic ray muons. The second crucial element is hydrogen-rich shielding to attenuate the neutrons arising from local radioactivity. Since the mean free path is short, a substantial fraction of neutron-induced events identify themselves by scattering more than once, making multiple bubbles. Finally, it is generally possible to understand and subtract residual neutron backgrounds on a statistical basis using neutron rate estimates based on events in which the neutron scatters more than once, or based on the self-shielding characteristics of a larger detector.

At SNOLAB depths the cosmic ray muon flux has been attenuated. The remaining neutron flux is dominated by natural radioactivity from two sources, spontaneous fission and (α,n) reactions. α-decays of U and Th daughters in materials near the detector have a small but finite probability to produce neutrons via (α, n) reactions in their very short range. Neutrons from these sources have energies below 8 MeV and can be strongly attenuated by modest thicknesses of hydrogenous materials such as polyethylene or water.

The neutron production rate by radioactivity of the detector itself is a concern. Table 1 shows the result of a detailed study of neutron backgrounds due to internal radioactivity for a detector comprised of five chambers each containing 50kg and all shielded by polyethylene. It is clear from this study that the intrinsic radioactivity in polyethylene is unacceptable. A natural alternative is high purity water for neutron moderator and shielding, as we use in the present COUPP-60 detector. Producing water more than 10x

[14] D.M. Mei, A. Hime, Phys. Rev. D73, 053004 (2006), V.A. Kudryavtsev, N.J.C. Spooner, J.E. McMillan, Nucl. Inst. Meth. A 505 688 (2003); M.J. Carson et al, Astropart. Phys. 21 (2004) 667-687, hep-ex/0404042

cleaner than polyethylene (<1 ppb of U and Th) is straightforward[15]. The next largest contribution is from spontaneous fission in the steel of the pressure vessel. We will need to select a pressure vessel material with U and Th contamination several times lower than 2 ppb. The contributions from the compression fluid and quartz vessel are negligible.

A detailed simulation like the one illustrated in Table 1 will be repeated with a fully designed COUPP-500 and with materials characterized for U and Th contamination. The purity improvements required in the neutron shielding water and pressure vessel steel are modest and achievable.

	Poly. (α,n)	**Poly. (SF)**	**Steel (α,n)**	**Steel (SF)**	**Min. oil**	**Quartz**
U,Th (ppb)	10	10	2	2	$<10^{-4}$	0.01
Mass (kg)	$1.1\text{x}10^{4}$	$1.1\text{x}10^{4}$	250	250	75	10
Alphas/day	$1.1\text{x}10^{9}$	n.a.	$5\text{x}10^{6}$	n.a.	<75	10^{3}
Yield (n/α)	$1.7\text{x}10^{-7}$	n.a.	$4\text{x}10^{-9}$	n.a.	$1.7\text{x}10^{-7}$	$2.5\text{x}10^{-7}$
n's / day	180	120	$2\text{x}10^{-2}$	0.56	$<1.3\text{x}10^{-5}$	$2.5\text{x}10^{-4}$
(1) Events /50kg /day	0.07	0.012	$7.7\text{x}10^{-4}$	0.01	$<1.5\text{x}10^{-6}$	$9.1\text{x}10^{-5}$
(2) Singles /50kg /day	0.016	$3.1\text{x}10^{-3}$	$1.9\text{x}10^{-4}$	$2.8\text{x}10^{-3}$	$<3.7\text{x}10^{-7}$	$2.3\text{x}10^{-5}$
(3) Singles in Fiducial Vol. /50kg/day	$3.9\text{x}10^{-3}$	$5.2\text{x}10^{-4}$	$3.4\text{x}10^{-5}$	$5.0\text{x}10^{-4}$	$<7.3\text{x}10^{-8}$	$3.5\text{x}10^{-6}$
(4) Irreducible rate /10^{5} kg-day	23	3.3	0.21	3.0	$<4.4\text{x}10^{-4}$	$2.1\text{x}10^{-2}$

Table 1: This table shows the results of a Monte Carlo simulation of an array of 5 x 50kg CF_3I bubble chambers surrounded by 50 cm of polyethylene. Contributions to the neutron flux from (α,n) reactions in polyethylene, steel, mineral oil and quartz were considered, based on the assumed ^{238}U and ^{232}Th concentrations listed in the first row. Additionally, the contribution from spontaneous fission (SF) was considered for polyethylene and steel. Neutrons were propagated from their material of origin into the sensitive volumes using the MCNP Monte Carlo code and events with nuclear recoils over a 10 keV threshold were counted. The bottom four rows show the number of 1) nucleation events, 2) events with single bubbles, 3) events with single bubbles in a fiducial volume defined to be the inner 1/3 (16.6kg) of each of the five detector volumes, 4) the resulting rate in events/10^5 kg-day after the fiducial volume cut.

One important feature of bubble chamber technology is the ability to spatially resolve multiple interaction sites over a large, homogeneous volume. At 5 MeV, neutrons have a 15 cm mean free path in CF_3I. A significant fraction of neutron events will have multiple interactions and will produce multiple bubbles. For the 50kg chambers simulated in Table 1, 76% of neutron events have multiple bubbles. The presence of these events both reduces the overall neutron background and allows us to measure and subtract any residual neutron background. The short mean free path will cause events to be

[15] I. Blevis et al., Nucl. Instrum. Meth. A, Nucl-ex/0305022., C. Arpesella et al., Astropart. Phys. 18, 1-25 (2002).

preferentially biased toward the walls. This self-shielding will provide a second independent tool for neutron rejection and measuring the neutron background.

4.3 Alphas

Nuclear recoils due to the α-decay of radioactive atoms in our target fluid present a source of background. For example, ^{222}Rn (radon) decays by emission of a 5.5 MeV alpha particle into ^{218}Po, which in turn recoils with 101 keV of kinetic energy, well above our 10 keV trigger threshold. There are two potential sources of such radioactive atoms, those that enter as residual contamination in the chamber fluids, and those that are injected as decay daughters from the inner surfaces of the target fluid vessel. We have two independent approaches to this problem, reduction of the contamination of fluids and surfaces and detection techniques to identify and reject α decay events.

As discussed in Section 3.1, radon decays in the target fluid were the dominant source of events in our first published results[16]. We also saw large numbers of α's coming from the walls of the natural quartz jar that was used at the time. In subsequent chambers we used synthetic quartz jars, reducing the wall rate to levels 2-3 order of magnitude below the natural quartz rate. We achieved α decay rates in the working fluid of ~1/kg/day in COUPP-4 using high purity water from SNO and a single distillation of CF_3I into the bubble chamber. For COUPP-60 we have built and used a high purity double distillation system for both water and CF_3I that should substantially improve the removal of α emitters. We have not yet measured this improvement factor.

