COUPP[*]- A Search for Dark Matter with a Continuously Sensitive Bubble Chamber

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Abstract

We propose to construct and operate a 60-kg room temperature CF_3I bubble chamber as a prototype dark matter (WIMP) detector. Operating in weakly-superheated mode, the chamber will be sensitive to WIMP induced nuclear recoils above 10 keV, while rejecting background electron recoils at a level approaching 10^{10}. We would first commission and operate this chamber in the MINOS near detector hall with the goal to demonstrate stable operation and measure internal contamination and any other backgrounds. This chamber, or an improved version, would then be relocated to an appropriate deep underground site such as the Soudan Mine. This detector will have unique sensitivity to spin-dependent WIMP-nucleon couplings, and even in this early stage of development will attain competitive sensitivity to spin-independent couplings.

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1.0 Introduction

There is by now a large body of evidence to support the widely accepted proposition that most of the matter of our universe is cold, dark, and non-baryonic. Supersymmetry provides an abundance of candidates which could account for the dark matter as a relic population of neutral, weakly interacting, massive particles or "WIMPS." The case for dark matter, the plethora of candidate dark matter particles, and the phenomenology of their interactions has been extensively reported and summarized[1] and we will not repeat it here. Suffice it to say that the direct observation of WIMP interactions in the laboratory would provide a decisive confirmation of this picture of our universe.

Many of the essential features of a terrestrial direct detection experiment are determined not by the specific model of dark matter but by the mass distribution of our galaxy's dark matter halo. A detector orbiting the Milky Way galactic center at a radius of 8 kpc would be expected to encounter a flux of dark matter particles with a density of 0.3 GeV/cm^3 and a typical velocity of ~300 km/sec. It is this typical collision velocity which dictates that nuclei recoiling from elastically scattered dark matter particles will have recoil kinetic energies on the order of tens of keV for the expected WIMP mass range from a few GeV to ~1 TeV.

Because the recoil energies are so small, the first and most obvious experimental challenge for direct detection is to develop a technology that can discriminate rare nuclear recoils from the abundant electron recoils arising from natural radioactivity. A detector which can unambiguously identify nuclear recoils must then be able to deal with the next tier of backgrounds which consists of actual nuclear recoils induced by neutrons from a variety of sources and also includes the α-decays of U and Th and their daughters. Each detector technology that has been brought to bear on the dark matter problem has employed some combination of intrinsic detector background rejection, shielding, and operation in a deep underground site to address these background issues.

The best current limits on excess nuclear recoil events due to dark matter interactions come from the CDMS experiment[2] which employs solid state silicon and germanium detectors. CDMS detectors provide both a bolometric measurement of the true recoil energy and the ionization yield of an event. The ratio of these two measured quantities provides a parameter which is used to discriminate nuclear recoil events from electron recoils. The CDMS detector array is also segmented, providing discrimination on a statistical basis between neutron and WIMP induced nuclear recoil events due to the multiple interactions of the neutron events. Finally, the ability to compare interaction rates between Si and Ge results in additional powerful discrimination between WIMP and neutron induced events, and the natural isotopic content of ^{29}Si and ^{73}Ge provides sensitivity to spin-dependent interactions. It is the CDMS detector's combination of

[1] G. Bertone et al. /Physics Reports 405 (2005) 279-390
[2] D.S. Akerib et al. Phys. Rev. D72 052009 (2005), astro-ph/0507190

powerful nuclear recoil discrimination, segmentation, and the ability to employ two target materials that provides the gold standard against which all new detection technology will be measured.

The CDMS collaboration has deployed a roughly 5-kilogram segmented array of solid state detectors in a deep underground site in the Soudan Mine and has obtained dark matter limits based on the absence of excess nuclear recoil events approaching the level of 0.01 events/kg-day. The most challenging background for the CDMS experiment has resulted from the interactions of beta radiation with a dead layer on the detector surface in which incomplete charge collection leads to events which mimic nuclear recoils. The CDMS collaboration is still accumulating data with the Soudan experiment, and is engaged in an aggressive development effort to fabricate larger and cleaner detectors in order to extend their current sensitivity.

Meanwhile, the race is on to develop other competitive dark matter detection technologies which have the capability to operate at the 1000 kg scale. A recent review conducted by the DMSAG sub-panel of the HEPAP Committee heard presentations from no less than eleven new detector development efforts. There is clearly a great interest in finding the technology that will best advance the sensitivity of future dark matter searches.

2.0 The Continuously Sensitive Bubble Chamber

This proposal addresses a new (old) detector technology which we believe to be the most promising candidate for a dark matter detector that will work at the ton scale. Our detector will be a *continuously (albeit weakly) superheated* bubble chamber, operated below the threshold for sensitivity to minimum ionizing particles. The idea is simple. The threshold for bubble nucleation in a superheated liquid is a strong function of temperature and pressure. A judicious choice of operating parameters will result in a bubble chamber that is sensitive to nuclear recoils but blind to minimum ionizing particles, γ, and β interactions. We have demonstrated that a CF_3I bubble chamber can be operated with a gamma rejection factor of $3x10^9$ at a nuclear recoil threshold of 10 keV. This gamma rejection is roughly five orders of magnitude beyond what has been demonstrated by CDMS, and is discussed in some detail in Appendix I. With the chamber operated in this weakly superheated mode, a nuclear recoil event will produce a single bubble, as shown in Figure 2.1 a.

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/lid, 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 extraordinary degree of radio-purity necessary to advance dark matter limits. The backgrounds which will determine the ultimate physics reach of our dark matter search are discussed in detail in Appendix II. We have successfully operated a 1 liter (2 kg) CF3I bubble chamber in continuously sensitive

mode for nine months, and we see no technical obstacles to building considerably larger and cleaner devices.
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 5 cm for the most troublesome background neutrons in most candidate fluids, neutron induced events will frequently appear as multiple bubbles. Inexpensive cameras can easily resolve bubbles at the millimeter level so very high effective segmentation is easily attained as seen in Figure 2.1 b. For large bubble chambers, neutron induced events will occur preferentially near the vessel walls and significant self-shielding will be possible.

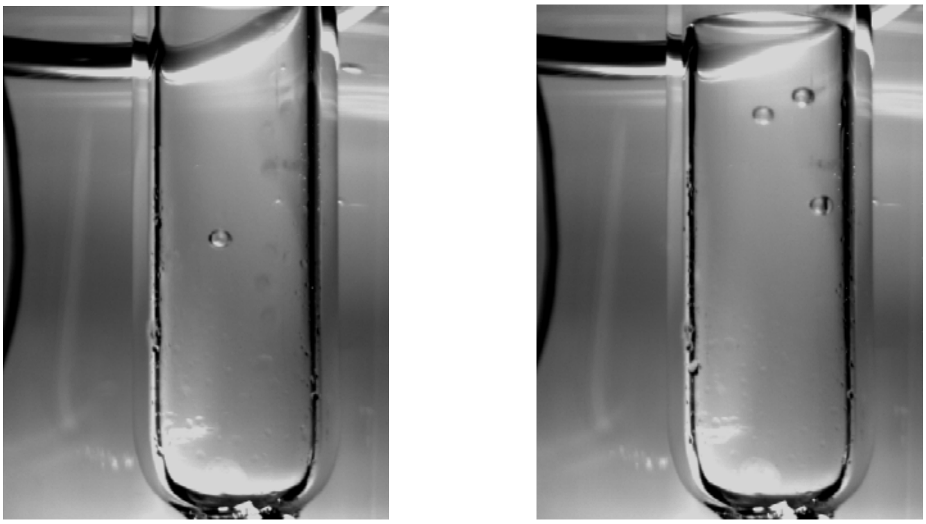


Figure 2.1 (a) A nuclear recoil induced single-bubble event in a 12 ml test chamber. Figure 2.1(b) shows a three-bubble event caused by a neutron.

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) which 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 by virtue of the fluorine which has ~100% isotopic abundance of spin ½ ^{19}F and has a favorable nuclear form factor. Figure 2.2 shows the level of sensitivity to a spin-dependent WIMP-nucleon coupling that we expect to explore with our 1-liter mechanical prototype chamber operating in the relatively shallow MINOS near detector hall. Figure 2.3 shows the equivalent sensitivity bands for a spin-independent coupling. It will be straight-forward 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. Operating at our most sensitive dark matter thresholds, events resulting from the α-decays of U and Th daughters which are in solution in our target fluid will be well above threshold (these are typically 100 keV recoils.) We will not be able to discriminate these events on an event by event basis, so the realization of our full physics reach will depend on our ability to purify our target fluid. While it is possible to measure and subtract this class of background by operating at two detector thresholds or by scanning the operating threshold, our best sensitivity will result from a detector that is free of this contamination. Fortunately, significant physics reach can be attained with levels of purification that have already been demonstrated by other groups. This is discussed in some detail in Appendix II.

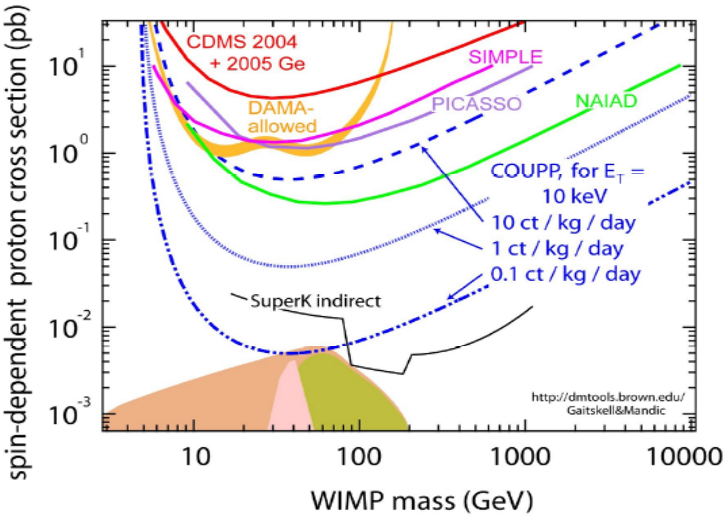


Figure 2.2: Spin dependent physics reach for a 1-liter prototype bubble chamber.

