

# Improved Limits on Spin-Dependent WIMP-Proton Interactions from a Two Liter CF<sub>3</sub>I Bubble Chamber

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(Dated: August 20, 2010)

Data from the operation of a bubble chamber filled with 3.5 kg of CF<sub>3</sub>I in a shallow underground site are reported. An analysis of ultrasound signals accompanying bubble nucleations confirms that alpha decays generate a significantly louder acoustic emission than single nuclear recoils, leading to an efficient background discrimination. Three dark matter candidate events were observed during an effective exposure of 28.1 kg-day, consistent with a neutron background. This observation provides the strongest direct detection constraint to date on WIMP-proton spin-dependent scattering for WIMP masses  $> 20$  GeV/c<sup>2</sup>.

PACS numbers: 29.40.-n, 95.35.+d, 95.30.Cq, FERMILAB-PUB-10-318-A-CD-E

There is abundant evidence that  $\sim 85\%$  of the matter in the Universe is cold, dark, and non-baryonic [1]. The combination of dark matter and dark energy are pillars in modern cosmology which form a simple framework to understand the detailed observations of baryonic structure, the Hubble diagram, the cosmic microwave background, and the abundances of light elements. However, present knowledge of the nature of these essential ingredients of cosmology is limited. A new weak-scale symmetry, such as the preservation of R-parity in supersymmetry, would predict a massive particle with properties that would conform with the current knowledge of dark matter [2]. If these Weakly Interacting Massive Particles (WIMPs) are the dark matter, then they may scatter off nuclei with enough energy, and at a high enough rate, to be detectable in the laboratory [3].

The Chicagoland Observatory for Underground Particle Physics (COUPP) employs the bubble chamber technique to search for WIMP-nucleon elastic scattering [4]. The bubble chamber is a powerful device to explore nuclear recoils in a rare event search. If the chamber pressure and temperature are chosen appropriately, electron recoils from the abundant gamma-ray and beta-decay backgrounds simply do not nucleate bubbles [5]. Neutrons from radioactivity can be moderated with low-Z shielding materials and cosmogenic neutrons can be reduced to negligible levels with an appropriate overburden. Due to the threshold nature of the bubble nucleation process, alpha-decays are more of a background concern for dark matter searches with superheated liquids than they are for technologies with event-by-event

energy measurements. Recently, however, the PICASSO Collaboration reported event-by-event alpha-decay identification based on the acoustic emission from bubbles [6]. This letter confirms the observation of alpha discrimination and utilizes this technique to set limits on spin-dependent WIMP-proton scattering.

This letter reports results from a 3.5 kg CF<sub>3</sub>I bubble chamber operated from August 19th to December 18th, 2009 in the MINOS near detector tunnel [7] at the Fermi National Accelerator Laboratory. The bubble chamber was located 3 meters off the axis of the NuMI neutrino beam [7], which operated with 10  $\mu$ s pulses, typically every 2.5 seconds. The short duty factor allowed for a calibration source of efficiently tagged, beam induced, fast neutrons. Additional calibration was provided using a switchable Americium Beryllium source (sAmBe) [5].

The 300 ft overburden of the NuMI site was sufficient to shield out the hadronic component of the cosmic ray flux and to significantly attenuate the cosmic ray muon flux. Residual cosmic ray muons passing near the bubble chamber were tagged using a 1000 gallon Bicron 517L liquid scintillator counter equipped with 19 RCA-2425 photomultiplier tubes which surrounded the experiment on the sides and above. The liquid scintillator, in conjunction with passive high-density polyethylene shielding below, provided a moderator for neutrons originating from natural radioactivity in the cavern rocks.

The bubble chamber consisted of a 150 mm diameter 3-liter synthetic fused silica [8] bell jar sealed to a flexible stainless steel bellows within a stainless steel pressure vessel. Propylene glycol, driven by an external pressure control unit, served as hydraulic fluid to manage the pressure of the bubble chamber. The flexible bellows served to ensure that the contents of the bell jar were at the same pressure as the hydraulic fluid. The bell jar contained 3.5 kg of CF<sub>3</sub>I topped with water. The water pro-

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vided a buffer to ensure that the  $\text{CF}_3\text{I}$  contacted only the smooth silica and not the rough stainless steel surfaces.

