Dark Matter Search Results from the PICO-2L $\text{C}_3\text{F}_8$ Bubble Chamber
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Dark Matter Search Results from the PICO-2L C$_3$F$_8$ Bubble Chamber


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New data are reported from the operation of a 2-liter C$_3$F$_8$ bubble chamber in the SNOLAB underground laboratory, with a total exposure of 211.5 kg-days at four different energy thresholds below 10 keV. These data show that C$_3$F$_8$ provides excellent electron recoil and alpha rejection capabilities at very low thresholds. The chamber exhibits an electron-recoil sensitivity of < 3.5 $\times$ 10$^{-10}$ and an alpha rejection factor of $\approx$ 98.2%. These data also include the first observation of a dependence of acoustic signal on alpha energy. Twelve single nuclear recoil event candidates were observed during the run. The candidate events exhibit timing characteristics that are not consistent with the hypothesis of a uniform time distribution, and no evidence for a dark matter signal is claimed. These data provide the most sensitive direct detection constraints on WIMP-proton spin-dependent scattering to date, with significant sensitivity at low WIMP masses for spin-independent WIMP-nucleon scattering.

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Understanding the nature of dark matter is one of the most important goals in modern particle physics [1, 2]. A leading candidate to explain the dark matter is a relic density of cold, non-baryonic Weakly Interacting Massive Particles or WIMPs, and direct detection dark matter experiments hope to observe the nuclei recoiling from the rare collisions of WIMPs with ordinary matter [3–6]. Historically, the interaction of dark matter with normal matter has been divided into two categories, spin-dependent (SD) and spin independent (SI).

The superheated detector technology has been at the forefront of SD searches [7–10], using refrigerant targets including CF$_3$I, CF$_4$F$_{10}$ and CF$_2$ClF$_5$, and two primary types of detectors: bubble chambers and droplet detectors. The PICO Collaboration (formed from the merger of PICASSO and COUPP) has now operated a 2.90 kg C$_3$F$_8$ bubble chamber from October 2013 to May 2014 in the SNOLAB underground laboratory in Canada, at 6010 meters of water equivalent depth. Here we report results from that run.

The bubble chamber (called PICO-2L) deployed in this experiment was very similar to the 2 liter chambers described previously [7, 8], primarily consisting of a fused-silica jar sealed to a flexible, stainless steel bellows, all
The chamber was exposed to an AmBe calibration source ten times during the run to monitor the detector response to nuclear recoils. All calibration data were handsampled to check bubble multiplicities, and handsampled single bubble events were used to determine the data cleaning cut efficiencies.

The data analysis begins with an image reconstruction algorithm to identify bubbles and their locations in 3D space. An optical-based fiducial volume cut is derived from neutron calibration data such that 1% or fewer of wall or surface events, defined as events located on the glass jar or at the interface between the C$_3$F$_8$ and water buffer respectively, are reconstructed as bulk events, defined as bubbles that do not touch either the glass or water. The efficiency of the optical fiducial cut is determined to be $0.82 \pm 0.01$ by volume (all error bars on cut efficiencies are 1σ and represent total uncertainties).

In [7], the rate-of-pressure-rise during an event was used as a highly efficient fiducial volume cut, as bubble growth is affected by proximity to the jar or the liquid interface. A similar analysis was implemented in PICO-2L with an efficiency of $0.92 \pm 0.02$, in agreement with [7]. The pressure-rise analysis could not be applied to all data as improvements to the PICO-2L data acquisition system and hydraulic cart reduced the time between trigger and compression, stopping bubble growth before the pressure could increase significantly. A trigger delay of 10-40 ms was imposed for most of the low threshold data to allow more time for the bubble to evolve, enabling use of the pressure rise cut. For the higher threshold data without the trigger delay, the optical fiducial cut is used.

The acoustic analysis follows the procedure described in [7] to define $AP$, a measurement of the acoustic power released in an event. Fig. 2 shows the $AP$ distributions for calibration and WIMP search data at a threshold of 4.4 keV. The $AP$ distribution is normalized to have a value of unity at the nuclear recoil peak observed in the AmBe data, and an acoustic cut is applied to select these events. For the two low threshold data sets, we adopt the same acoustic cut as in [7, 8], such that $0.7 < AP < 1.3$. Due to decreased acoustic signal at higher operating pressure, the width of the calibration peak at 6.1 keV threshold is a factor of 1.5 larger than at low thresholds; the acceptance region for this data set is chosen such that the difference between the cut value and the mean divided by the resolution is the same as for low thresholds ($0.55 < AP < 1.45$). At 8.1 keV threshold, some neutron-induced events are too quiet to be registered acoustically, so all events with $AP < 2$ are counted as nuclear recoil events. The acceptance of these cuts for neutron-induced single bubble events was statistically indistinguishable for all data sets with a value of $0.91 \pm 0.01$.