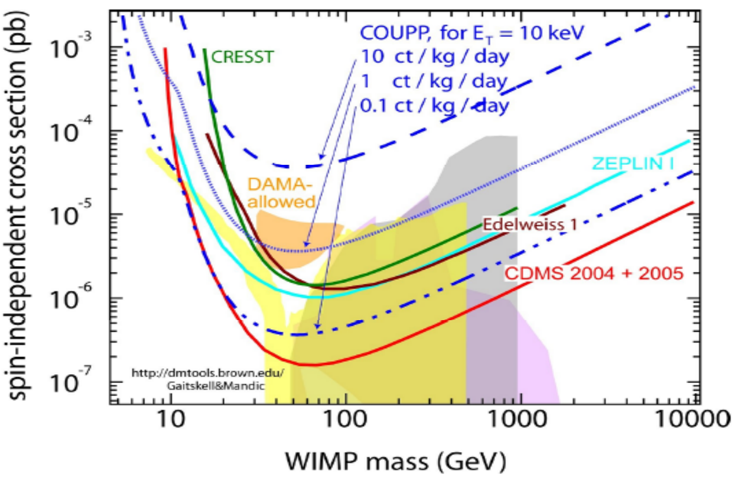


Figure 2.3: Spin-independent physics reach for a 1-liter prototype bubble chamber.

4.0 Designs for Continuously-Sensitive Bubble Chambers

The familiar bubble chambers operated in the 1950's-1980's were operated as tracking devices and required a high degree of superheating to attain the necessary sensitivity to minimum ionizing particles. To prevent spontaneous boiling, these *ultra*-superheated chambers could only be sensitive for ~10 milliseconds at a time. These devices were operated in a pulsed mode, synchronized to a particle beam. The engineering challenges presented by the large bubble chambers were mostly related to accomplishing the rapid pressure cycling that was necessary.

The detection of dark matter will require a detector that is continuously sensitive, which would at face value seem to preclude a bubble chamber as a candidate device. However the goal of dark matter searches is to be blind to minimum ionizing particles, so a chamber can be operated with only a modest degree of superheating. In a clean, *weakly*-superheated chamber, the problem of spontaneous boiling is not present[3]. The pressure cycling is infrequent and can be done rather slowly. In this mode of operation, the chamber behaves as a *threshold calorimeter* in that the range of a recoiling nucleus is significantly smaller than the critical radius for bubble nucleation. All of the nuclear recoil energy is applied to a single bubble. That bubble will grow if the nuclear recoil energy exceeds an energy threshold determined by the temperature and pressure of the fluid as illustrated in Figure 4.1. Operating in this mode, the energy density required to initiate a bubble nucleation is simply not present without a nuclear interaction. This leads to a chamber which would remain permanently superheated in the absence of radiation[4].

Figure 4.2 illustrates the general features of the design for a continuously sensitive 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. The diaphragm flexes to equalize the pressure inside the quartz with the pressure of a surrounding hydraulic fluid which 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 view ports.

We have already explored many variations of the design. For the pressure balancing element, we have tested many diaphragm designs and a variety of bellows. All options seem to work. We have looked at a variety of types of digital cameras and readout options. We have also considered and tested video cameras which are potted and deployed *inside* the pressure vessel directly in the hydraulic fluid. The encapsulated cameras would eliminate the need for viewing ports and would reduce the mass and complexity of the pressure vessel. Several small chambers have been constructed to test the various design options, including the 1-liter (2-kg) chamber installed in the NUMI

[3] Waters, Petroff, and Koski, IEEE Trans. Nuc. Sci. 16(1) 398-401 (1969)

[4] B. Hahn, Nuc. Phys. B (Proc Suppl.) 36 459 (1994), V. Zacek, Nuovo Cimento 107 291 (1994), J.I. Collar, Phys. Rev. D54, 1247 (1996)

tunnel in 2005 (T-945). 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 and also serves, together with the external hydraulic fluid, as a neutron shield and heat-exchange medium.

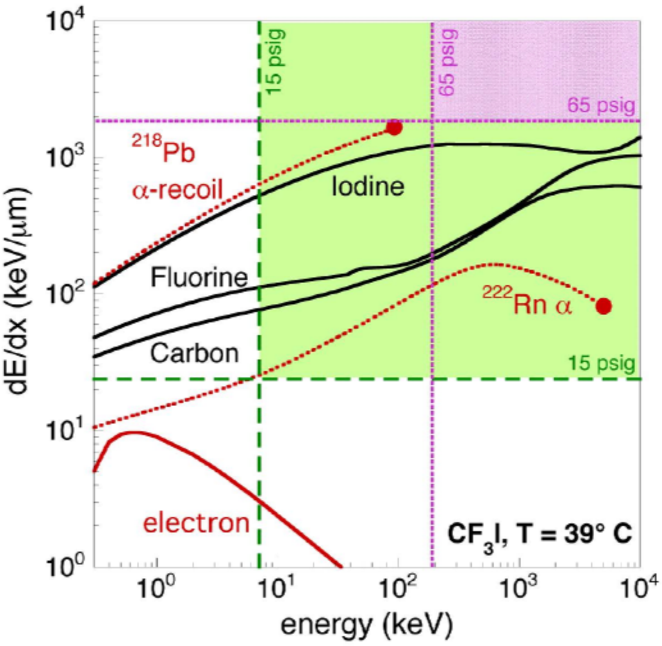


Figure 4.1: Chart illustrating the dependence of bubble nucleation on both of the total deposited energy and dE/dx. The purple (green) shaded regions in the upper right quadrant of the plot indicate the region of efficient bubble nucleation threshold for 65 psig (15 psig).

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 which is switched on or off via solenoid valves. The compressed air drives a pneumatic cylinder which actuates a hydraulic cylinder which transmits the pressure to the compression fluid. The fluid in the inner vessel is maintained in equilibrium with the hydraulic fluid through the flexible diaphragm. 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 via analysis of the streaming video images. When a bubble is detected, the solenoid valve is actuated and the chamber is rapidly re-pressurized.

It is worth noting that all of the design options we have considered seem to work very well. We can use diaphragms or bellows to balance the pressure. We can use camera ports or encapsulated cameras. We can trigger using pressure sensors, fast AC pressure transducers, piezo-electric acoustic sensors, or video image analysis. We are confident that the availability of such a variety of viable engineering options will allow us to develop robust, cost effective, and virtually maintenance-free bubble chambers.

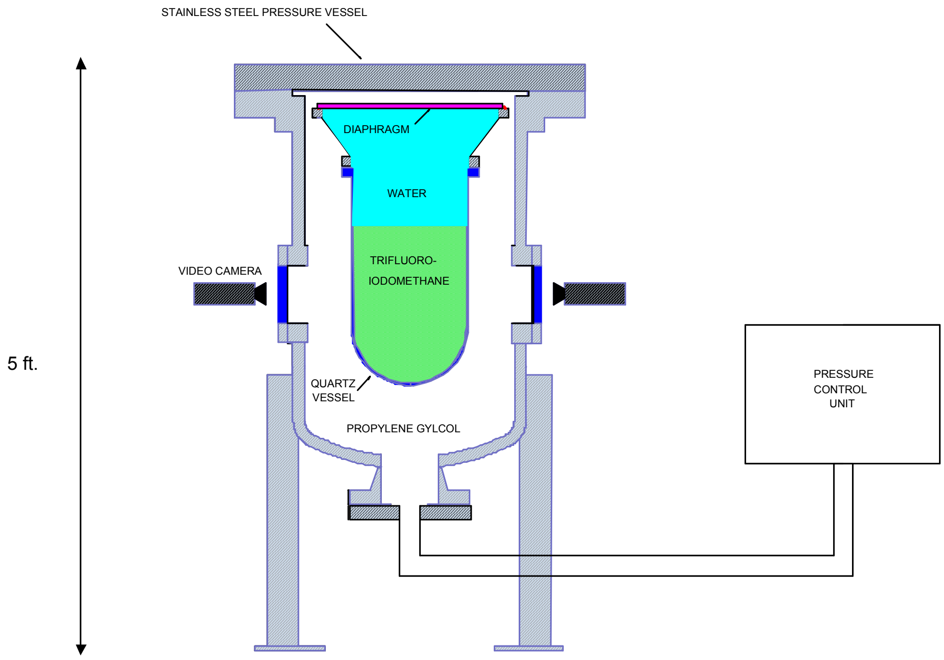


Figure 4.2: Conceptual design for the 60-kg bubble chamber showing the inner quartz vessel, the pressure balancing diaphragm, the outer pressure vessel, and the external cameras and hydraulic control unit.

5.0 Recent Progress on Bubble Chamber R&D

Our first clear technical demonstration of the stable bubble chamber technology was accomplished with the 12-ml "test-tube" chamber (Figure 2.1) filled with CF_3Br. With this device, which was operated in the period 2002-2003 at the University of Chicago, we were able to demonstrate sensitivity to neutron-induced nuclear recoils and threshold behavior that was both consistent with theoretical expectations and very promising for dark matter searches[5]. We were also able to demonstrate excellent immunity to electron recoils

The next step was the development of a 2-kg device, with a design similar to the larger chamber shown in Figure 4.2. It was built and commissioned at the University of Chicago and installed 300 feet underground in the NUMI tunnel at Fermilab in March, 2005. This

[5] W.J. Bolte et al, astro-ph/0503398

device 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. It 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 constriction materials, most materials do not require any special screening process or assembly in clean room conditions. Therefore, we were free to construct almost the entire apparatus using commercially available components and industry standard materials and construction techniques. This allowed us to bring the detector on-line very quickly and at low cost. The 2-kg detector was designed, built and commissioned in 14 months with an M&S cost approximately $40 k.