The thermodynamic conditions of the chamber were monitored with two temperature sensors mounted on the bellows flanges and with three pressure transducers. Four lead zirconate piezoelectric acoustic transducers were epoxied to the exterior of the bell jar to record the acoustic emissions from bubble nucleations, the audible “plink” used to trigger the flash lamps in early bubble chambers [9]. Two VGA resolution CCD cameras were used to photograph the chamber with a 20-degree stereo angle at a rate of 100 frames per second. Frame-to-frame differences in the image data provided the primary trigger for the experiment, typically initiating a compression within 20 ms of a bubble nucleation. Stereo image data from the cameras were used to reconstruct the spatial coordinates of each bubble within the chamber.

The chamber was operated at a temperature of  $29.5^\circ\text{C}$  and a pressure of 26.5 psia when sensitive to particle interactions, providing a nominal Seitz model bubble nucleation threshold of 21 keV nuclear recoil energy [10]. Following the nucleation of a bubble, the chamber was compressed to 215 psia for 30 seconds (300 seconds every 10th event) to re-condense the  $\text{CF}_3\text{I}$  vapor. During the compression period, data from the bubble event were logged, and the chamber was prepared for the next expansion. To allow for equilibration of the bubble chamber fluid, the valid live time for the chamber began 30 seconds after an expansion. From the outset, the performance of this chamber was a significant improvement over previous COUPP bubble chambers [5]. There was no evidence of radon beyond a few dozen events immediately after the chamber fill. Vessel wall nucleations due to alpha decays, observed at a rate of  $0.7 \text{ events cm}^{-2} \text{ day}^{-1}$  in natural quartz vessels, were at an unmeasurably low level in this synthetic fused silica vessel.

The data presented in this letter confirm the observation by PICASSO [6] of a difference between the acoustic power spectra of bubbles caused by single nuclear recoils and those caused by alpha decays. The present understanding of the process is that the range of keV nuclear recoils, like those expected from neutron or WIMP interactions, is tens of nanometers, comparable to the critical radius of formation of a single proto-bubble. Alphas from radioactive decay are expected to create a larger number of proto-bubbles along their  $\sim 40$  micron path in addition to one proto-bubble guaranteed by the recoiling daughter nucleus. These individual early proto-bubbles are expected to provide the dominant contribution to the ultrasound component of the acoustic emission [11]. Because the COUPP bubble chamber fluid is a homogeneous medium, it is expected that acoustic alpha/nuclear recoil discrimination should be more distinct than in the aqueous gel emulsion of superheated droplets used by PICASSO.

The acoustic transducer signals were digitized with a 2.5 MHz sampling rate and recorded for 100 ms for each event. The sound of bubble nucleation showed a broad

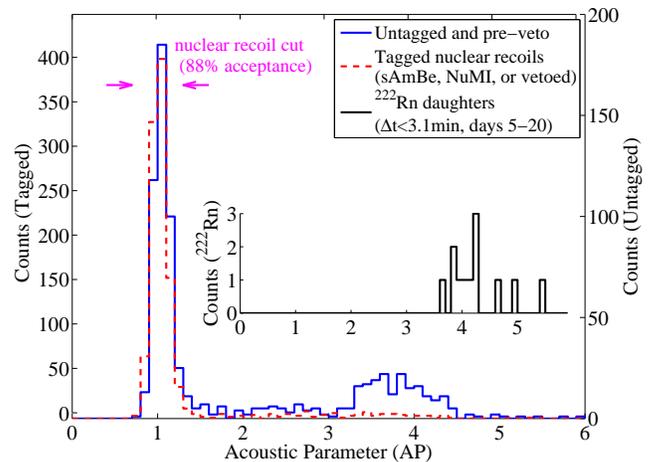


FIG. 1: The acoustic parameter, defined in the text, is a measure of the loudness of the acoustic “plink” resulting from bubble nucleations. The red, dashed histogram in the main panel is from the nuclear recoil calibration datasets (sAmBe, NuMI, cosmic). The blue, solid histogram in the main panel is from all the untagged data, including data taken before the muon veto was commissioned. The inset histogram contains events from  $^{222}\text{Rn}$  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%.