The state of the art in the suppression of α activity in liquids belongs to the solar neutrino experiments like Kamland, Borexino, and SNO. These experiments have achieved α activities in water and scintillator at the 10^{-2} - 10^{-4} /kg/day levels depending on the technique, liquid, and isotope. We have not yet reached the state of the art in α purification of liquids.

In 2008, the PICASSO collaboration discovered[17] that events initiated by alpha decays have louder acoustic emissions than events initiated by neutron scattering. This is speculated to be due to the fact that acoustic traces may be sensitive to the number of protobubbles, or precursors to the visibly observed bubble, produced in a track. Nuclear recoils have a short range (~100 nm) that only produces a single protobubble, Alpha particles, with their long range (~35 microns) and their associated recoiling daughter nucleus, result in the formation of multiple protobubbles that merge to form the observed bubble. The observed fact is that events initiated by alpha decays are louder and have larger contributions at high frequencies than do those initiated by neutrons.

COUPP has recently confirmed this result[18] and demonstrated event-by-event discrimination of events caused by radioactivity from those caused by neutrons. Figure 4-

[16] E. Behnke et al., *Science* Vol. 319. no. 5865, pp. 933 – 936 (www.sciencemag.org/cgi/content/full/319/5865/933/DC1)

[17] F. Aubin et al., New J. Phys. 10, 103017 (2008)

[18] E. Behnke et al., arXiv:1008.3518 accepted by Phys. Rev. Lett.

1 shows the distribution of an acoustic parameter (AP) representing the loudness of an event for different data types. Tagged nuclear recoils have a peak at AP = 1, while untagged data that include alpha contamination have a second peak at larger AP, consistent with the distribution of AP observed for a small set of tagged ^{222}Rn daughters. From these data, we have set a conservative limit on the efficiency with which we can tag alpha events of >74% at the 90%CL.

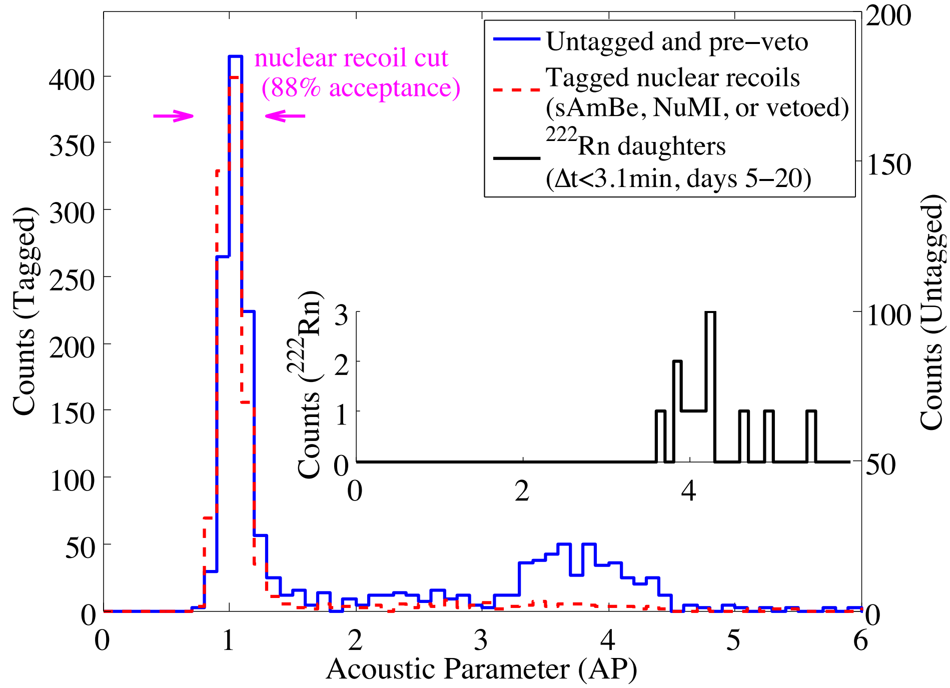

Figure 4-1: The Acoustic Parameter (AP), is a measure of the loudness of the acoustic "plink" resulting from bubble nucleations. The red, dashed histogram in the main panel is from the nuclear recoil calibration datasets (sAmBe, NuMI, cosmic). The blue, solid histogram in the main panel is from all the untagged data from the COUPP-4 run. The inset histogram contains events from 222Rn early in the run, which reproduce the second peak in the untagged dataset. The acceptance of the nuclear recoil cut, indicated with arrows, is 88%.

To move to the ton scale, we require a suppression of α decay events of $<1 \times 10^{-5}$ /kg/day from a combination of fluid purification and acoustic α decay rejection, and we will measure each of these factors separately using data from COUPP-4 and COUPP-60.

5 COUPP-500 Conceptual Design

In this chapter the elements of a COUPP-500 conceptual design are described. In most cases the design is based on a scaling up of what has been used before in the smaller chambers. In some places this is not the case and the text goes into more details on those aspects.

5.1 Inner Vessel

The function of the Inner Vessel (IV) is to contain the active bubble chamber liquid (CF_3I) in a clean environment that is free from the rough surfaces and radioactivity that can cause bubble nucleation. The IV must be transparent to allow photography and must allow for pressure cycling of the liquid. It must be hermetically sealed to avoid intrusion of radon gas from external, lower-purity components of the chamber. Finally, the IV must allow piezoelectric sensors to be mounted in a way that allows them to record acoustic signals from the liquid.

Figure 5-1: COUPP-60 Inner Vessel under assembly in clean room.

We expect the COUPP-500 IV to closely resemble a scaled-up version (by about a factor of two in diameter) of the COUPP-60 IV (Figure 5-1). This existing vessel meets all the requirements stated above and represents a substantial investment in engineering and R&D that can be reused for the new detector.

The most challenging part of the inner vessel to fabricate is the quartz bell jar that contains the CF_3I. To avoid alpha-induced bubble nucleation at the quartz wall, this jar must be made from ultra-high-purity synthetic fused silica, which has purity grades up to 5 orders of magnitude lower in U than the 50 ppb present in natural quartz. Thanks to technology developed for the flat panel display industry, synthetic fused silica can be fabricated into bell jars up to 1.7 meters in diameter, comfortably in excess of the requirement for COUPP-500 where a diameter in the range 60-80 cm is expected.

The metal parts of the inner vessel are made of standard (type 304 and 316) stainless steel alloys and finished with a smooth, electro-polished surface commonly found in vessels produced for the biotechnology and high-purity gas handling industries. Such surfaces are easy to clean and have been used to produce vessels that exhibit low levels of radon gas emanation. The scaling of the metal parts appears to present no particular difficulty, since the materials and fabrication techniques are widely available.

The assembly and cleaning of the inner vessel will follow special procedures similar to those developed for COUPP-60. These procedures are intended to keep dust out of the final assembly and minimize the contamination of the inner surfaces by airborne radioisotopes, especially ^{210}Pb from the decay of radon in air. Such precautions are essential, since the alpha emitting daughters of radon in 250 liters of normal room air (approximately the volume of the IV) will produce a long term steady-state decay rate of ~200 alphas per day.