There are several components in these designs that will ultimately require extraordinary care in selection of materials and assembly: the inner quartz vessel, its metal support flanges, the diaphragm or bellows and associated tubing and instruments that are in direct contact with the superheated liquid or water blanket. These parts must have very low rates of alpha radioactivity, which would otherwise produce bubbles that are difficult to distinguish from those that would be made by dark matter interactions. Of particular concern is the possibility that alpha-active isotopes, such as ^{222}Rn (radon) or its daughters will be released from the surfaces into the liquids. Another issue is the intrinsic level of bulk contamination of the water and target liquid by alpha emitters. A more detailed discussion of these background issues is contained in Appendix II.

For the initial runs with the 2-kg chamber, only a modest effort was made in material selection and clean assembly for the inner vessel components. This allowed rapid commissioning and testing of all mechanical and control aspects of the system at the cost of moderately high backgrounds from alpha activity in the target liquid. We took advantage of the testing period to fabricate a second inner vessel assembly with much greater attention paid to material selection and clean assembly. The new inner vessel is scheduled to be installed in Fall 2006.

This testing of the 2-kg bubble chamber at the Fermilab NuMi site was done as T-945 in the framework of Fermilab's test beam program. The goals we accomplished included:

1) The successful development of data acquisition, controls, and triggering hardware and software. We are now able to operate the device remotely with >75% livetime.

2) Development of off-line image processing software for bubble detection and measurement.

3) Detailed studies of gamma, neutron, and radon backgrounds.

A summary of results obtained with the 2-kg chamber is included as Appendix I.

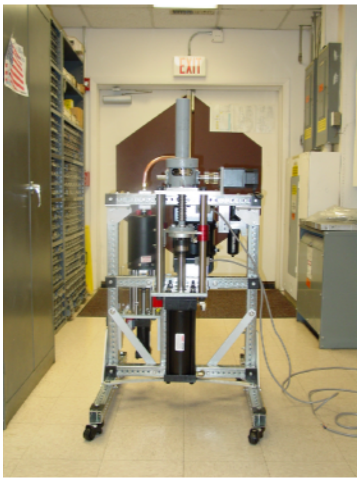
Other R&D work we have completed in the past year includes:

1) The exploration of a simple, very inexpensive chamber design that uses a flanged pipe as a pressure vessel. This device is instrumented with encapsulated cameras and acoustic sensors, all inside the pressure vessel. If this design is successful, large target masses could be achieved by mass production of small modules.

2) The development of a number of specialized small chambers which have been used in studies of the physics of bubble nucleation and determination of threshold properties with radioisotope neutron sources.

3) The construction of a second 2-kg chamber designed for calibration studies. This device will be used in the Fermilab test beam. We plan to study the response of the bubble chamber to nuclear recoils induced by the elastic scattering of high energy charged pions. This test will allow us to precisely measure the efficiency for bubble formation due to iodine recoils near our desired 10 keV trigger threshold.

4) The development of a more advanced pressure control system shown below. This unit will permit very rapid, precise pressure control for large chambers.



5) The further development of neutron simulations based on the MCNP and GEANT4 Monte Carlo packages. These have been used to help to understand the backgrounds in the existing 2-kg detector and design shielding configurations for future detectors.

6) Testing of higher performance cameras, better light sources and optics appropriate for a 60-kg chamber.

7) Development of techniques to measure radon emanation.

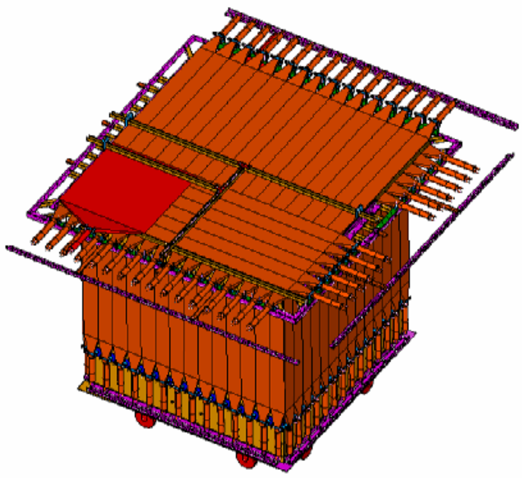
6.0 2007 Goals for the T-945 Test Beam Program

In the coming year we expect to continue our research and development activities. Our R&D goals are:

1) We expect that by early fall 2006, we will have completed all of our work with Run I with the 2-kg chamber in the MINOS area. This will include measurements of gamma and neutron response for a range of operating temperatures and pressures, and extensive studies of radon events.

2) We plan to rebuild the 2-kg chamber in order to test new inner components with reduced radioactive contamination. Specifically we will
   a. Use a new quartz inner vessel which has been fabricated with a special etching technique and kept in a radon free container to minimize implantation of radon daughters.
   b. Use a new bellows, fabricated with non-thoriated welding.
   c. Use metal seals to replace the viton rubber o-rings.

3) We plan to commission and test a new cosmic ray veto shield that was completed last year as an addendum to T-945. This veto system illustrated below has already been installed in the MINOS area downstream of the original COUPP installation. The new location is in a wider part of the tunnel and was selected to minimize any interference with MINERνA installation activities.



4) We plan to decommission the original COUPP installation, and commission a second run with the improved 1-liter chamber in the new MINOS location under the cosmic ray veto. We expect to see significant reduction of our radon background. We plan to repeat the gamma and neutron calibrations, to study cosmic neutron backgrounds, and to attain significant physics reach for spin-

dependent couplings. We expect that the preparation and commissioning activities for Run II of the 2-kg chamber will be completed by the end of calendar 2006, and that data taking will continue for several months.

5) We plan to complete upgrades to the tracking chambers which instrument the Fermilab test beam. These modifications are necessary to allow for measurement of scattering angles which determine the nuclear recoil energy.

6) We plan to commission our calibration chamber and operate it in the test beam in 2007.

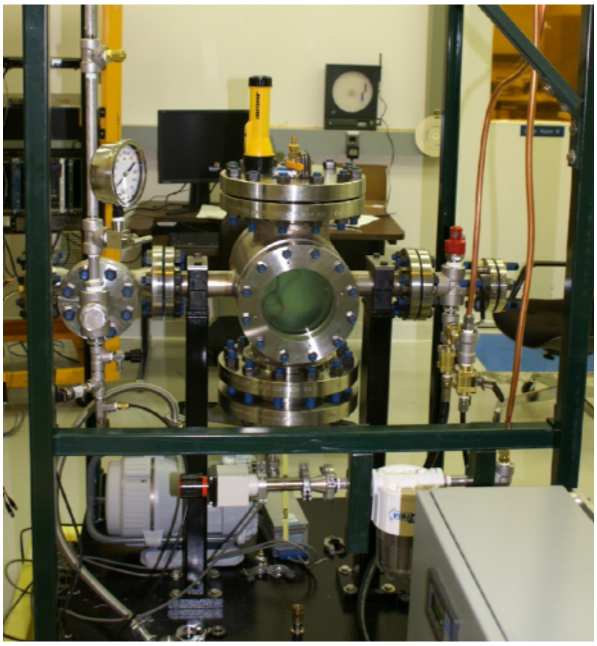


Figure 6.1 The 2-kg calibration chamber which will be used for an elastic scattering experiment in the meson test beam to determine the chamber response to Iodine recoils near the 10 keV threshold.

7.0 THE SCOPE OF THIS PROPOSAL

The ultimate goal of the COUPP collaboration is to mount a one ton scale dark matter search experiment based on continuously sensitive bubble chamber technology. Here we ask for a staged approval to proceed with the development of a 60 kg search experiment. We propose an initial stage which would include the construction of a 60 kg prototype bubble chamber at Fermilab and the commissioning and testing of this bubble chamber in our already established infrastructure in the tunnel upstream from the MINOS apparatus. The initial phase would also include the engineering and design support necessary to develop a detailed proposal for a deep underground site. If successful in our efforts with the 60 kg device in the MINOS tunnel, we would seek approval to proceed with the construction of an appropriate deep underground site for the operation of the 60 kg chamber.

The timing of this proposal is dictated by the evolution of our work with the 2-kg CF_3I chamber. We are currently operating this device with a greater than 75% duty factor and a background count rate from known sources of roughly 10 events per kg per day. The R&D efforts outlined in the previous section will lead us to a 2-kilogram CF_3I experiment operating in the MINOS area with well understood (and controlled) backgrounds and a muon veto sometime early in 2007. We expect that our background count rates in that experiment will be no greater than 0.1 to 1 event per kg per day. This count rate will represent new physics reach for spin-dependent WIMP-nucleon couplings and competitive physics reach for spin-independent couplings. We will also enter a regime in which we cannot count our background rates in a reasonable time. Now is clearly the time to begin construction of our next, larger chamber so that it will be ready for commissioning when we have exhausted the capability of our 2-kg experiment.

Our choice of a 30-liter (60 kg) device is influenced by a handful of practical considerations such as the capacity of our existing shielding array and muon veto, the available sizes of standard commercial flanges, and the guidance of our quartz vendor about the maximum comfortable size for vessel fabrication. In short, we have chosen a size that we know we can build without special engineering considerations. We plan to commission this chamber in the MINOS site, and to understand any mechanical engineering issues that may arise with a larger device. And of course we will advance to the next level of understanding of our background rates. Based on our background estimates, we feel that a sensitivity of ~.03 events/kg-day is attainable in the MINOS site.

When we are no longer limited by internal contamination in the 60 kg chamber, we will have a device with significant new physics reach for all WIMP-Nucleon couplings. To fully realize the physics potential of a 60 kg experiment we will need a deeper site and a thicker shielding array to avoid backgrounds from cosmic ray and environmental neutrons. We are not at this stage committed to a specific deep underground site. The Soudan Mine would be sufficient, as would SNOLAB. The infrastructure we require for a deep underground experiment at the 60 kg (or for the 1000 kg experiment) is neither complicated nor expensive. In the deep underground experiment, we imagine that the 60 kg bubble chamber is equipped with water-tight camera housings and electrical connections, and that for shielding we would simply immerse the entire apparatus in a large water tank, perhaps 2 meters in diameter and 3 meters tall. The water tank would also provide a robust thermal bath for temperature control. It would also be instrumented with photomultiplier tubes to provide a muon veto based on Cerenkov radiation. Our ability to use a water-only shield is due to the special ability of the bubble chamber to reject electron recoils so that no high-Z component is required in the shielding. Some provision would be necessary for handling the vessel in and out of the water tank, and for working on the vessel in a clean area. One simple possibility is a platform above the water tank equipped with an appropriate hoist, and perhaps enclosed in a soft-walled clean room. An artists concept of such an installation is shown below as Figure 7.1.