emission distinctly above background noise up to a frequency of 200 kHz. The analysis of these signals was based on an acoustic parameter ( $AP$ ) which is a measure of loudness. The  $AP$  is a frequency weighted acoustic power density integral, corrected for sensor gain and bubble position.  $AP$  was scaled to have a value of unity at the peak observed in its distribution for nuclear recoils induced by known neutron sources (the sAmBe source, the pulsed NuMI beam, or cosmic muons). The  $AP$  distribution for these known neutron sources is shown in Fig. 1. Also shown is the distribution of untagged data, mostly the  $\sim 300$  kg-day exposure before the scintillator veto was installed, which showed a peak at  $AP = 1$  similar to the calibration data, with an additional component with  $3 \leq AP \leq 5$ . The low  $AP$  peak in the untagged data is caused by nuclear recoils and the higher  $AP$  peak is understood to be caused by alpha decays.

All data have been subject to a fiducial volume cut requiring the stereoscopically reconstructed bubble positions to be no closer than 5 mm from the wall. The acceptance of this fiducial volume cut was 75% for nuclear recoils from the sAmBe and NuMI calibration samples. The definition of  $AP$  and of the  $AP$  cut were specified before the veto was installed and neither was tuned based on the WIMP search data sample. The nuclear recoil acceptance of the  $AP$  cut was measured to be 88% in the fiducial volume using the NuMI coincident and sAmBe calibration events.

There was no viable method of injecting alpha-emitting isotopes into this bubble chamber. On the contrary, ef-

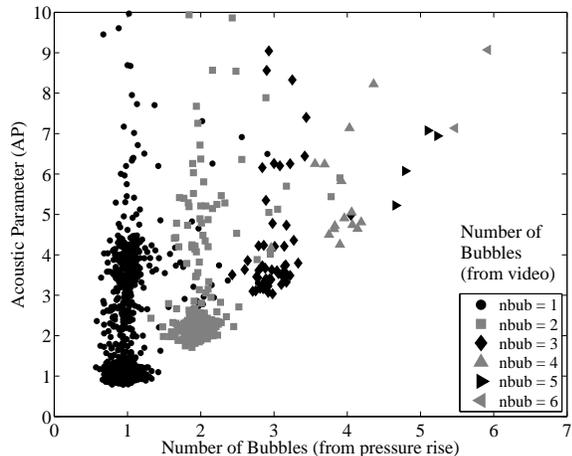


FIG. 2: The two methods of measuring the bubble multiplicity are plotted for the full data set of 291 kg-day exposure. The first method, based on automated video reconstruction software, searches for clusters of pixels changing between frames and is represented by the various symbols labeled in the legend. The second method of counting bubbles was to measure the  $dP/dt$  associated with an event. The abscissa is the pressure rise, scaled to the number of bubbles. The ordinate is the acoustic parameter  $AP$  (see text).

forts were focused on removing these from the active volume, achieving a rate of  $\simeq 0.7$  alpha decays per kg day. A small amount of  $^{222}\text{Rn}$  injected during the fill of the chamber was identifiable via its characteristic decay time. These events were selected by requiring a time difference between bubbles of  $< 3$  minutes, corresponding to the sequence of alpha decays from  $^{222}\text{Rn}$  decaying to  $^{218}\text{Po}$  ( $T_{1/2} = 3.1$  min) which then emits a second alpha particle. This small sample of 10 known alpha decay events shown in the inset of Fig. 1 is consistent with the peak observed in the untagged data at  $3 \leq AP \leq 5$ , confirming the expectation of a louder alpha acoustic emission.