5.2 Outer Vessel

The function of the Outer Vessel (OV) is to contain the pressure necessary to compress the CF_3I bubble chamber fluid. The pressure is communicated from the OV to the IV by motion of a bellows on the top of the IV, which equalizes pressure in the two volumes. The region between the OV and IV is filled with a hydraulic working fluid (propylene glycol in COUPP-60 and the smaller chambers). In addition to being required for pressure control, the hydraulic fluid also shields the IV from neutrons emitted by the lower-purity components of the OV.

The OV of COUPP-500 will also be based on a scaled up version of the 60 kg chamber vessel, taking into account lessons learned since COUPP-60 was designed about the required operating pressure range and optical layout. The final sizing of the OV will depend on detailed optical and neutron shielding studies which have not yet been performed, but we can anticipate that the OV diameter will be scaled by a factor of 2-3, from 24 inches to 48-72 inches. The COUPP-60 design was conservative, in that it was designed for about twice the operating pressure (600 psi) that turned out to be useful and there was a provision for three camera ports, only one of which was used. Our understanding of the optimal illumination and optical system has evolved significantly since this now four-year old design. Therefore, some changes to the aspect ratio of the vessel and the camera ports are anticipated in addition to the overall increase in size.

The construction of the OV for COUPP-500 is not challenging, since it will be similar to many existing pressure vessels used in the chemical industry and there are numerous possible vendors. Attention will need to be paid to the specification of the welding for the vessel and the stainless steel stock will need to be screened by germanium spectroscopy to avoid high levels of Uranium and Thorium (See Section 4.2).

5.3 Outer Neutron Shield

Nuclear recoils arising from the scattering of incident neutrons represent one of the key backgrounds in the COUPP-500 experiment. The COUPP detector is sensitive only to nuclear recoils above several keV and thus to incident neutrons with kinetic energy above approximately 1 MeV ('high energy', or 'fast' neutrons). Although the depth of the SNOLAB cavern ensures that cosmogenic neutron production is minimal, there still exists a flux of fast neutrons generated from natural radioactive decays. As discussed in Section 4.2, we will screen materials used in the detector itself to minimize (α,n) reactions and fission neutrons arising close to the active volume. However, there remains the difficulty in reducing the neutron flux arising from such reactions in the rock walls of the cavern. A simulation of the SNOLAB cavern, confirmed by measurements, indicates that the fast neutron flux is approximately 1×10^{-6} neutrons per square centimeter per second[19]. This corresponds to about 1 million fast neutrons hitting a COUPP-500 detector per year if there were no neutron shield.

It is generally agreed in the dark matter community that the cheapest, most effective, and lowest background level shielding material is water. In the case of COUPP-60, we have decided to actually immerse the detector directly in a water bath. This bath ensures a clean shielding material that hermetically surrounds the detector. The attenuation length for fast neutrons in water is approximately 10 cm. Our MCNP Monte Carlo simulations indicate that 1 meter of water surrounding the active volume of the detector would result in less than 0.1 events per 10^5 kg-days.

In addition to its role as a neutron shield, the COUPP-60 device uses the water itself as the temperature control for the experiment. We have found that this method ensures a very uniform temperature profile in the detector. If instrumented, the pure water surrounding the experiment might also act as a Cerenkov detector for the few cosmic rays that traverse our detector in SNOLAB.

The specifications for the water shield for the 500kg detector are as follows:-

- A water tank whose sides are approximately 1 meter away from the active volume of the detector. This would be a tank of approximately 20,000 gallons

- The tank should be filled with purified SNOLAB water and be able to be drained and refilled up to several times per year.

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[19] M. Dayou, "Study of the Cavity Wall Background in the SNO Detector". Master's thesis Queen's University. September, 1999

- A method of craning the detector into and out of the tank.
- A circulation pump with approximately 2 kW of heating power.
- A tight fitting lid to the tank, allowing for the possibility of an array of phototubes viewing the water.

5.4 Pressure Control Unit

The pressure control unit is responsible for expanding and recompressing the chamber, regulating chamber pressure in the expanded and compressed states, and maintaining the chamber in a safe state in the face of subsystem failures. The pressure control system for COUPP-60 satisfies these requirements. This section lists potential upgrades to the COUPP-60 system that would be implemented for a COUPP-500 device.

COUPP-60 is compressed using a pressure-multiplying pneumatic-hydraulic piston with a fast solenoid valve on the pneumatic side. To compress, the valve opens to a ~50 psig compressed air line, raising the chamber pressure to ~200 psig in ~0.1 seconds. The piston experiences friction and will only regulate the hydraulic side to +/- ~10psi. For this reason it may be desirable to replace the compression piston with a bellows accumulator tank. This would also require a fast solenoid rated to 300 psig, which would need to be designed in house (while the current lower pressure solenoid is an off-the-shelf item).

COUPP-60 regulates pressure in the compressed state using the pneumatic-hydraulic piston described above. Again, because this piston only regulates to within ~10 psi, we may wish to replace this with a bellows accumulator. This may be done separately from the change above by keeping the piston for fast compression, relieving the need for a new solenoid design.

In the expanded state, COUPP-60 regulates pressure using a hydraulic pump. This works well, but is susceptible to pump failure. Flow indicators to identify pump failure should be installed and included in the controller logic. Alternative regulation schemes using bellows accumulators along with a hydraulic pump should also being investigated.

The COUPP-60 pressure unit is run by a Programmable Logic Controller (PLC) to avoid unsafe or undesirable states. Routine changes to the PLC logic (e.g. the adjustment of self-triggering conditions, addition of new instruments, or changes to the power-on state) currently require an engineer. It may be appropriate to switch to a platform that is accessible to scientists, such as LabView Realtime. This may also result in more robust communication with the DAQ, which is also a LabView system.

COUPP-60 uses propylene glycol as its hydraulic fluid. We do not anticipate changing this, but may want to select components that are compatible with other fluids, including high-purity water, in case the radio-purity of the hydraulic fluid becomes an issue.

5.5 Acoustic Sensors

A significant portion of the free energy in a superheated liquid undergoing a phase transition is released in the form of acoustic emissions. These can be used to register the phase transition and reveal detailed information about the cause of the event, as described in Section 4.3.

Acoustic transducers based on piezoelectric ceramic elements have been used by the COUPP collaboration since 2007. Their first use was as part of the cosmic ray veto system for shallow-site experiments. These sensors need to be either bonded to the glass vessel or suspended inside the water above the target liquid. The piezo-electric element is bonded directly to a preamplifier circuit, and the output of this amplifier is feed out through the pressure vessel and into an external amplifier with signal conditioning appropriate to the digitizer (typically a 625 kHz low pass filter matched to a 2.5 Ms/s digitizer). Although COUPP bubble chambers have not included an acoustic trigger thus far, a trigger based on the signals from the acoustic transducers is a possibility.

