Commissioning the COUPP-60 Bubble Chamber at Fermilab

Juan Collar [spokesman] (PI), C. Eric Dahl, Drew Fustin, Luke Goetzke,
Nathan Riley, Hannes Schimmelpfennig, Matthew Szydagis
Kavli Institute for Cosmological Physics
University of Chicago

Ed Behnke, Henry Hinnefeld, Ilan Levine (PI), Andrea Palenchar,
Tina Marie Shepherd, Brendan Sweeney
Department of Physics
Indiana University South Bend

Stephen Brice, Daniel Broemmelsiek, Peter Cooper, Michael Crisler,
Jeter Hall, Erik Ramberg, Russ Rucinski, Andrew Sonnenschein, Robert Tschirhart
Fermi National Accelerator Laboratory

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ABSTRACT

Bubble chambers are promising devices for the detection of WIMP dark matter, due to their easy scalability to large target masses and, when thermodynamic conditions are optimized, insensitivity to background gamma and beta radiation. The COUPP collaboration has constructed several small chambers, which have achieved competitive sensitivity for spin-dependent WIMP-nucleon scattering. A new chamber, COUPP-60, containing 60-kg of CF3I target liquid has been built. We propose to complete the commissioning of the detector and measure alpha-particle induced backgrounds in the NuMI tunnel at Fermilab. This is an important prerequisite to moving the detector to a deep underground site where sensitivity to WIMPs can be maximized. In the course of the commissioning in the NuMI tunnel, we expect to improve on our current sensitivity to WIMPs by as much as two orders of magnitude.

1. Introduction

COUPP-60, Fermilab E961, is an experiment with the goal of detecting dark matter in the form of Weakly Interacting Massive Particles (WIMPs) by observing the single bubbles produced by recoils of nuclei struck by dark matter particles [1]. The detector is a continuously sensitive bubble chamber, operated at mildly superheated conditions, which is sensitive only to the highly concentrated energy deposition from nuclear recoils. The fluid used is the fluorocarbon CF_3I. The operating temperature is near 40 degrees C, with operating pressures from about 5 psig up to about 90 psig. This range corresponds to an energy threshold for the detection of nuclear recoils from 5 KeV to several hundred keV. At the lowest threshold this detector will be sensitive to most nuclear recoils from WIMPs with masses greater than 10 GeV. At the highest pressure, the threshold is above the range expected for nuclear recoils from WIMPs. The integral spectrum as a function of threshold energy has a specific shape for a given WIMP mass, which can be used to discriminate WIMPs from backgrounds.

The COUPP-60 detector was built in the period 2007-2009 and is now being commissioned. We expect the commissioning phase at Fermilab to continue through mid-2010. To achieve its full potential sensitivity, this detector must be operated at a deep underground site, such as SNOLAB, where backgrounds from cosmic-ray induced neutrons would be negligible. The current proposal, however, concerns only the commissioning phase and no support is requested for moving the detector deep underground.

2. The Bubble Chamber Technique

The COUPP detectors are continuously-live, mildly superheated bubble chambers, which operate below the threshold for sensitivity to minimum ionizing particles. This simple technology appears to offer an attractive route to low background, low-cost dark matter detectors with multi-ton target masses. Since many fluids can be used in bubble chambers, the spin and mass dependence of the dark matter nuclear coupling could be explored by using a variety of target liquids.

Bubble nucleation in a superheated fluid requires a minimum energy input, which can be supplied by a particle interaction. The additional requirement of achieving a critical energy density in order to nucleate bubbles allows for operating modes which discriminate between different particle interactions on the basis of their specific stopping power (dE/dX). Since nuclear recoils deposit their energy in very short length scales (nanometers) as compared to electron recoils (micrometers) of the same energy, an appropriate choice of operating parameters will result in a bubble chamber that is sensitive to nuclear recoils but blind to minimum ionizing particles and γ and β interactions. The collaboration has proven that the intrinsic rejection against γ interactions is larger than 10^{10}, at a nuclear recoil threshold of 10 keV. This is the same background discrimination mechanism which has been used successfully in superheated droplet detectors, such as PICASSO and SIMPLE [2,3].