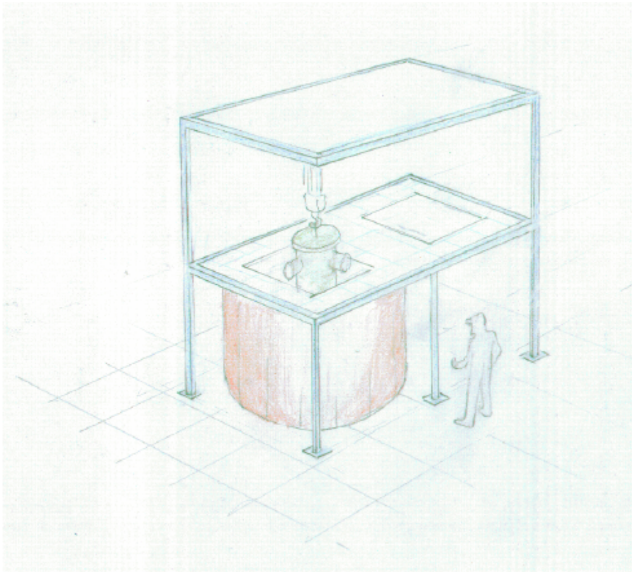


Figure 7.1: Artists rendition of a deep underground installation for a 60 kg device showing a utility platform for handling the bubble chamber above a 2-3 meter diameter 3 meter tall water shield.

The specific goals and specific resources that we request from Fermilab in Stage I of our proposal include:

1) Completion of a 60-kg mechanical prototype device which would be commissioned and tested in the MINOS site. This will require some dedicated mechanical engineering, design, drafting, and technician support.

2) Upgrade and improvement of our data acquisition and controls systems. This will require dedicated engineering and technician support from the Computing and Particle Physics Divisions.

3) A commissioning/physics data run in the MINOS site with the 30-liter device.

4) Engineering and design for the shielding and infrastructure appropriate for a 60 kg experiment in a deep underground site.

5) Preparation of necessary agreements or memoranda of understanding for the future work in a deep underground site.

Upon successful completion of our work with a 60-kg device in the MINOS site we would seek Stage II approval to proceed with

1) Site preparation work in a deep underground site.

2) Fabrication/procurement of the shielding array for the deep underground site.

3) Refurbishing the 60 kg device or the construction of an improved 60-kg device based on our experiences.

4) Commissioning of a physics run of the 60 kg experiment in the deep underground site.

An estimate of the resources required from Fermilab for Stage I (FY07 and FY08) of our 60 kg proposal is tabulated below.

2 year timeline to deployment of 60kg detector

Institution	Year	*FY06*	FY07	FY08	totals
Fermilab	M&S R&D ($k)	*250*	250		500
Fermilab	M&S ($k)			250	250
Fermilab	Mechanical Engineer	*0.25*	1	1	2.25
Fermilab	Designer/Drafter	*0.5*	1	1	2.5
Fermilab	Mechanical Technician	*2*	3	3	8
Fermilab	Electrical Engineer		0.25	0.25	0.5
Fermilab	Electrical Technician		0.5	0.5	1
Fermilab	Computing Professional		0.5	0.5	1
Fermilab	DAQ Professional		0.5	0.5	1
Fermilab	total FTE's	*2.75*	6.75	6.75	16.25

There will be additional NSF funding requests in support of the COUPP efforts at KICP and IUSB. These requests will also be or order \$250k/year over the next 3 years. In the case of the NSF proposal approximately 50% of the request will be for personnel (1 postdoc and 1 grad student at UC, 1 engineer at IUSB), the rest for chamber construction costs.

APPENDIX I: Analysis and Results from T-945

T-945 is a Fermilab experiment to operate a prototype 2-kg bubble chamber 300 feet underground in the MINOS near detector hall. The chamber was initially commissioned in a shallow underground site at the Kavli Institute for Cosmological Physics (KICP) at the University of Chicago and was then transported to Fermilab in February 2005 for testing in the low background environment. Preliminary runs in 2005 led to a better understanding of purification, filling, and operational procedures. A very successful fill of the chamber was completed December 2005 which began a data run which is still in progress. The goals of this run have been to establish stable long-term operation and to characterize the response of the chamber to internal radiation sources, mainly α decays from the U and Th decay chains, and to externally applied γ and neutron sources.

The chamber system consists of 2-kg (1-liter) of CF_3I liquid in a quartz vessel with a "lid" of pure water sealed by viton o-rings to a metal bellows. This sealed vessel is contained in a stainless steel pressure vessel filled with propylene glycol as a hydraulic fluid. The pressure vessel has two camera ports viewing the quartz vessel and is surrounded on 5 sides by 30cm of polyethylene neutron shielding. There is an external hydraulic compression system (an air to glycol piston), a regulation system to keep the glycol at a constant temperature, and a computer to control the cameras and chamber. Figure I-1 shows the pressure vessel assembly. Figure I-2 shows the insertion of the inner quartz vessel and bellows assembly, and the stacking of the polyethylene shielding.

The chamber is operated autonomously under computer control. In its "off" state, the vessel is compressed to a pressure around 180 psig, well above the boiling pressure for CF_3I for anywhere near room temperature. From its compressed, de-sensitized state at 180 psig, a cycle begins with the actuation of a solenoid valve to release the hydraulic pressure and allow the CF_3I to expand to a sensitive (superheated) state. The expansion rate is regulated by a needle valve and is typically a few seconds. The formation of a bubble is detected either by a pressure sensor or by an analysis of the streaming images from our video cameras. Upon event (bubble) detection, the chamber rapidly recompressed, and the event information is recorded. Event information includes a sequence of ten digital pictures from each camera, along with timing, pressure, and temperature information. The chamber is kept compressed for typically 30 seconds prior to the initiation of a new cycle.

The offline analysis for each trigger in each camera is a simple code to find the first recorded image with a candidate bubble(s) and to reconstruct all bubbles in the image. Figure I-3 shows the image data from a typical single bubble event. The frames in which the bubble first appeared have been identified, and the pixel coordinates of the bubbles have been determined and noted on the images by the red and green marks. The CF_3I water interface is clear and parts of the mechanical connection to the bellow assembly can be seen. The wire is for a temperature sensor at the bottom of the vessel.

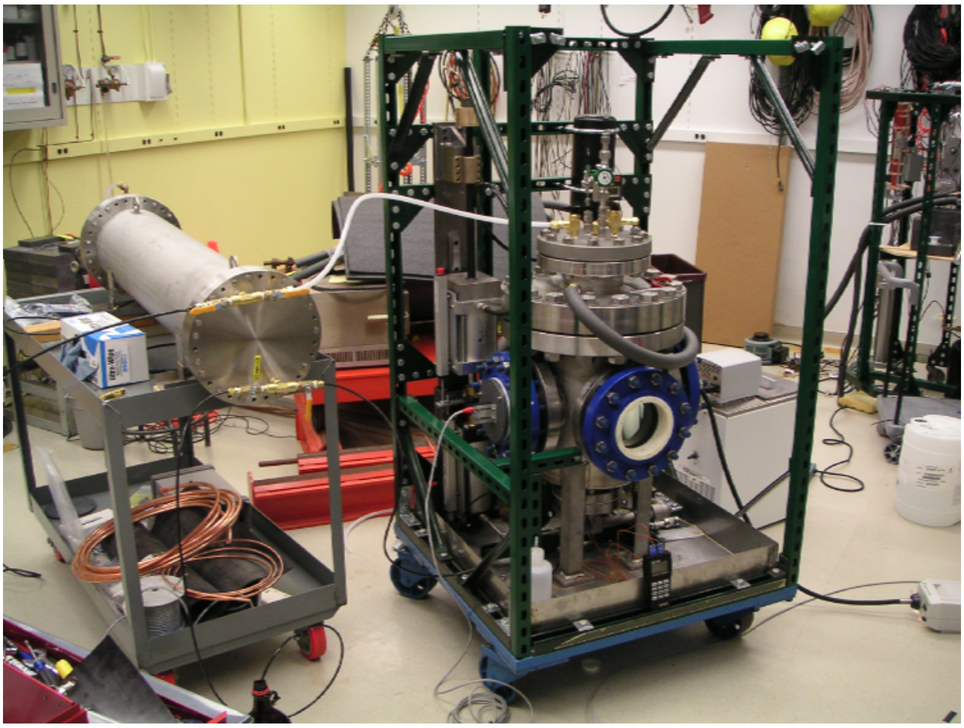


Figure I-1: The 1-liter bubble chamber in a glycol filling operation during commissioning at the University of Chicago.

Figure I-2: The insertion of the inner vessel/bellows assembly into the pressure vessel in the MINOS area at Fermilab (left), and the complete apparatus partially enclosed during the stacking of the polyethylene neutron shielding.