In moving to the large COUPP-500 chamber is it likely that more transducers will be needed than have been used in past chambers. Few additional transducers should be required as the degradation in signal quality with increased distance from acoustic source has been shown in the COUPP-4 chamber to be small.

5.6 Data Acquisition

The data acquisition for COUPP bubble chambers is simple on the scale of high energy experiments. For a COUPP-500 device, like the smaller chambers, a number of sensors reading pressure and temperature will be installed on and near the bubble chamber to monitor the thermodynamic conditions of the chamber and its environment. There will be a set of machine vision cameras monitoring portions of the chamber for any bubble activity. Finally, a number of acoustic transducers will be mounted in the experiment. The acoustic transducers will be digitized at a modest rate of a few million samples per second. The data acquisition is accomplished with LabView running on an embedded controller in a PXI crate, and the signals are acquired using commercial PXI devices.

In order to understand the sensitivity to particle interactions, the thermodynamic conditions of the bubble chamber must be constantly monitored. A number of temperature and pressure measurements are made. Precise knowledge of any thermal gradient is important for thermal modeling of the chamber. In most laboratory environments, the pressure and temperature fluctuate, so additional pressure and temperature transducers monitor the local environment.

The data acquisition is closely tied to the controls system. Any boiling in the active volume needs to be halted immediately to minimize the deadtime required to re-condense the CF_3I. The fastest trigger that the COUPP bubble chambers have implemented is based on the camera images. The data acquisition software is capable of capturing images at a rate of ~100 frames per second and searching for differences in consecutive images that indicate bubble growth. The photography system requires light at an appropriate level to allow good contrast and low noise for two millisecond exposures. CF_3I, the favored COUPP target, is sensitive to visible and ultraviolet light, so the lighting needs to be red or infrared. Additionally a smooth background of retro-reflector allows for pseudo backlighting which has been shown to give excellent signal to noise for the identification of bubbles in the chamber. It is intended that COUPP-500 will reproduce this design.

COUPP has successfully used the LabView running on an embedded PXI controller to accomplish data acquisition, and the plan is to continue using this scheme for the ton scale bubble chamber. PXI analog to digital devices are used to record the necessary signals. PXI digital outputs are used to communicate to the pressure control unit, and PXI frame grabbers are used to capture the camera images and pass them to the embedded controller for trigger creation and event recording.

A MySQL database has been developed to monitor the state of the COUPP bubble chambers. The DAQ writes monitoring information to the database, and the database then serves these data out to experimenters monitoring the status of the chamber. The main copy of this database exists in the local DAQ rack and is mirrored at an external server as network conditions permit.

Computing infrastructure requirements are modest and a Linux server is typically used to firewall the DAQ crate and store the data. Since COUPP bubble chambers are limited to ~1500 events per day, the data rate is typically limited to <1 TB per month and the load is either dominated by the acoustic digitizers or shared between these digitizers and the bubble images.

5.7 Detector Simulation

In the past COUPP has relied on simulation only to answer questions about neutron propagation and detection. The insensitivity of the technology to electrons and gammas removed all need for simulation of these backgrounds. In future, however, as we dig down to new types of background concerns there will be a need for a real campaign of simulations to study new questions like the rate of bubbles caused by (α,n) reactions and to make a much more careful assessment of systematic. The process of designing the COUPP-500 detector will need to be intimately coupled to the process of simulating particle production, propagation, and detection in it.

It is possible that our R&D efforts on acoustic sensors and bubble acoustics may require a finite element analysis of our equipment in order to understand sound propagation and how the acoustics sensors and their locations may be optimized to provide the best background rejection.

6 Calibration and R&D

In the series of COUPP bubble chambers operated to date many R&D questions have arisen and been answered (see Chapter 3 for details). There are still a small number of calibrations that need to be performed and a set of R&D questions that need answering and these are described in this chapter. We expect that these issues will be tackled over the next year in parallel with a COUPP-500 design being finalized.

6.1 Calibration of low-energy nuclear recoil response

Bubble nucleation in COUPP is theoretically a threshold process. The bubble nucleation efficiency as a function of recoil energy and degree of superheat is required for the calculation of WIMP sensitivity. Current estimates of the bubble nucleation efficiency are based on the Seitz theory of bubble nucleation[20]. This theory assumes that a particle deposits energy along its wake and the heat vaporizes the liquid. If there is sufficient heat locally available to create a bubble larger than a critical size, nucleation occurs. The critical size is calculated from the temperature, pressure, vapor pressure, surface tension and other thermophysical parameters of the liquid[21].

The nucleation threshold of COUPP bubble chambers has been studied by exposing the chambers to moderated neutrons from ^{241}Am-Be and ^{88}Y-Be sources[22]. This measurement provided a calibration for nuclear recoils with energy down to few keV. Ideally, COUPP chambers should be sensitive to recoil energies of less than 10keV, the limitation being the onset of sensitivity to electron recoils. We plan to further investigate these thresholds, in particular studying the exact shape of the nucleation efficiency function (i.e., sigmoid vs. step function).

Even though this is not expected based on theory, the nucleation efficiency for recoiling iodine may be different than that of fluorine or carbon. Gamma emissions from inelastic neutron scattering produced by a 2.8 MeV monochromatic neutron generator may be used to tag ^{127}I and ^{19}F recoils, and to measure the nucleation efficiency for these two species. Detailed simulations have confirmed the feasibility of this mode of calibration.

A model-independent method of determining the bubble nucleation efficiency may be required in order to confirm a groundbreaking COUPP result. Using a low intensity 1-10 GeV hadronic test beam, a tracker, and a small bubble chamber, the nuclear recoil energy of individual elastic collisions can be measured. A count of bubble nucleations versus the number of scattered hadrons and their scattering angle would translate into a nucleation efficiency function.

[20] http://www.iop.org/EJ/abstract/1367-2630/2/1/14 and references therein.

[21] M. Das et al., Nucl. Instr. and Meth. A 531 (2004), p. 577 and Bell et al., Nuc. Sci. and Engin. 53 p.458 1974

[22] W.J. Bolte et al, Nucl.Instrum.Meth.A577:569,2007

6.2 Further Calibration of Gamma Rejection

Although the discrimination power of a bubble chamber against electronic recoils produced by gamma and beta particles is extremely strong, current limits on external gamma rays and internal ^{14}C backgrounds in an unshielded detector are at the level of 10-100 events for an exposure of 1e5 kg-days and an energy threshold of 10 keV. While increasing the energy threshold to 15 keV would likely improve the discrimination against electronic recoils by ~1000 without greatly degrading the sensitivity to dark matter, further calibrations will be needed to determine the relationship of both ^{14}C and external shielding requirements to the target threshold of 10 keV and the ultimate energy threshold of the experiment.