Although bubble chambers can be made intrinsically insensitive to γ and β interactions while retaining a high efficiency for nuclear recoils, this is not the case with α interactions. Each α decay has an associated recoiling daughter nucleus, with recoil energy ~ 100 keV for α decays in the Uranium and Thorium chain. On an event-by-event basis, these decays produce bubbles which are visually indistinguishable from those produced by WIMP recoils. Two events, correlated in time, are indicative of an α decay chain and can be removed. It is possible to distinguish between a population of multiple α decay events and a population of WIMP events by using energy threshold scanning strategies, but the sensitivity of a WIMP detection experiment is sharply reduced by the need to statistically subtract the background. Therefore, it is important to reduce contamination of the bubble chamber fluids by α emitting isotopes to very low levels. If α contamination can be reduced to the levels that have been achieved in solar neutrino experiments, such as SNO and Borexino [4], it will be possible to improve on our current spin-dependent dark matter sensitivity by four orders of magnitude.

3. The COUPP-60 Detector

One virtue of bubble chamber technology is its mechanical simplicity. The detector consists only of a quartz bell jar, a surrounding stainless steel pressure vessel, a bellows arrangement to equalize pressures, a few seals, and fluids. All of these materials are easy to purify or clean, which is crucial given the radiopurity needed to reach relevant dark matter sensitivity levels.

We show a drawing of the COUPP-60 chamber in Figure 1 and photos in Figure 2. The superheated liquid (CF_3I) is contained in a quartz vessel, with a volume of pure water floating on top. The water isolates the superheated liquid from contact with a set of metal pressure-transmitting bellows. The bellows equalize the pressure inside the quartz with the pressure of the surrounding buffer fluid, thus maintaining low stress in the quartz. The buffer fluid and quartz inner vessel are inside a conventional stainless steel pressure vessel. Pressure control of the superheated liquid is provided by a piston and pump module connected to the buffer fluid. This design allows the pressure to be controlled in a completely hermetic, high purity environment.

The initial target fluid of choice is trifluoroiodomethane (CF_3I), which has a density of 2 g/cm^3. Because of its modest boiling point, it is possible to operate a CF_3I bubble chamber very near atmospheric pressure and room temperature. CF_3I provides excellent sensitivity to spin-independent couplings because of the large A^2 enhancement for scattering on iodine and 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 coupling.

The detector is installed inside an insulated water tank, shown in Figure 3, which provides a shield against environmental neutrons. The temperature of the water, controlled with a heater, is used as the thermal regulator and buffer for the detector. For operation at our shallow commissioning site (the NuMI tunnel at Fermilab), phototubes are floated on a foam raft on the top of the water, turning the tank into a water Cerenkov detector for cosmic ray muon detection.

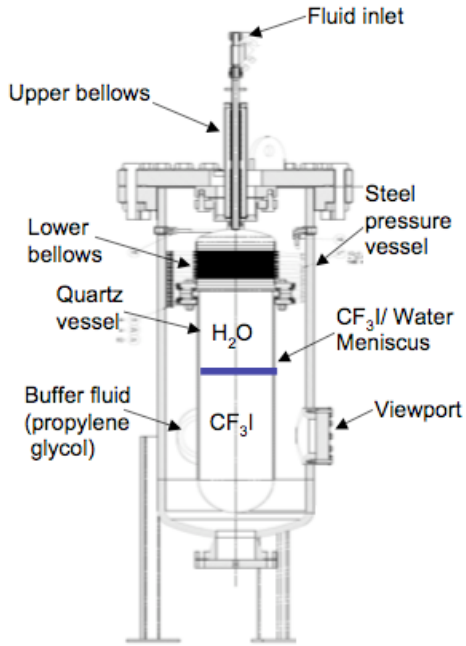

Figure 1: Drawing of the COUPP-60 bubble chamber.