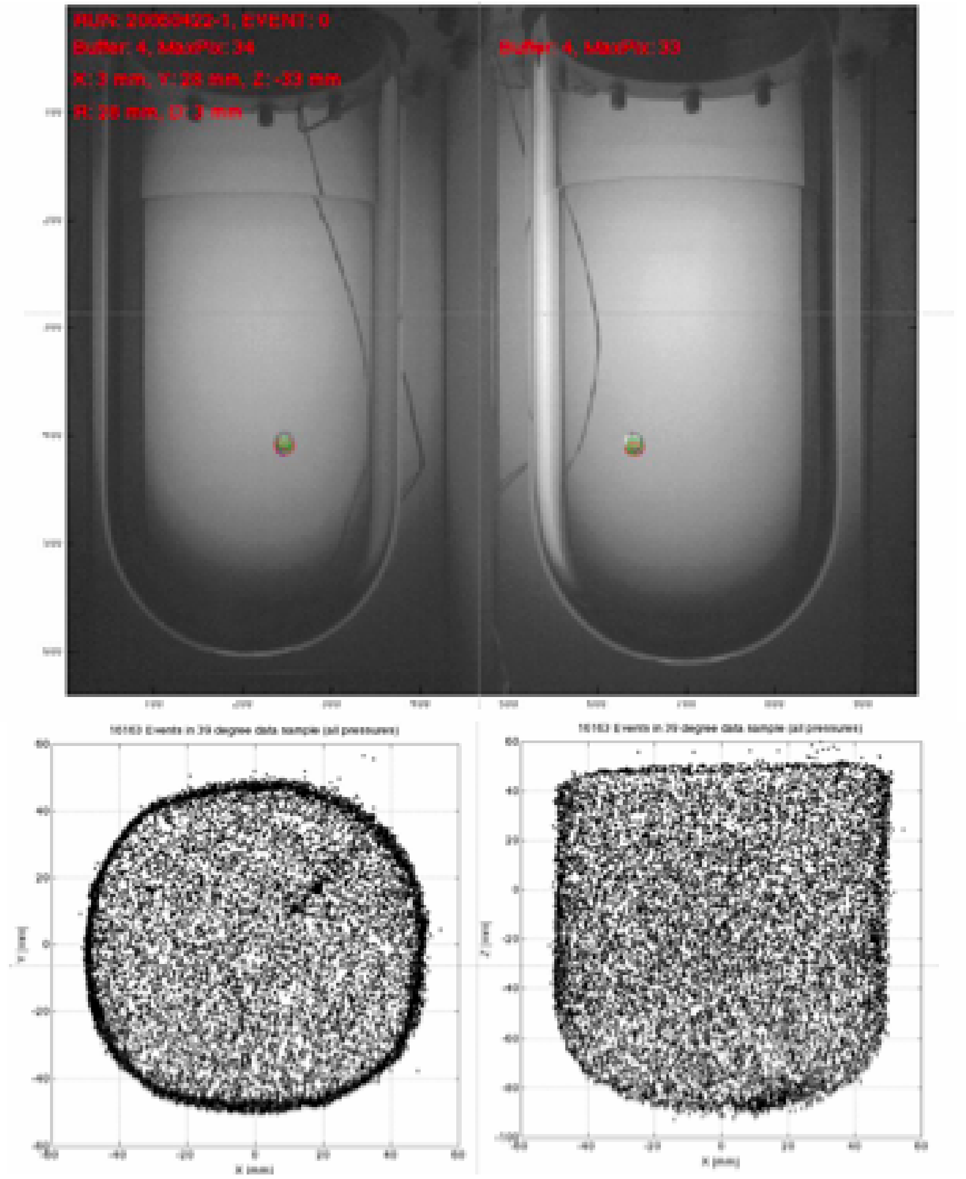


Figure I-3 – Typical Single bubble event Photographed in stereo with reconstructed bubble positions in plan and side views.

The scatter plots below the photographs in Figure I-3 are the centers of all bubbles reconstructed from the two stereo camera views for most of the data taken. In Figure I-4 we have plotted Z vs. R^2 for each bubble and divided all triggers into classes. Bulk bubble events (blue), have a single bubble found away from any boundaries. Wall events (red), have a single bubble on the wall of the quartz vessel (these are clearly seen in the plan view scatter plot in Figure I-3). Surface events (magenta), have a bubble on the interface between the CF_3I and the water. A fourth event class is those triggers with more that one bubble found.

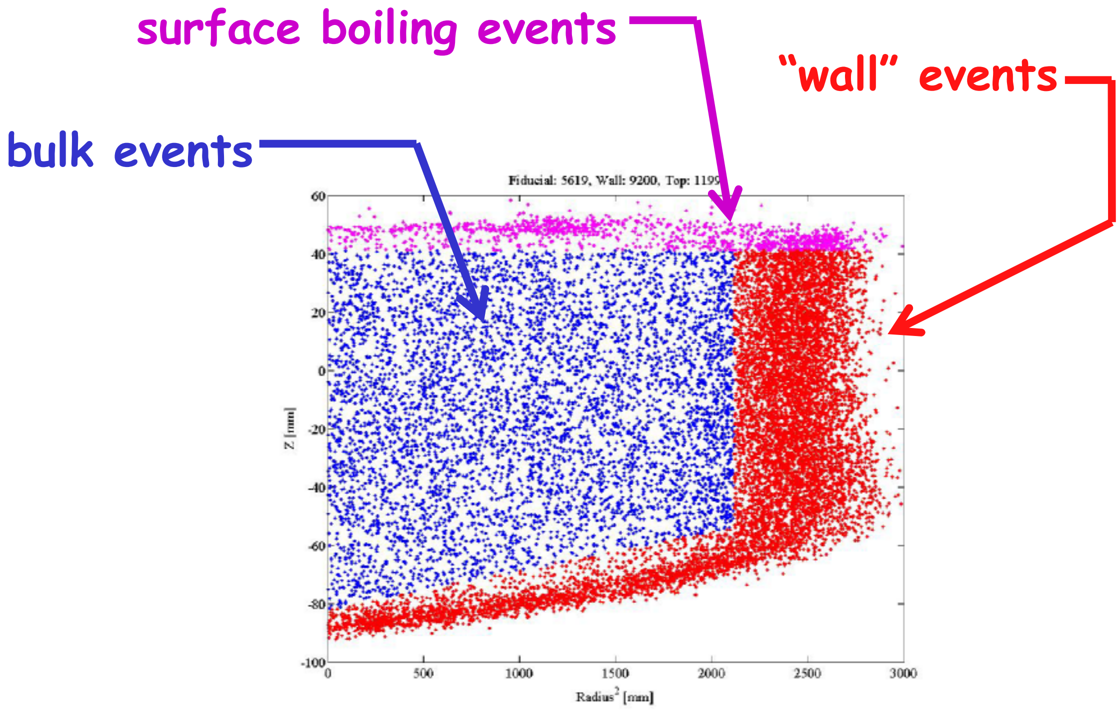


Figure I-4 – Reconstructed bubble positions plotted as R^2 vs Z. Bulk, Wall, and Surface samples are shown. In this preliminary analysis, there has been only an approximate correction for the optical distortions in the camera reconstruction. The deviations from a perfect circle visible in the left scatter-plot of figure I-3 translate into a broadening of the "wall-event" band on this plot.

Our principal tool for analyzing the recoil energy spectrum of our events is the pressure scan. Operating in the *weakly-superheated* mode, the bubble chamber behaves like a threshold calorimeter for nuclear recoils. All of the kinetic energy of a recoiling nucleus will be applied to the formation of a single bubble, and the bubble nucleation threshold is determined by the temperature and pressure of the fluid. By scanning the operating pressure and recording the event rate as a function of pressure, we are able to measure a distribution which corresponds to the integral of the recoil energy distribution. For a monochromatic source of internal nuclear recoils, as in the case of α-recoils, we would see a step function pressure scan with the step occurring at the pressure corresponding to the recoil energy. Although Radon decays will ultimately be a source of background, they provide an excellent calibration in our test chamber.

Figure I-5 shows the result of a pressure scan which identifies the principal component of the bulk single bubble events to arise from α-decays in the CF_3I. The most likely culprits are elements of the radium decay chain ^{222}Rn-> ^{218}Po, ^{218}Po -> ^{214}Pb, and ^{214}Po -> ^{210}Pb. In addition to the sharp turn on at 100 keV, we have also observed evidence for the 3.8 day half-life of ^{222}Rn, and of the 3.1 minute half-life of ^{218}Po. The most likely source for the bulk radon decays is the intrinsic radium concentration in the Viton rubber o-rings.

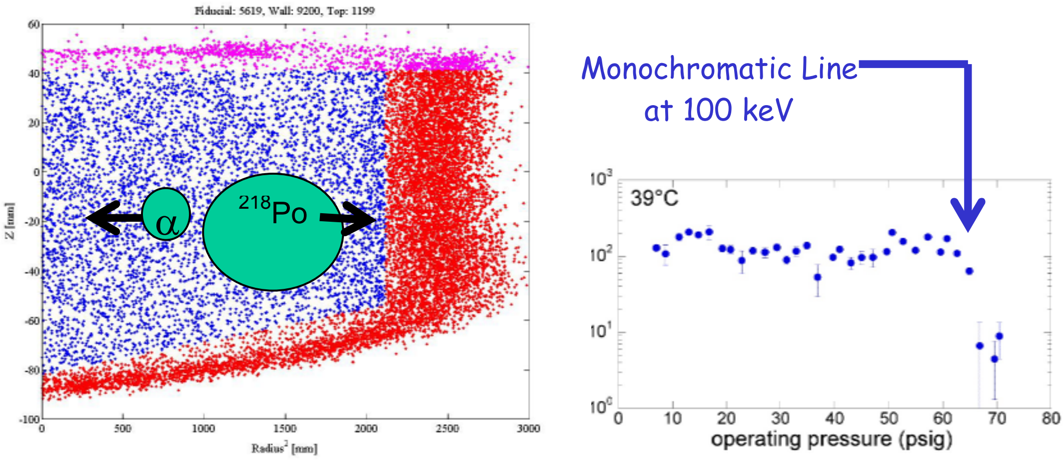


Figure I-5 Pressure scan for bubble events in the bulk. Bulk bubble events are consistent with α-decays of ^{222}Rd -> ^{218}Po + α in solution in the CF_3I.

The pressure scan for wall events reveals a distinctly different structure, consistent with the predicted chamber response to α-particles. These events are consistent with the α-decays of radon daughters which are implanted in the walls of the quartz vessel.