Gamma calibrations to date have consisted of exposing COUPP detectors to ^{137}Cs sources of varying strengths and using simulations to account for the number of interactions in the liquid. Because cosmogenic activity limits the sensitivity of the existing calibrations in the energy range of interest, data with and without sources will be retaken in the COUPP-4 detector at SNOLAB with emphasis on exploring the low energy region of 2-20 keV.

Lastly, a study of the gamma ray flux in the SNOLAB cavern will be undertaken to determine if any additional shielding is needed, and the materials selection process of the COUPP-500 design will be performed with gamma backgrounds in mind.

6.3 Calibration of acoustic Alpha/recoil separation

Our strongest lower bound on alpha/recoil discrimination to date, >74% alpha rejection with 88% nuclear recoil acceptance, comes from the WIMP-search data from the COUPP-4 run at NuMI. This measurement was limited by the low alpha rate (0.7 bulk alphas / kg-day) and high untagged-neutron rate (~0.1 untagged single-bubble acoustic neutrons / kg-day) from the shallow site and will be repeated with the COUPP-4 device at SNOLAB. With a similar alpha rate and no neutron background for three months, we can reach a lower bound for alpha rejection of 99.5%. This type of measurement, using a single fixed alpha contamination, can only produce a lower bound, as we will be unable to distinguish alpha leakage from other backgrounds (or a WIMP signal).

6.4 R&D on an In-Situ Source for Alpha Calibration

A measurement of (as opposed to a lower-bound on) alpha/recoil discrimination will require injecting an alpha-decaying isotope into the active volume of the chamber. Once the background for the COUPP-4 device at SNOLAB is well measured, or after a three-month background-free run, we propose to spike the chamber with ^{220}Rn filtered from a ^{228}Th source. The alpha rates observed following a 1000 atom spike are shown in Figure 6-1. The rate falls below background within ~4 days of the spike. The short half-life (10.6 hours for ^{212}Pb) and stable end product (^{208}Pb) protect against over-spiking, providing a safe way to measure alpha/recoil discrimination in-situ in future detectors. This relies on the delivery mechanism filtering out the longer-lived ^{228}Th and ^{224}Ra parent isotopes. The delivery mechanism, including ^{220}Rn permeable filters, spike activity control and remote operation capability, will be tested on the COUPP-4 chamber.

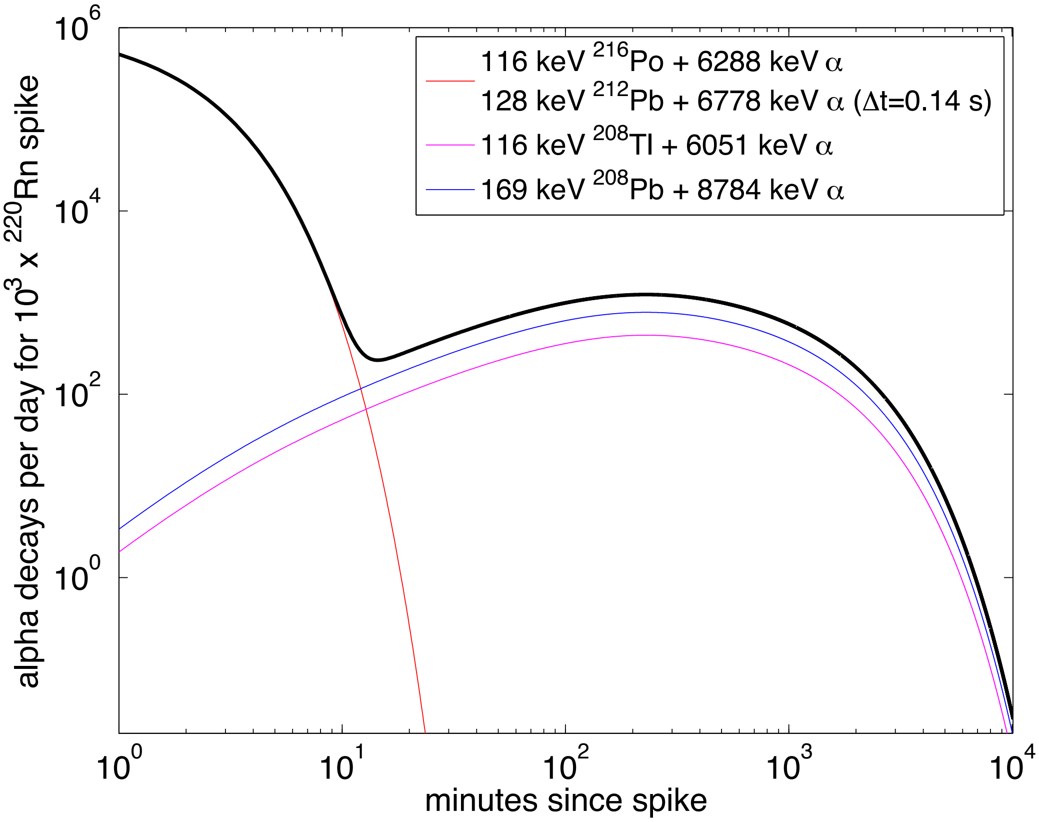

Figure 6-1: Alpha rates in the week following a 1000 atom ^{220}Rn spike. The ^{220}Rn decays with a 55 second half-life to ^{212}Pb (10.6 hour half-life), which takes one of two paths to stable ^{208}Pb, one giving an 8784 keV alpha (64%) and the other a 6051 or 6090 keV alpha (36%).

6.5 R&D on bubble acoustics and acoustic sensors

The complete power spectrum of the acoustic emission from bubble formation is unknown and there might be unexploited higher frequencies where the difference between nuclear recoil events and alpha decays is greater than the ones currently being used. Also, the emissions at lower degrees of superheat are less energetic and not detected by the current generation of transducers. Both of these challenges are being addressed by studying modifications in the backing material composition and geometry. The goal is to have the sound waves enter the front face of the piezo element, pass through once and exit the back of the element after a single transit, rather than bouncing around inside the piezo.

Figure 6-2 shows a cartoon of a COUPP acoustic sensor. The collaboration is studying backing composition modifications to make the overall acoustic impedance of the backing equal to that of the piezoelectric element. This would eliminate reflection at the piezo/backing interface. If the backing is composed of a mixture of different materials with very different acoustic properties (such as epoxy/metal flakes/rubber inclusions), then once the sound waves enter the backing, they should undergo specular reflection and dissipate to heat rather than re-entering the piezo. This might also be aided by having an appropriate geometry to the backing material that would disfavor reflections at the backing/backplate interface that might re-enter the piezo (perhaps a conical backing.)