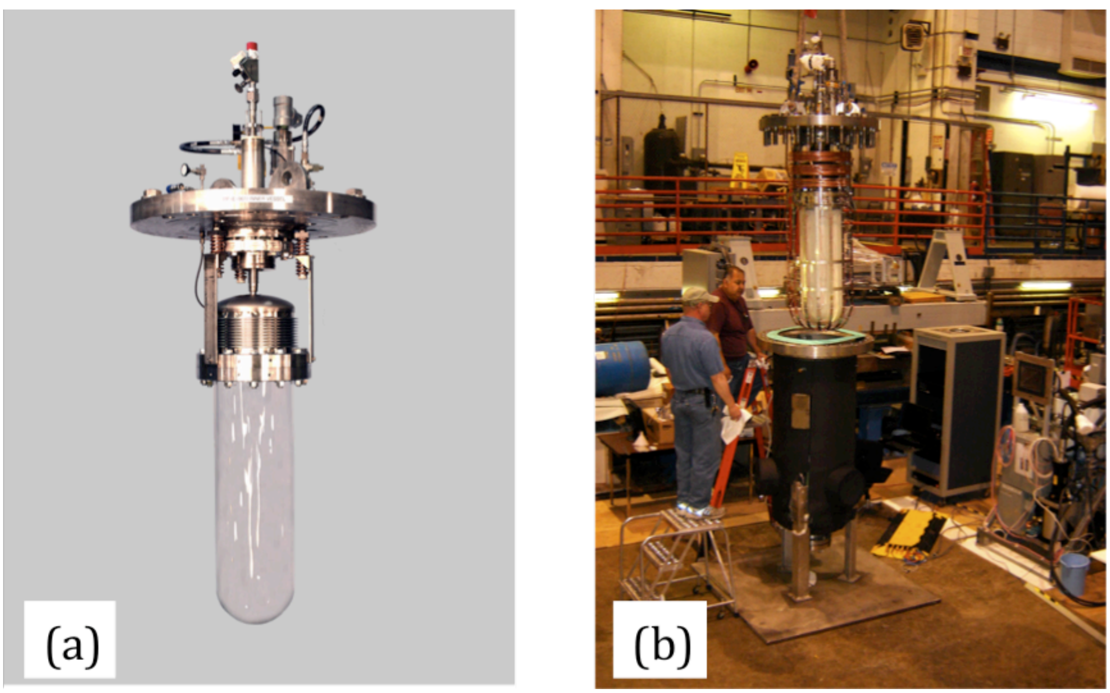

Figure 2: Photos of the COUPP-60 chamber: (a) The inner vessel assembly and (b) the inner vessel assembly being inserted into the pressure vessel.

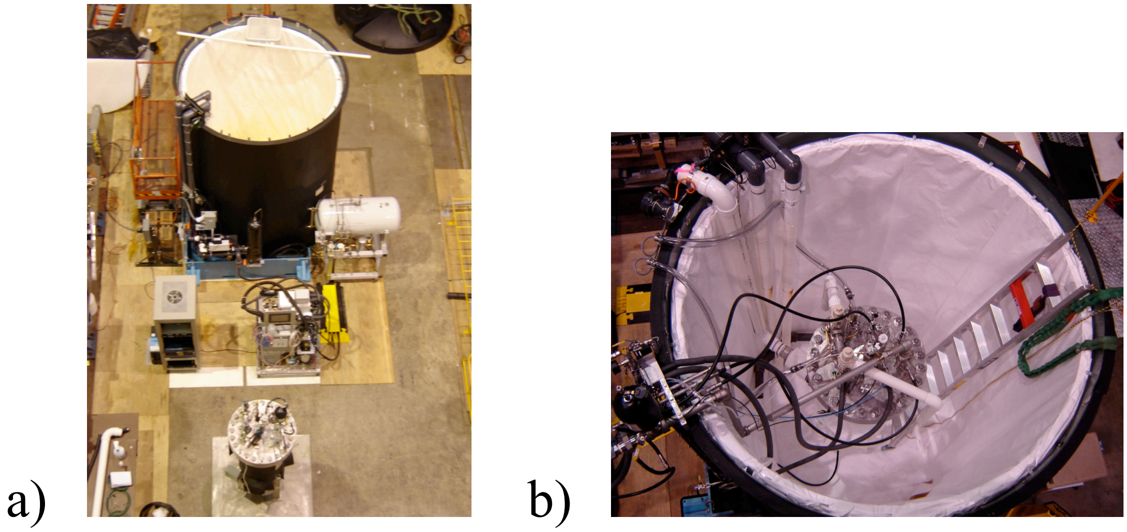

Figure 3. The 60 kg bubble chamber at the D0 Assembly Hall. a) shows the detector and water shield before insertion. b) shows the detector inside the water tank.