The  $AP$  is a measure of the number of proto-bubbles before they have merged to form macroscopic bubbles. The camera images and the slow pressure rise associated with bubble expansion provided two methods to count macroscopic bubbles in an event. These bubble counting methods were used to produce Fig. 2, where the  $AP$  is plotted as a function of bubble number inferred from the pressure rise. The symbols indicate how many bubbles were inferred from camera images. WIMP interactions will nucleate only one bubble. Neutrons are the only significant background able to produce multiple macroscopic bubbles during an event. The  $AP$  is observed to scale with the number of macroscopic bubbles. Tails in the  $AP$  distribution for a given number of macroscopic bubbles were all towards louder values; there were no tails towards low values. This is consistent with the  $AP$  counting proto-bubbles and a minimum acoustic energy being produced by critically-sized proto-bubbles.

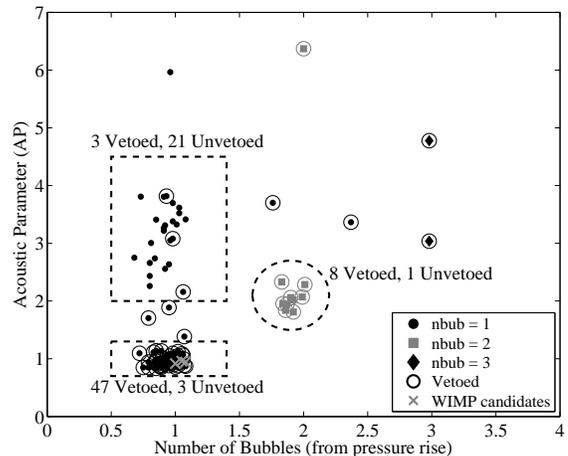


FIG. 3: Data from a 28.1 kg-day WIMP search, plotted as in Fig. 2. In the alpha region (large dashed box) 21 events with no evidence for muon activity were observed, with 3 events having coincident muon activity (labeled vetoed). The smaller dashed box indicates the WIMP signal region, containing 3 candidate events and 47 events coincident with muons in the veto. The neutron double scatter region, indicated with a dashed circle, contains 8 vetoed events and 1 unvetoed event, the latter indicating an irreducible neutron background contamination (see text).

Based on comparing neutron simulations with the  $s\text{AmBe}$  neutron source sample, a bubble nucleation efficiency of 50%, independent of energy, was measured for this dataset and was included in the calculation of WIMP sensitivity. This efficiency is consistent with our previous COUPP calibrations for data taken at  $30^\circ\text{C}$ [5]. The same comparison yielded an efficiency of 100% for calibration data taken at  $40^\circ\text{C}$ . A mechanical failure forced an early termination of this run, restricting data-taking to  $30^\circ\text{C}$ .

The WIMP search data spanned November 19th to December 18th. They are shown in Fig. 3 along with the signal acceptance regions for various classes of event. There were 23 days of livetime with the muon veto active. A number of data quality cuts were imposed to remove periods of poor detector performance. An effective exposure of 28.1 kg-days remained after imposing all data quality cuts, the fiducial volume cut, and the  $AP$  nuclear recoil cut. In the signal acceptance region there were 3 WIMP candidate events and 47 events coincident with muon activity in the veto. In the alpha region there were 24 events, 3 of which were coincident with muon activity. These are statistically consistent with the high- $AP$  tail expected from the 47 cosmic ray events in the signal region. Of 9 events with two macroscopic bubbles, one was not coincident with the veto. This event is proof of an unvetoed neutron background component with sufficient rate to result in the observed 3 single-scatter WIMP candidate events.