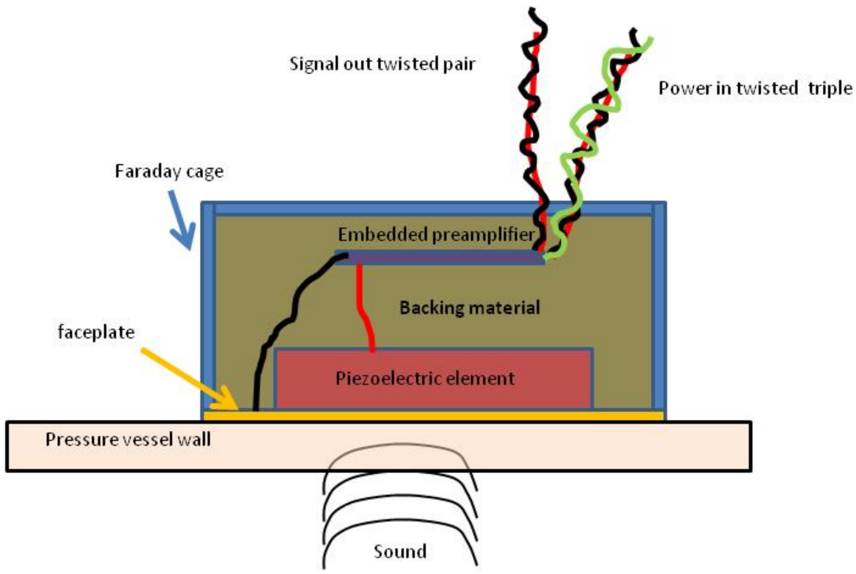

Figure 6-2: Conceptual design of the COUPP acoustic sensors.

The method of construction is also being studied to protect the piezo element. Currently, the piezo element is soldered to the faceplate, which might degrade the poling of the ceramic. We are studying the mechanical and acoustic properties of conductive epoxy as a replacement to soldering.

For very large detectors, the ceramic of the current piezo elements might become the largest source of background neutrons from (α,n) reactions in the ceramic or backing material. Sensors based upon plastic piezoelectric elements (PVDF) will be studied along with calculations of the neutron contribution from the current technology.

The density of sensors needs to be planned as well. A proper balance of maximizing the types of information COUPP can derive from acoustic sensors alone and the need to not block camera views for large detectors needs to be understood.

All of the R&D goals require the use of a dedicated acoustic test-bed bubble chamber. Currently, all sensor R&D is done with acoustic white noise sources that are unlike the bubbles produced in bubble chambers.

6.6 R&D: Aging Tests

The components of the detector inside the compression fluid (propylene glycol) are subjected to pressure and temperature variation and potential chemical interactions with the fluid during the experiment. The compression fluid has been observed to yellow during previous runs and some corrosion of parts has been observed. Also, acoustic sensors have failed over time due to interaction with the fluid. The robustness of the system to these potential interactions needs to be assured prior to construction of a large-scale detector. As shown in Figure 6-3, a multi-chamber pressure vessel simulation system has been constructed and is now being used for this purpose. Acoustic sensors installed on the 4kg chamber have been subjected to pressure and temperature cycling and their acoustic performance has been tested in situ, with embedded white noise sources.

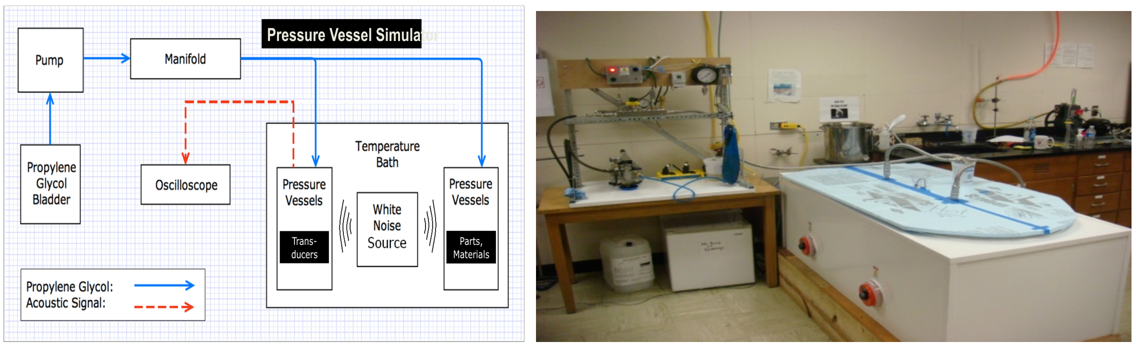

Figure 6-3: Pressure vessel simulation system (functional cartoon and photograph of constructed system.)

We are also studying the yellowing effect and have been able to reproduce it. The cause seems to be copper catalyzed reactions in the propylene glycol producing lactic acid. This study continues and other potential problems and solutions will be tested in these small chambers prior to material selections in large-scale chambers.

6.7 R&D: Chemical Studies of the Active Fluid.

The chemical purity of the CF_3I target needs to be assured and a gas chromatography / mass spectrometry system has been adapted at IUSB to study samples of this fluid. The system has been commissioned and preliminary qualitative tests show that the fluid as provided by the vendor has significant contamination from various chemical products of the CF_3I production (Figure 6-4) process, but that the COUPP-60 detector vacuum distillation system has significantly reduced the contaminant level of the fluid that has passed through it. Since CF_3I is used as a fire-extinguishing agent, its interactions with common materials over an extended period of time have been extensively studied[23]. Nonetheless, it is important we have the capability to assure ourselves of the purity of our active fluid.

[23] Michelle K. Donnelly et al, “CF_3I Stability Under Storage”, NIST Technical Note 1452, 2004

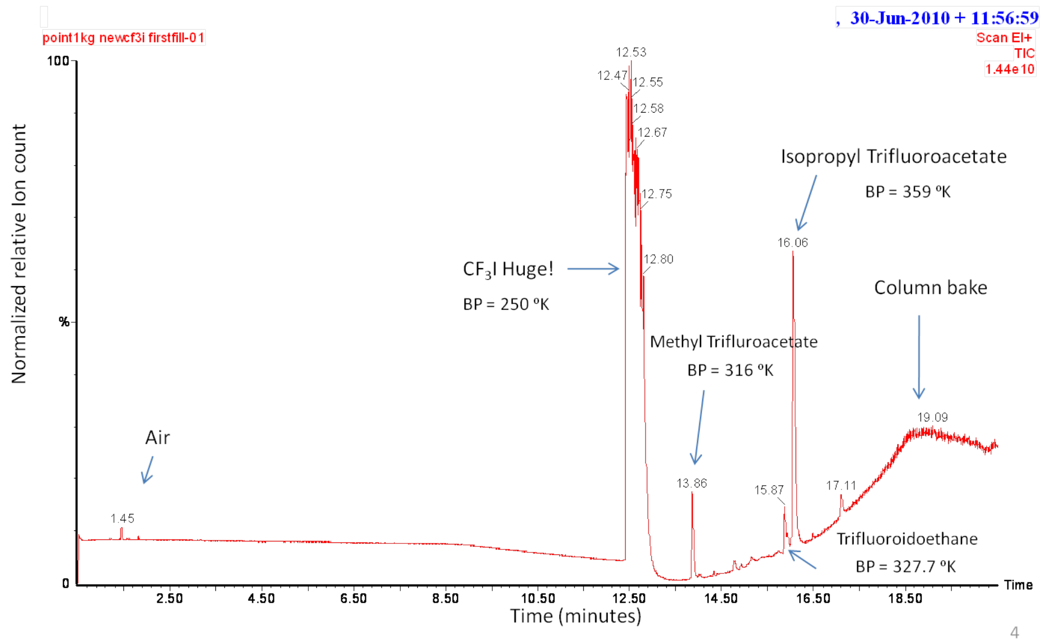

Figure 6-4: Chromatogram of CF_3I provided by vendor, prior to vacuum distillation by the COUPP purification system.