The sensitive volume inside the quartz inner vessel is viewed by a stereoscopic pair of video cameras. The detector is triggered by comparing each video frame to a reference image. If there are a significant number of pixels that have changed their intensity, then a fast compression of the detector is induced, which forces any bubbles that may have formed to reenter the liquid phase. A set of video frames and chamber status information corresponding to the event is stored. The analysis of these data determines whether a single bubble occurred (WIMPs will never produce multiple scatters) and whether the bubble occurred in the bulk volume, rather than on one of the surfaces of the vessel or at the boundary between the CF_3I and the water. A fit to the rate of single bubbles as a function of recoil energy threshold separates backgrounds and extracts WIMP cross-section limits.

4. Commissioning goals

Our detector deployment strategy includes a lengthy commissioning phase at Fermilab, in order to avoid the difficulties and expenses that might otherwise be involved in starting up detector operation at a remote underground site. Specifically, the goals of the COUPP-60 commissioning phase are to:

(1) Demonstrate that the detector is fully functional. This includes tests of the achievable live time fraction, the quality of the video images, the stability of the pressure and temperature control systems, the efficiency of the video trigger, the speed of hydraulic compression and the functionality of the data acquisition hardware and software.

(2) Demonstrate that the detector can operate reliably for long periods of time without operator intervention. This is essential for efficient operation at a remote underground site.

(3) Demonstrate that the backgrounds due to α-emitters dissolved in the bubble chamber liquids are low enough to achieve leading sensitivity to spin-dependent WIMP interactions. This depends on the continuing success of our efforts to purfy the CF_3I liquid by distillation and the adaption of other cleaning and high-purity fluid handling techniques developed for solar neutrino experiments. Our goal in the commissioning phase is to reach a level below 60 alpha decays per day in 60-kg of target liquid, or 1 event/kg-day. This is about one order of magnitude below the lowest rate we reached with our smaller 2-kg detector and two orders of magnitude above the lowest rate seen in solar neutrino experiments.

5. Physics sensitivity

Due to the very high sensitivity of COUPP-60, it is likely that, even in the commissioning phase, we will improve on the current world's best sensitivity to spin-dependent WIMP-nucleon scattering. The sensitivity of the detector depends on the level of α-emitter background that is actually achieved in the device. Figure 4 illustrates the sensitivity level that we would reach in the NuMI tunnel at a background level of 1 event/kg-day. In addition to removing trace α-emitter impurities, achieving this background level requires tagging muon-coincident neutrons using Cerenkov light from the water shielding tank. We have measured the rate of such events to be ~8 events/kg-day in our 2-kg detector and expect to reject them at the 99% level with our Cerenkov light detection system.

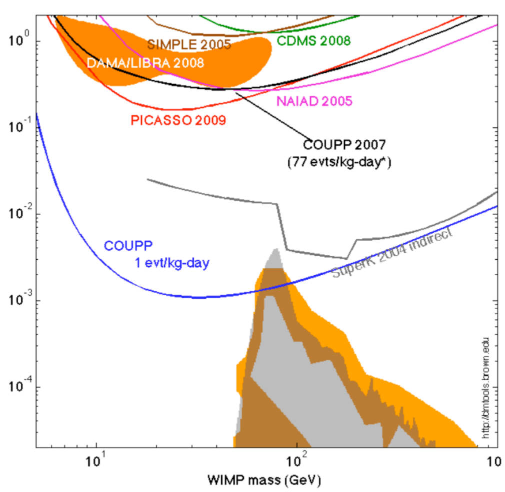

Figure 4: Expected physics sensitivity at NuMI site for spin-dependent WIMP-proton interactions and 10^4 kg-days of exposure, assuming statistical subtraction of an alpha background of 1 event/kg-day.

6. Commissioning plan and schedule.

The anticipated schedule for this work is shown in Figure 5.

The COUPP-60 detector is currently at a quite advanced stage of construction. All components are set up in the D0 assembly pit at Fermilab, as shown in Figure 3, and laboratory safety committees have approved the operation of the detector. The run at D0 will be primarily a system integration test, to insure that the separately tested pieces of the system work well together and that the chamber is therefore “fully functional”, satisfying the first of the three commissioning goals mentioned in Section 4. At D0, we will be able to test the complete functionality of the hydraulic pressure control, video, trigger and data acquisition systems, but will not be able to measure backgrounds from internal radioactivity, due to the large flux of cosmic rays.