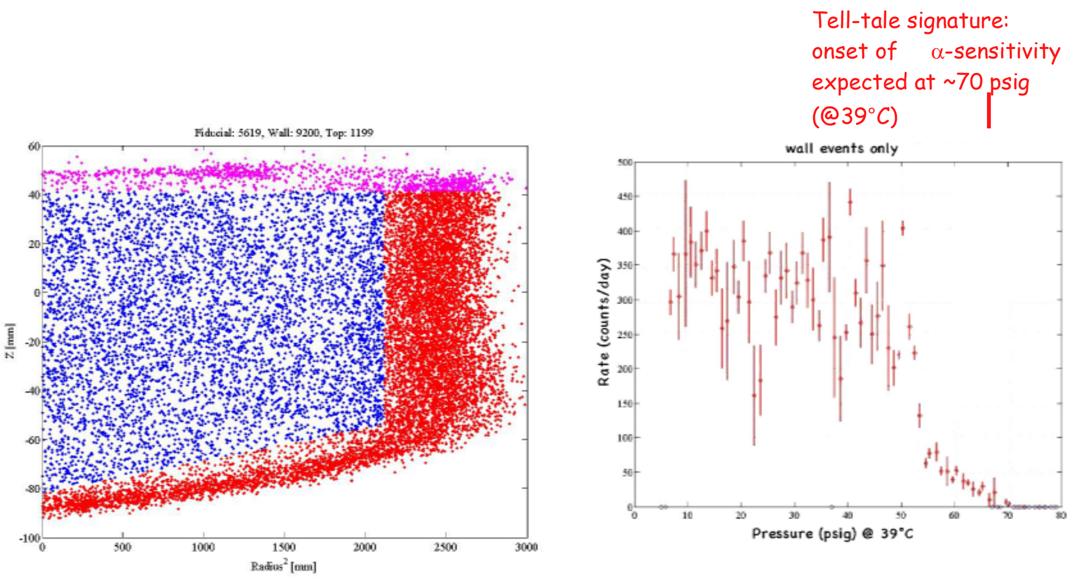


Figure I-6 Pressure scan for wall events. Wall events are consistent with the emission of α-particles from the decays of radon daughter nuclei that have been implanted in the walls of the quartz vessel.

Source Calibrations:

Additional information about the response of the chamber to nuclear recoils has been obtained using a novel source developed for this purpose. The source, which is shown in Figure I-7 is a Switch-able AMericium BEryllium or SAMBE source made using an array of americium sources from smoke detectors mounted on a rotating shutter which can be brought into close proximity to a Be foil to generate neutrons. The ability to turn the source on and off is valuable for obtaining a clean neutron scattering sample in the presence of a non-trivial baseline of events from radon decay. Figure I-8 shows the comparison of a neutron data sample obtained in this way with a simulation.

Our second important source calibration result is the response to photons. Figure I-8 shows the installation of a 13 mCi ^{137}Cs source directly on the side of our pressure vessel. A pressure scan obtained in this configuration shows our dramatic *insensitivity* to the >MHz interaction rate of photons in the active fluid. The gamma rejection curve displayed on the right in Figure I-9 shows that we will be able to operate the chamber with very little consideration for any γ or β related backgrounds. Figure I-10 shows the comparison of the pressure curves with and without the ^{137}Cs source. This figure provides a very elegant demonstration of our first crucial detector development milestone. The dark matter search region indicated on the plot has immunity to γ interactions with a rejection factor greater than 10^9, and demonstrated efficiency for nuclear recoils in the important 10-100keV range.

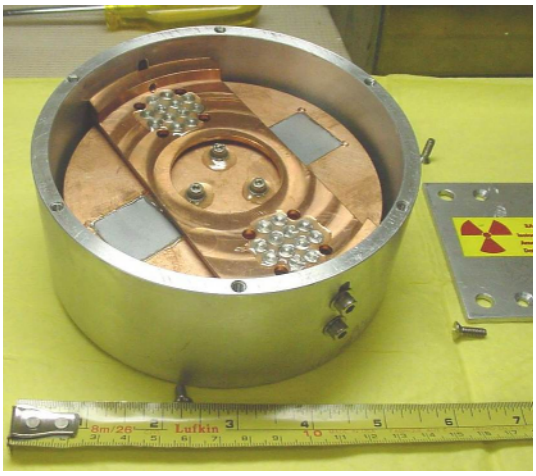


Figure I-7: A Switch-able AMericium BEryllium or SAMBE source constructed for bubble chamber calibration. Visible are the individual americium sources and the beryllium foils. The source is in the OFF position. When the shutter is rotated roughly 90° the americium sources are brought into close proximity to the Be foils and neutrons are generated via the (α,n) reaction with Be.

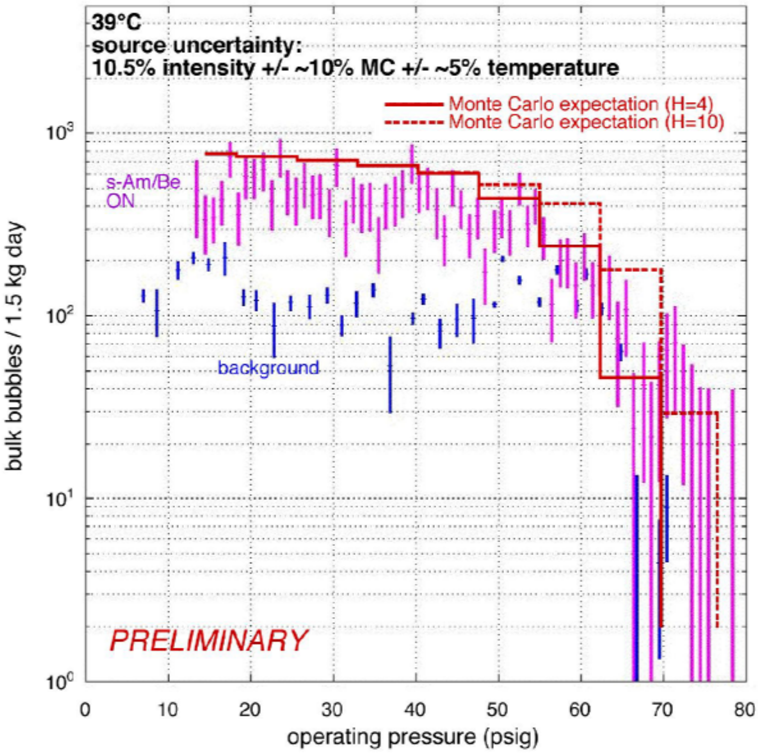


Figure I-8: Comparison of neutron calibration results to a simulation.

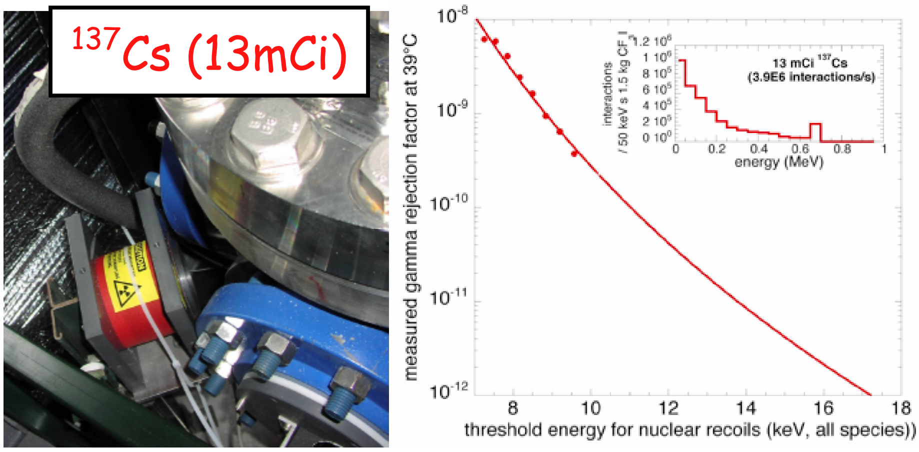


Figure I-9: The 137Cs source mounted on the side of the chamber (left) and the resulting g efficiency curve as a function of calculated nuclear recoil energy threshold.

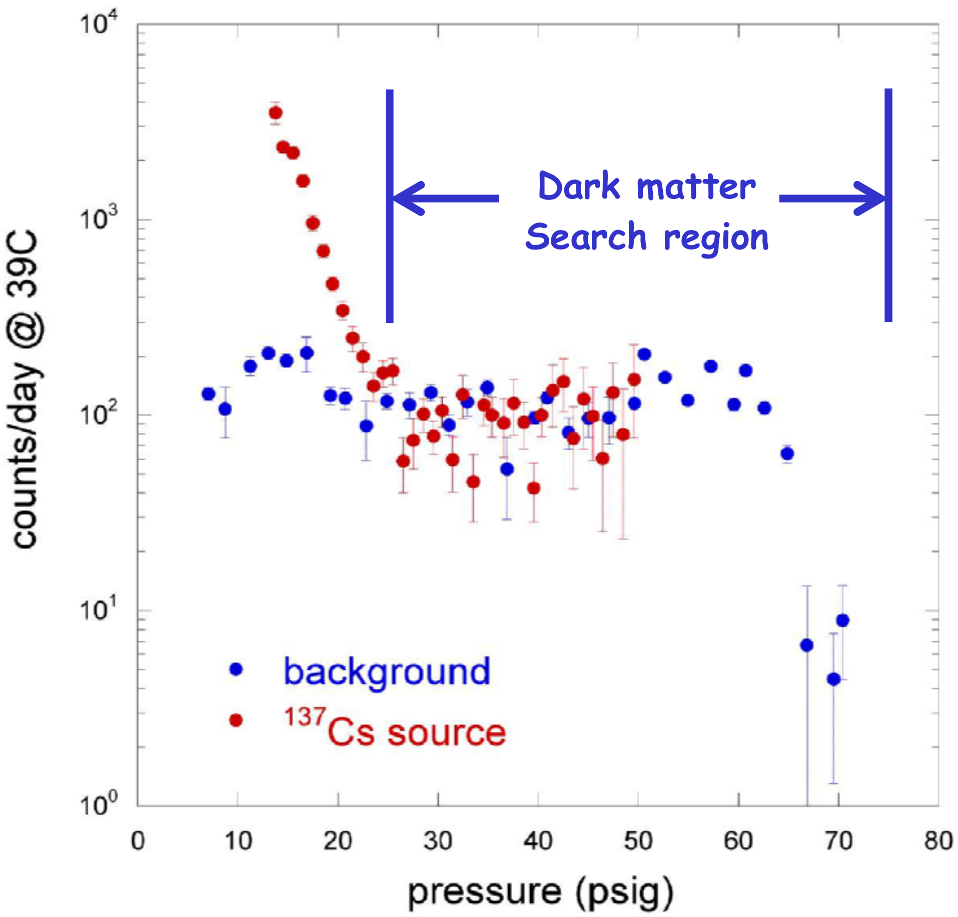


Figure I-10: Pressure scan comparing bubble chamber response to an internal α-recoil source and external γ source. The comparison illustrates efficiency over a 10-100 keV dark matter search region.