7 Physics Reach

With the successful accomplishment of the R&D goals , it will be possible to achieve a background free exposure of 1 live year with a 500kg fiducial volume. A full live year of exposure can be expected in two years given the expected rate of alpha and surface bubbling expected from the construction materials and CF_3I purity. This results in a sensitivity of 1×10^{-5} dark matter interactions per kilogram per year. Under standard dark matter halo assumptions[24], this translates into a sensitivity of 6×10^{-47} cm^2 for spin-independent WIMP-nucleon elastic scattering as shown in Figure 7-1. This sensitivity puts a ton scale COUPP bubble chamber at the forefront of the generation two (G2) experiments defined by PASAG[25]. This sensitivity also allows an exploration of most of the favored parameter space in the constrained minimal supersymmetric model[26].

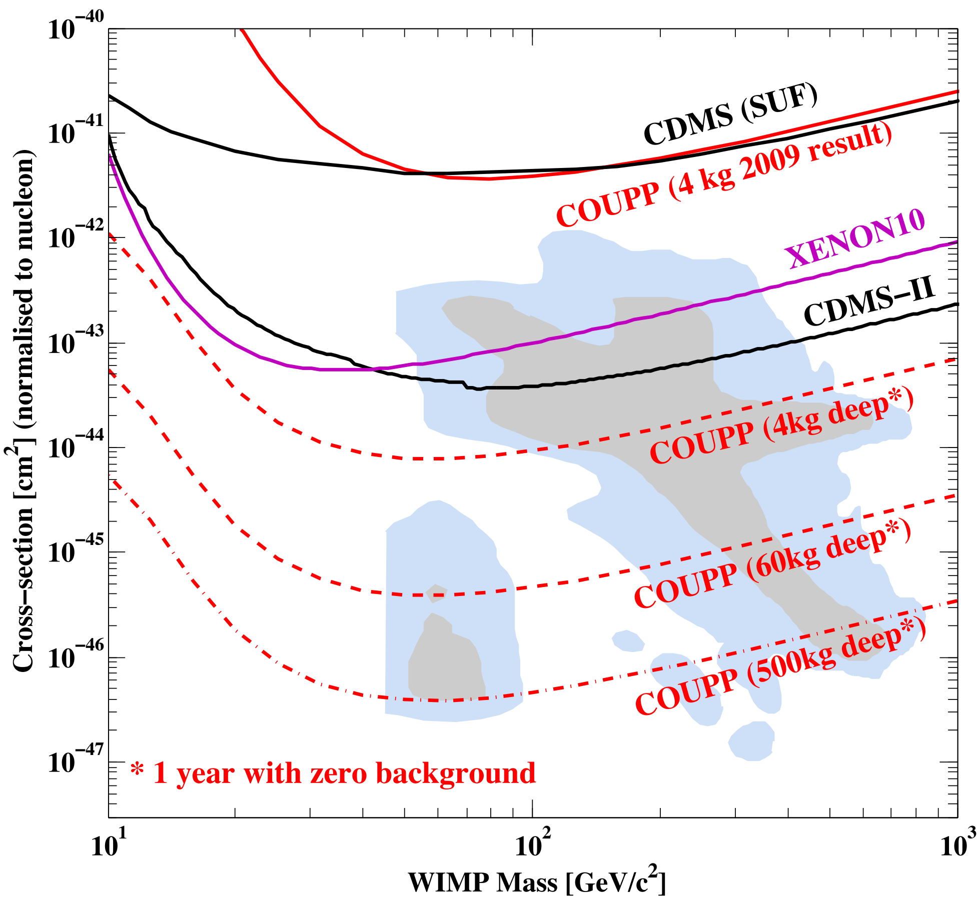

Figure 7-1. The expected spin-independent sensitivity of the COUPP program. The 500kg chamber will be able to cover much of the favored parameter space in the constrained minimal supersymmetric model parameter space (shown as solid regions.)

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[24] J.D. Lewin and P.F. Smith, Astrop. Phys. 6, 87 (1996)
[25] http://www.er.doe.gov/hep/files/pdfs/PASAG_Report.pdf
[26] L. Roszkowski, R.R. de Austri, and R. Trotta, JHEP 0707, 075 (2007).

The sensitivity to spin-dependent WIMP-proton scattering of the COUPP-500 detector would be unparalleled with sensitivity exceeding 10^{-42} cm^2, as shown in Figure 7-2, . Note that current experimental constraints do not probe expected cMSSM cross-sections. COUPP-500 will be sensitive to cross-sections four orders of magnitude smaller than the largest predicted in the cMSSM. Additionally, direct detection bounds from COUPP would be less model dependent than those from neutrino telescopes like SuperK and IceCube since they do not depend on the Majorana nature of the neutralino or the branching ratios to specific annihilation products. Models of spin-dependent and spin-independent WIMP interactions are highly uncorrelated[27] and no other proposed G2 experiment would have a similar spin-dependent WIMP proton scattering sensitivity.