In late 2009, the experiment should be ready to be deployed underground in the NuMI tunnel. At that time, we will replace the prototype inner vessel used for engineering runs with a precision cleaned, high-purity version using synthetic fused silica in place of the natural fused quartz of the prototype. The new inner vessel will be filled with deionized water and distilled CF_3I from a new high-purity fluid handling system. The move from D0 to NuMI should take on the order of one month. The duration of tests at NuMI depends considerably on the level of background we observe. Once we achieve a bulk background level of 1 event/kg-day, we will want to move as soon as possible to a deep site. Alternatively, improvements to the inner vessel and fluid handling system would be indicated if the α backgrounds are high. Similarly, we expect to correct any problems which develop with the technical functioning of the detector (video system, hydraulics, etc.) before moving to a deep site. If no improvements are required, the tests at NuMI could take as little as three months, while major improvements, such as the fabrication of a complete new inner vessel, might require as long as a full year to complete and test.

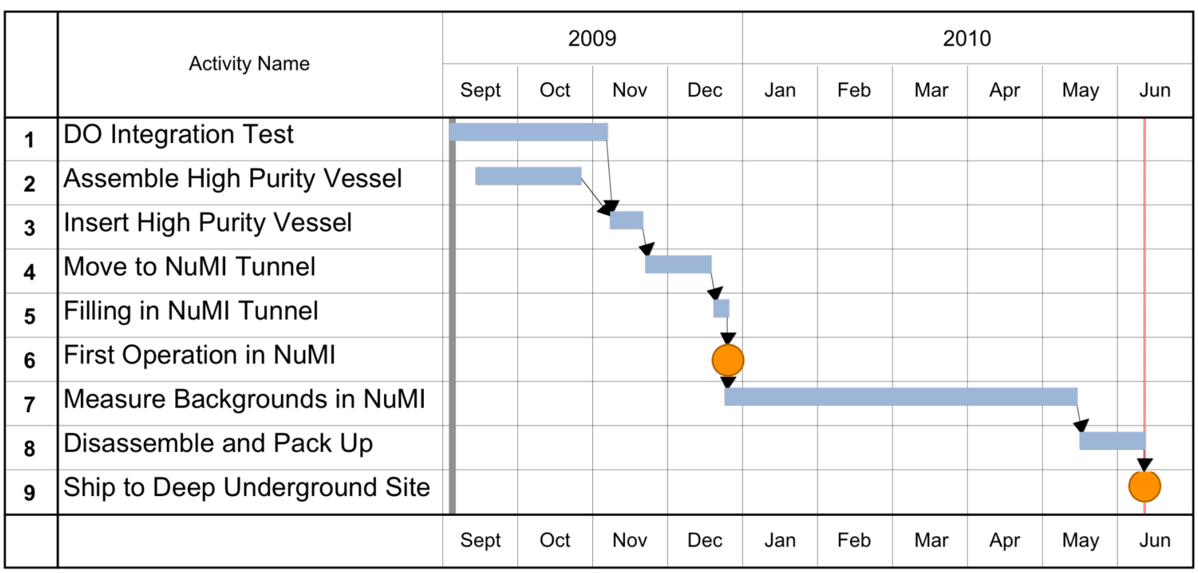

Figure 5: Schedule for Proposed Work.

7. Budget.

The budget for the proposed work totals $418,000 in M&S (60 k$) , SWF (216 k$) and indirect costs (142 k$). The expected M&S costs are summarized in Table 1.

The costs for manpower are extrapolated from the actual 2009 costs, under the assumption that the work of the technical staff continues at the same rate for the first four months of FY10, through the completion of the detector installation in the NuMI tunnel.

	Cost (k$)
Analysis of gas samples	3.5
Analysis of water samples	2
New light source for illumination	5.1
Feedthroughs for acoustic sensors	0.8
Bias power for sensors	4
Digitizers for acoustic sensors	10
100 kg CF3I	17.6
NuMI installation equipment	5
Computer software	2
Travel	10
Total	**60**

Table 1: Estimated direct M&S costs.

References

[1] Science **319**, 933(2008). COUPP website http://www-coupp.fnal.gov/
[2] Phys.Lett.B624:186-194,2005
[3] Phys.Lett.B621:233-238,2005
[4] Nucl.Instrum.Meth. A517 (2004) 139-153; Phys.Rev.Lett.101:091302,2008