Appendix II: Expected 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.

(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 which loses energy primarily by ionization. These events are indistinguishable from events resulting from β-decays internal to the chamber. In spite of the large natural abundance, this class of events presents no significant background problem for our dark matter search because of the very high degree of rejection 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.[6] This prediction was verified in early bubble chamber experiments[7] and in experiments with superheated droplets[8]. We have directly measured the probability of bubble nucleation from 662 keV gamma rays from ^{137}Cs in our 2-kg chamber and find that it is $\sim 2\times10^{-10}$ under conditions of temperature and pressure where the nuclear recoil threshold is calculated to be 10 keV.

This extraordinary level of rejection means that even an *unshielded* detector, confronting a typical external gamma and beta rate of $\sim 10^7$/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.

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.

Clearly, 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.

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[6] F. Seitz, The Physics of Fluids, Volume 1, Number 1 (2-13) 1958
[7] 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
[8] 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

(2) Neutrons.

Elastic scattering by neutrons produces nuclear recoil events which 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.[9] The sources of neutron backgrounds 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 which arise from local radioactivity. 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 characteristic of a larger detector.

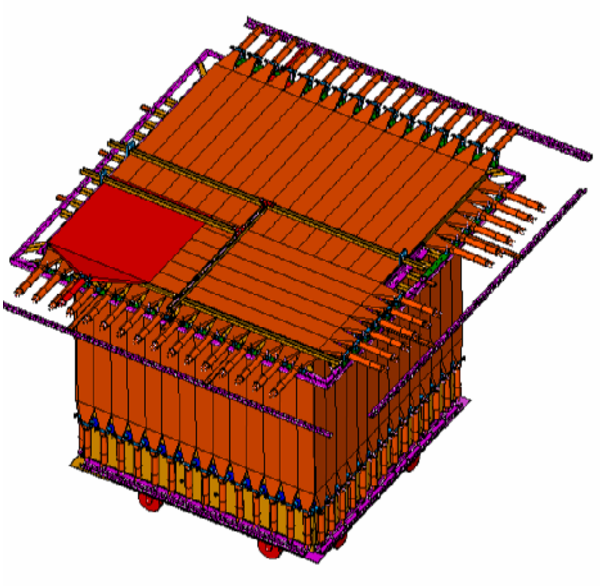
Neutron fluxes depend strongly on the depth of earth overburden protecting the experiment. On the Earth's surface, the dominant neutron flux comes from cosmic ray interactions in the atmosphere. At underground depths greater than 10 meters water equivalent (MWE), the atmospheric neutrons have been attenuated, and the remaining rate is typically dominated by cosmic ray muon interactions in materials near the detector. At depths greater than 100 MWE, the cosmic ray muon flux has itself been attenuated, and the remaining neutron flux begins to be dominated by natural radioactivity from two sources. One source is spontaneous fission. The other source is a two-step process beginning with the α-decays of U and Th daughters in materials near the detector. The range of α-particles is extremely small, but some of them will produce neutrons via (α, n) reactions. 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.

It is challenging to operate a dark matter experiment at a moderate depth underground, as in the case of our 300 MWE NUMI site. At that depth there is still a non-trivial component of high-energy cosmic ray muons which will produce relatively high energy (~100 MeV) neutrons for which shielding is not very effective. Monte-Carlo studies predict that our dominant source of this background will be muon interactions in the 900 kg steel pressure vessel, resulting in ~2 neutron events per kg-day. We have constructed a muon veto array using scintillator paddles salvaged from the KTeV experiment. The double-walled veto array is illustrated in Figure II-1a. This array is currently being tested and has an expected total efficiency of >95% which will reduce the neutron background in the 2-kg chamber to less than 0.1 events per kg-day. Cosmic ray muons are not expected to present a serious problem at very deep underground sites.

The 2-kg bubble chamber is also surrounded by 12 inch of polyethylene neutron moderator as illustrated in Figure II-1b. The external neutron moderator, together with

[9] 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

the additional moderation from 4 inches of propylene glycol hydraulic fluid inside the chamber, provides 3 orders of magnitude attenuation for neutrons due to external radioactivity. Simulations based on a typical rock neutron spectrum indicate that the resulting bubble rate from neutrons penetrating the shield will be ~0.015/ per kg-day.



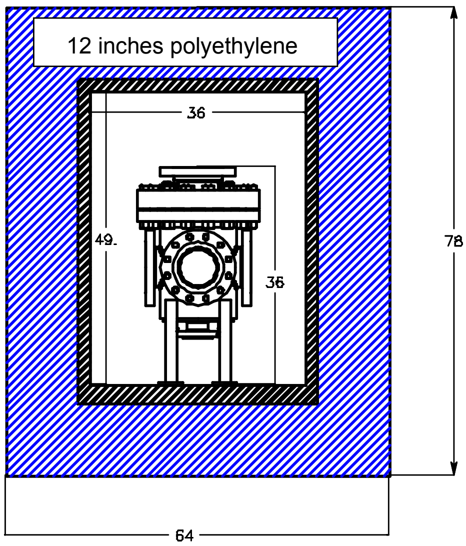


Figure II-1: (a) Muon veto array for 2-kg bubble chamber. The design uses ~150 counters arranged into a double-walled box, which will surround the bubble chamber and polyethylene (b) The 2-kg bubble chamber inside the polyethylene neutron moderator.

For larger detectors operating in a deep underground site, the neutron production rate by radioactivity of the detector itself may become a concern. Table I shows the result of a detailed study of neutron backgrounds due to internal radioactivity. This analysis indicates that the typical activity level found in the bulk materials used in bubble chamber construction would result in backgrounds <0.001 events/kg-day. Small components not considered in this table, such as pressure vessel windows, instruments and video cameras might have the potential to increase this, so measurements will be required to screen such items.

One surprise from this study was that the intrinsic radioactivity in polyethylene may limit the utility of that material as a neutron moderator for large experiments. A natural alternative for the bubble chamber would be to use high purity water for neutron moderator.

	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)	$1.06x10^{4}$	$1.06x10^{4}$	250	250	75	10
Alphas/day	$1.06x10^{9}$	n.a.	$5x10^{6}$	n.a.	<75	10^{3}
Yield (n/α)	$1.7x10^{-7}$	n.a.	$4x10^{-9}$	n.a.	$1.7x10^{-7}$	$2.5x10^{-7}$
n's / day	180	120	$2x10^{-2}$	0.56	$<1.3x10^{-5}$	$2.5x10^{-4}$
(1) Events /50 kg /day	0.07	0.012	$7.7x10^{-4}$	0.01	$<1.5x10^{-6}$	$9.1x10^{-5}$
(2) Singles /50 kg /day	0.016	$3.1x10^{-3}$	$1.9x10^{-4}$	$2.8x10^{-3}$	$<3.7x10^{-7}$	$2.3x10^{-5}$
(3) Singles in Fiducial Vol. /50 kg/day	$3.9x10^{-3}$	$5.2x10^{-4}$	$3.4x10^{-5}$	$5.0x10^{-4}$	$<7.3x10^{-8}$	$3.5x10^{-6}$
(4) Irreducible rate /100 kg-yr	8.5	1.2	0.075	1.1	$<1.6x10^{-4}$	$7.7x10^{-3}$

Table I: Expected neutron backgrounds due to internal radioactivity. This table shows the results of a Monte- Carlo simulation of an array of 5 x 50 kg 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 (16.6 kg) of each of the five detector volumes, 4) the resulting rate in events/100 kg-year 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 50 kg chambers simulated in Table I, 76% of neutron events have multiple bubbles. The presence of these events will allow us to measure and subtract any residual neutron background. In very large chambers, the short mean free path will cause events to be preferentially biased toward the walls. This will provide a second independent tool for measuring the neutron background.

(3) Alpha contamination

Nuclear recoils due to the α-decay of radioactive atoms within our apparatus or in solution in our target fluid present a source of background that is a unique problem for the bubble chamber technique. For example, ^{222}Rn (radon) decays by emission of a 5.5 MeV alpha particle into ^{218}Po which recoils with 101 keV of kinetic energy, well above our 10 keV trigger threshold. α-decay backgrounds can be identified and subtracted by comparing data at two operating pressures, but to take full advantage of the physics reach it will be necessary to control the contamination of α-emitters in the bubble chamber.

Trace levels of alpha emitting radioisotopes are ubiquitously present in the environment. Previous dark matter other low-radioactivity experiments have concerned themselves only with the alpha emitters in the primary ^{238}U and ^{232}Th decay chains and particularly with the part of the ^{238}U chain lying below ^{222}Rn. This is because radon is a noble gas and is highly mobile in the environment. Long-lived radon daughters ^{210}Pb and ^{210}Po are continuously plated out on any exposed materials which will then themselves become sources of alpha particle emission. The radium isotopes ^{224}Ra and especially ^{226}Ra are also of special concern, because they are leached from the ground by water and may be incorporated into manufactured materials which in turn become sources of radon emanation.