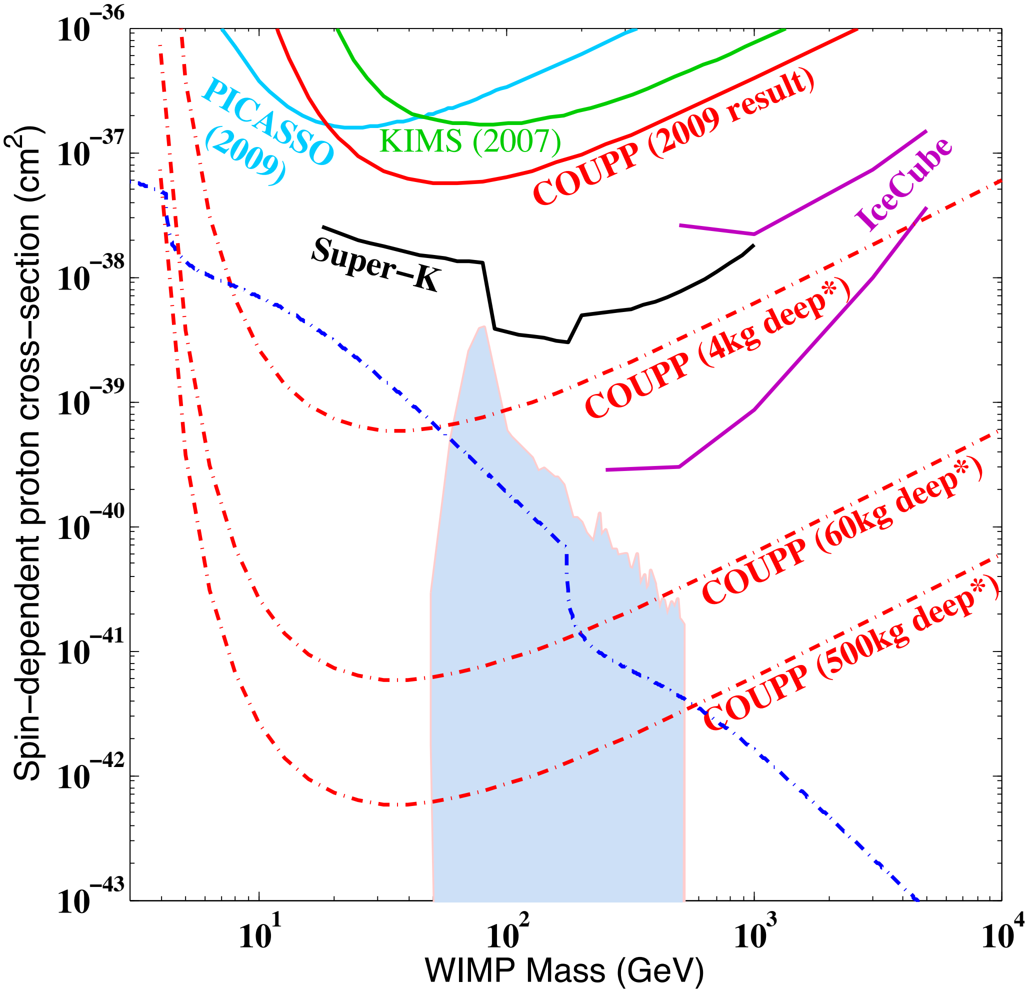

Figure 7-2. Sensitivity of the COUPP program to spin-dependent WIMP-proton scattering. No other planned generation two experiments have such a significant sensitivity to this scattering process. This is the equivalent of hundreds of kilometer square neutrino detectors such as ICECUBE.

[27] G.Bertone et al., Phys.Rev.Lett.99:151301,2007

8 Schedule, Budget, and Request

8.1 Schedule and Budget

COUPP-500Kg	FY10	FY11	FY12	FY13	FY14	FY15	Totals
DOE							
R&D	0	400	400	200			1000
Construction	0	0	750	1750	1500	0	4000
NSF							
R&D	610	584	404	0	0	0	1598
Construction	0	0	350	700	350	0	1400
Total DOE	0	400	1150	1950	1500	0	5000
Total NSF	610	584	754	700	350	0	2998
Total	610	984	1904	2650	1850	0	7998

Table 2: A breakdown by year and by funding source of the anticipated cost of a COUPP-500 device.

Table 2 provides a breakdown by year and by funding agency of the anticipated cost to design and build a COUPP-500 device. These numbers exclude "base" funding at universities and "research" funding at Fermilab (i.e. they exclude scientific salaries at both universities and the lab), but they do include engineer and technician time. The division of the burden between NSF and DOE is illustrative only and has yet to be agreed upon, although the row labeled “NSF R&D” refers to an NSF S4 grant that has already been secured. The equipment costs are contained in the numbers of Table 2 and are detailed in Table 3.

	Cost Estimate (K$)	Contingency	Total W/ Contingency
High Purity Quartz	120	50%	180
Pressure Vessel	160	100%	320
CF3I	125	25%	156
Inner Vessel Steel Parts	50	50%	75
High Purity Fluid Handling System	150	50%	225
Pressure Controller	75	50%	113
Data Acquisition and Computing	50	50%	75
Video Cameras	25	100%	50
Assembly Fixtures	50	100%	100
Water Tank	100	100%	200
Muon Veto	50	100%	100
Total Equipment Cost (k$)	**955**	**70%**	**1594**

Table 3: A breakdown of just the equipment costs of a COUPP-500 device

8.2 Request

At this time COUPP requests the following of Fermilab:-

1. Sufficient engineering time to bring the COUPP-500 proposal to a level where its cost can be firmly established.

2. Support to continue operations of our 4kg chamber in SNOLAB.

3. Support to execute the calibration and R&D tasks that will inform the design of the COUPP-500 device.

Note that support to bring the 60kg device to SNOLAB and operate it there is not being requested here as this was the subject of a separate proposal to the PAC in 2009 and the funds to do this are being separately requested from DOE.

Appendix

Bubble Chamber FAQ

1) *Isn't there boiling on the walls of the vessel?* No. The familiar phenomenon of bubble nucleation on the walls of a champagne glass is caused not by the flaws in the glass surface but by the gas trapped in the flaws. When a vessel is filled, surface tension prevents the liquid from penetrating into the depths the smallest fissures. The resulting small gas bubbles are the nucleation sites. If the vessel is filled by condensation, then there is no surface tension barrier and it is possible to perfectly wet even rough surfaces. A vessel prepared in this manner does not exhibit bubble nucleation on surface flaws.

2) *Is there a problem with spontaneous bubble nucleation in the bulk?* No. At large degrees of superheat spontaneous boiling can occur. For the modest superheat required for dark matter sensitivity, the mean time between spontaneous bubble nucleation would be comparable to the age of the universe.

3) *Is the mechanical stress on the quartz vessel a problem?* No. In our chamber designs the active fluid contained in quartz bell jar is in hydrostatic equilibrium with the hydraulic fluid filling the rest of the pressure vessel. A diaphragm or bellows separates the two fluids and maintains hydrostatic equilibrium.

4) *Are these devices really as inexpensive as they seem?* Yes. There is simply not much room to hide large costs in this experiment. The apparatus consists of a relatively conventional pressure vessel and has few components. Most of the parts are commercial. There is no sophisticated electronics. The inner components (quartz vessel, diaphragm/bellows, plumbing, H_2O, CF_3I) must be clean and the costs associated with purification may become significant as a fraction of the project M&S cost, but on an absolute scale the M&S costs will never compete with the personnel costs.

5) *How about shielding? Isn't the cost going to be ultimately dominated by the large shielding array?* No. For a variety of reasons, we are considering a water tank as our sole neutron shield. The bubble chamber lends itself to a water-tight design, and its natural immunity to γ-radiation means that there is probably no need for a high-Z component to the shielding (though this needs confirmation by further, detailed γ calibrations). A water tank is a simple and inexpensive option.