Assessments of event-by-event discrimination against alpha decays and of the sensitivity to WIMP-nucleon

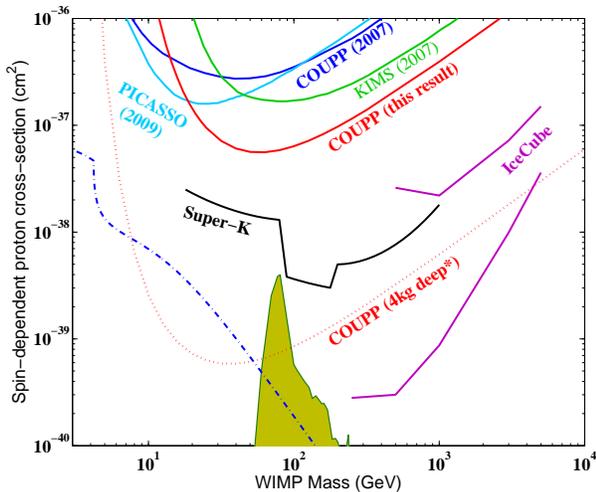


FIG. 4: Improved limits on spin-dependent WIMP-proton elastic scattering from the data presented in this letter. A previous COUPP result [5] is shown for comparison. Direct detection limits from the PICASSO experiment [12], cyan, and the KIMS experiment [13], green, are shown. Limits on neutralino annihilation in the Sun from the IceCube [15], magenta, and Super Kamiokande [14], black, neutrino observatories are also plotted. The gold region indicates favored regions in cMSSM [16]. The blue, dashed-dotted line is the expected cross-section for “maverick” dark matter with  $\Omega h^2 = 0.1$  [17]. Expectations from the operation of this chamber in a deep underground site are shown as a dotted line, under the assumption of a 40°C operating temperature, a 4 kg target mass, and that a deeper site will result in at least three months background free operation.

scattering are limited by the unvetted neutron background in this dataset. Interpreting the three events in the signal region as alpha decays results in a conservative 90% C.L. upper limit on the binomial probability of an alpha decay registering in the nuclear recoil signal region of  $< 26\%$ . In the Seitz theory of bubble formation [10], and at this operating pressure and temperature, it is un-

likely that either the heavy recoiling daughter nucleus or the alpha particle itself would fail to nucleate bubbles. Therefore the presently derived alpha background rejection should be considered a conservative assessment for the potential of this technique. We expect an improved estimate from runs in a deeper underground site, where the residual neutron background should be absent.

Interpreting the three events in the signal region as WIMP candidates results in a 90% Poisson upper limit of 6.7 for the mean of the signal. The resulting improved limits on spin-dependent WIMP-proton couplings are shown in Fig. 4. The spin-independent sensitivity that can be extracted from present data is comparable to that obtained by CDMS in another shallow underground facility [18]. The calculations assume the standard halo parameterization [19], with  $\rho_D = 0.3 \text{ GeV c}^{-2} \text{ cm}^{-3}$ ,  $v_{esc} = 650 \text{ km/s}$ ,  $v_E = 244 \text{ km/s}$ ,  $v_0 = 230 \text{ km/s}$ , and the spin-dependent couplings from the compilation in Tovey *et al.*[20]. This result is consistent with a background from neutrons induced by residual cosmic radiation in the shallow site.

In view of the  $\sim 10^{-11}$  intrinsic rejection against minimum ionizing backgrounds [5] and the acoustic alpha rejection demonstrated in this letter, a leading sensitivity to both spin-dependent and -independent WIMP couplings can be expected from the operation of CF<sub>3</sub>I bubble chambers deep underground. A first exploration of the cMSSM spin-dependent parameter space [16] of supersymmetric dark matter candidates is expected from operation of this chamber in a deeper site (Fig. 4). At the time of this writing, a 60 kg CF<sub>3</sub>I COUPP bubble chamber is being commissioned.

The COUPP collaboration would like to thank Fermi National Accelerator Laboratory, the Department of Energy and the National Science Foundation for their support including grants PHY-0856273, PHY-0555472, PHY-0937500 and PHY-0919526. We acknowledge technical assistance from Fermilab’s Computing, Particle Physics, and Accelerator Divisions, and from E. Greiner, P. Marks, B. Sweeney, and A. Vollrath at IUSB.

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