Radon daughters implanted on the quartz wall of the bubble chamber will cause bubbles if the alpha particles are emitted into the chamber liquid. We have observed this type of contamination in our 2-kg chamber which exhibits a wall-bubble rate of 1/cm^2-day, compatible with the known history of its exposure to room air. Bubbles produced by this mechanism are not a background for the experiment because they occur on the vessel walls, outside of the fiducial volume of the experiment. This class of events does cause dead time and leads to a limitation on the size of chamber that can be constructed, depending on the attainable degree of surface cleanliness. We estimate that simple procedures to control radon exposure and etching of the quartz surface will improve our newer vessels by a factor of at least 30 compared to the prototype chamber. This will be adequate for operation of our 60-kg device.

Our most important background concern is from α-emitters in solution in our target fluid. We do not have *a priori* estimates or measurements of the radiopurity of CF_3I. Our best information comes from our 2-kg prototype chamber, and it may always be the case that our detector is the best measure of its own α-emitter contamination. Conventional instruments for counting alpha decays simply do not have the sensitivity. It *is* possible to measure the parent contamination of ^{238}U and ^{232}Th and we have initiated a collaboration with Argonne National Laboratory to make these measurements with Accelerator Mass Spectroscopy. We hope with this method to achieve sensitivity equivalent to ~0.005 events/kg-day.

If we look to other low background experiments for experience with precision radiopurity measurements, we find that measurements at relevant sensitivity levels have been made for only a few liquids. The best examples are measurements of water and of several organic liquid scintillator mixtures by the SNO, Borexino and Kamland solar neutrino collaborations. These measurements are summarized in Table II. While it is arguably dangerous to extrapolate from these data to liquids used in our bubble chambers, we believe that some lessons can be learned. The solar neutrino R&D has resulted in widely applicable purification methods and some special analytical techniques that can be used to produce and screen new materials. In particular, Borexino and Kamland have demonstrated that pseudocumene, dodecane and phenylxylylethane (scintillator components) tend to be naturally very free of U and Th series activities above radon (^{222}Rn in the ^{238}U chain and ^{220}Rn in the ^{232}Th chain) after filtration to remove dust. This has been demonstrated by Neutron Activation Analysis and Inductively Coupled Plasma Mass Spectroscopy (ICPMS) as well as by direct counting. It is believed that the reason for this high level of purity is that the "upper chain" U and Th compounds found in nature have low solubility in oil-like liquids. By the same arguments, CF_3I, which has solvent properties roughly similar to pseudocumene and dodecane, is likely to be naturally clean of isotopes above the radons. On the other hand, radon itself is known to be highly soluble in both water and oils and the ^{222}Rn daughters ^{210}Pb (a beta emitter) and ^{210}Po (an alpha emitter) have been found in Borexino and Kamland scintillator, often at very significant levels. For example, the Kamland collaboration reports a rate of ^{210}Po in their scintillator equivalent to ~4 decays / liter-day[10].

Radon itself can be removed from liquids by nitrogen stripping, used in Borexino for scintillator and water and by vacuum degassing, used in SNO for water. The Borexino R&D program has demonstrated that the daughters of radon can be removed from pseudocumene by a number of purification techniques, including water extraction, distillation and silica gel chromatography. Of these, distillation appears to be the most promising and this is particularly easy to implement for the highly-volatile bubble chamber liquids.[11] Tests of distilled scintillator in the Borexino Counting Test Facility have achieved total alpha counting rates ~ 0.01 decays/L-day.

For the water used in our bubble chambers, the SNO R&D is directly applicable. SNO has produced water that would very likely satisfy our needs down to a level of <0.01 decays/L-day. This level of purity can be achieved with commercially available ion-exchange equipment followed by vacuum degassing to remove radon before it decays to ^{210}Pb. The isotopes ^{232}Th and ^{238}U can be measured at the required sensitivity level (10^{-15} g/g) by ICPMS at several commercial laboratories and the ^{226}Ra content can be checked by trapping on adsorbers followed by counting radon emanation (though only the SNO collaboration currently has the facilities to do this).

Radon emanation by radium contained in internal components of bubble chambers is of concern. The 1-liter chamber at NuMi currently sees 20-150 events/day attributable to radon, with a strong dependence on temperature. This rate is compatible with the emanation expected from two Viton rubber O-rings used to seal the inner vessel, based

[10] N. Tolich, Ph.D. thesis, Stanford University, 2005
[11] M. Leung PhD thesis, Princeton University, 2006

on Borexino Viton measurements[12]. While this is a clearly identifiable and removable source, the fabrication of vessels with radon emanation levels below a few counts per day remains an art. It is encouraging that techniques exist that would allow direct measurement of radon at the level of <1 event/day from an almost arbitrarily large chamber if necessary. At rates below ~1 count per hour, effective use can be made of the delayed decay sequence ^{218}Po->^{214}Pb ($T_{1/2}$= 3.1 minutes) to cut away backgrounds based on time coincidences between bubbles. At rates below ~1 per day, the chain ^{214}Pb->^{214}Bi->^{214}Po->^{210}Pb (sum of $T_{1/2}$=47 minutes) can be similarly exploited. The level of background rejection that can be obtained using these cuts depends on the operating cycle of the chamber (i.e. the dead time following each event), among other factors, but will be >90% under reasonable assumptions.

Table II: Measured Alpha Activity in Liquids Used in Solar Neutrino Experiments.

Isotope	Material	Activity (Counts/L-day)	References and Comments
U-238	Scintillator	<0.008	Kamland (NAA) [c]
	Scintillator	$<10^{-5}$	Borexino (NAA) [b]
	Water	<0.005	TAMA, ICPMS
	Water	~0.01	Borexino, ICPMS [a]
U-235	Scintillator	$<9 \times 10^{-6}$	Borexino, CTF (Rn-Po coincidence) [f]
Th-232	Scintillator	<0.002	Kamland NAA [c]
	Scintillator	$<6 \times 10^{-5}$	Borexino, NAA [b]
	Water	<0.002	TAMA, ICPMS
	Water	~0.01	Borexino, ICPMS [a]
Ra-224	Heavy water	2.8×10^{-4}	SNO, ^{220}Rn emanation from HTiO adsorbent [h]
Ra-226	Heavy water	5.3×10^{-4}	SNO, HTiO [h]
	Water	~0.1	Borexino, nitrogen stripping, proportional counters [a]
Rn-222	Water	0.3-100	Borexino water plant, with nitrogen stripping [a]
	Heavy water	0.009	SNO, in-situ counting of ^{214}Bi [k]
	Heavy water	~0.01-0.001	SNO, vacuum degassing, counting in Lucas cell [g]
	Scintillator	1.2×10^{-4}	Kamland (Bi-Po coincidence) [d]
Rn-220	Scintillator	1.4×10^{-5}	Kamland (Bi-Po coincidence) [d]
	Heavy water	5.6×10^{-4}	SNO, in-situ counting of ^{208}Tl [k]
Po-210	Scintillator	0.31	Borexino-CTF, filtered [f]
	Scintillator	0.13	Borexino-CTF, silica gel purification [f]
	Scintillator	0.02	Borexino-CTF, water extraction [f]
	Scintillator	<0.01	Borexino-CTF, distillation
	Scintillator	3.7	Kamland [e]

[a] C. Arpesella et al., (The Borexino Collaboration) "Measurements of extremely low radioactivity levels in Borexino", hep-ex/0109031, Astropart. Phys. 18, 1-25 (2002).
[b] R. V. Hentig et al., Nulc Phys. B (Proc. Suppl.) 78, 115.
[c] Djurcic et al., Hep-ex 0210038, 2003.
[d] O. Tajima, Ph.D. thesis, Tohoku University, 2003.
[e] N. Tolich, Ph.D. thesis, Stanford University, 2005
[f] K. McCarty PhD thesis, Princeton University, 2006.
[g] I. Blevis et al., Nucl. Instrum. Meth. A, Nucl-ex/0305022.
[h] T.C. Anderson et al., Nucl. Instrum. Meth. A, Nucl-ex/0208015.
[k] V. Rusu, Ph.D. thesis, University of Pennsylvania, 2003.

12 R. V. Hentig et al., Nulc Phys. B (Proc. Suppl.) 78, 115

(4) Estimated backgrounds for the 30- liter chamber at NUMI

Order-of-magnitude background expectations for a 30 liter chamber in the NUMI tunnel are given in Table III below. To estimate the neutron backgrounds, we assume that our muon veto system at NUMI will be upgraded to achieve a level of efficiency such that muon-coincident neutrons (~4/L-day) are not the limiting background. This will allow us to explore alpha background levels approaching the "state of the art" for water purity, as demonstrated by SNO, and CF_3I purity as demonstrated by Borexino and Kamland for similar solvents. At this background level, we will be sensitive to spin-dependent WIMP-nucleon couplings approximately three orders of magnitude lower than the best current limits.

Table III: Estimated backgrounds for 30-Liter chamber in the NuMi tunnel.

	Rate (Counts/L-day)
Gammas and betas	$<10^{-3}$
Neutrons	~0.03
^{222}Rn from water	~0.01
Other alpha activities	<0.01

APPENDIX III: Obvious Questions, with Answers. "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) *Don't the differing responses of the three target nuclei confound your ability to calibrate the threshold? Is there a calibration technique that specifically singles out the iodine recoils?* Yes, having three target nuclei complicates calibration. Our original calibration technique involved using the end point of a neutron spectrum to determine the chamber response. With that technique, we were always dominated by the C and F recoils and did not have sensitivity to the iodine recoils. Using the elastic scattering of 10GeV π^- as a source of tagged nuclear recoils, we expect to obtain a calibration that will specifically isolate the chamber's response to iodine recoils.

5) *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, 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.

6) *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 no need for a high-Z component to the shielding. A water tank is a simple and inexpensive option.