A set of quality cuts is applied to all data to eliminate events with excessive acoustic noise, events where the cameras failed to capture the initiation of the bub-
TABLE I: Table describing the four operating conditions and their associated exposures. The experimental uncertainty on the threshold comes from uncertainties on the temperature (0.3 °C) and pressure (0.7 psi), while the theoretical uncertainty comes from the thermodynamic properties of C$_3$F$_8$ (primarily the surface tension).

<table>
<thead>
<tr>
<th>T (°C)</th>
<th>P (psia)</th>
<th>Seitz threshold, $E_T$ (keV)</th>
<th>Livetime (d)</th>
<th>WIMP exposure (kg-d)</th>
<th>No. of candidate events</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.2</td>
<td>31.1</td>
<td>3.2 ± 0.2 (exp) ± 0.2 (th)</td>
<td>32.2</td>
<td>74.8</td>
<td>9</td>
</tr>
<tr>
<td>12.2</td>
<td>31.1</td>
<td>4.4 ± 0.3 (exp) ± 0.3 (th)</td>
<td>7.5</td>
<td>16.8</td>
<td>0</td>
</tr>
<tr>
<td>11.6</td>
<td>36.1</td>
<td>6.1 ± 0.3 (exp) ± 0.3 (th)</td>
<td>39.7</td>
<td>82.2</td>
<td>3</td>
</tr>
<tr>
<td>11.6</td>
<td>41.1</td>
<td>8.1 ± 0.5 (exp) ± 0.4 (th)</td>
<td>18.2</td>
<td>37.8</td>
<td>0</td>
</tr>
</tbody>
</table>

FIG. 2: (Color online) $AP$ distributions for neutron calibration data (black) and WIMP search data (red) at 4.4 keV threshold. Note that the x-axis shows ln$(AP)$. As discussed in the text, alphas from the $^{222}$Rn decay chain can be identified by their time signature and populate the two peaks in the WIMP search data at high $AP$, with higher energy alphas from $^{214}$Po producing larger acoustic signals.

One of the main strengths of the superheated fluid detectors is their insensitivity to electronic recoils. The PICO-2L chamber was exposed to a 1 mCi $^{133}$Ba source to confirm this behavior in C$_3$F$_8$. With no candidate events observed during the gamma exposure at 3.2 keV, the probability for a gamma interaction to nucleate a bubble was determined to be less than $3.5 \times 10^{-10}$ at 90% C.L. by performing a Geant4 [13] Monte Carlo of the source and counting the total number of above-threshold interactions of any kind in the active target. Combining these results with a dedicated NaI measurement of the gamma flux at the location of the chamber in the absence of any sources [14], we expect electronic recoils to produce fewer than 0.05 events in the PICO-2L WIMP search data.

A second key method for background rejection in superheated detectors is the acoustic rejection of alpha decays [7, 8, 10, 15]. PICO-2L observed a rate of high-$AP$ events at 4.4 keV threshold immediately after the initial fill that decayed with a half-life consistent with that of $^{222}$Rn to a steady state of about 4 events/day. None of the high acoustic power events leak into the nuclear recoil acceptance band in that data set, confirming that acoustic alpha rejection is present in the C$_3$F$_8$ target. The 4.4 keV data provide a statistics-limited, 90% lower limit on the alpha-rejection in PICO-2L of 98.2%.

In addition to the acoustic discrimination, PICO-2L data show a dependence of $AP$ on alpha energy that was not previously observed in C$_3$F$_8$. At low threshold, two distinct peaks appear at high $AP$ (see Fig. 2). The time structure of the high-$AP$ peaks is consistent with that of the fast radon chain ($^{222}$Rn, $^{218}$Po, and $^{214}$Po decays having energies of 5.5 MeV, 6.0 MeV, and 7.7 MeV, respectively). The events in the louder peak come primarily from the third event in the chain, the high energy $^{214}$Po decay. To our knowledge, this constitutes a first instance of particle energy spectroscopy using acoustic methods.

Background neutrons produced primarily by $(\alpha, n)$ and spontaneous fission from nearby $^{238}$U and $^{232}$Th can produce both single and multiple bubble events. We perform a detailed Monte Carlo simulation of the detector to model the neutron backgrounds, predicting 0.9(1.6) single(multiple) bubble events in the entire data set, for an event rate of 0.004(0.006) cts/kg/day, with a total uncertainty of 50%. There were no multiple bubble events observed in the WIMP search data, providing a 90% C.L. upper limit of 0.008 cts/kg/day, consistent with the background model.

The sensitivity of the experiment to dark matter depends crucially on the efficiency with which nuclear recoils at a given energy produce bubbles. The classical Seitz model [16] indicates that nuclear recoils of energy greater than $E_T$ will create bubbles with 100% efficiency, but past results show that the model does not accurately describe the efficiency for detecting low energy carbon and fluorine recoils in CF$_3$I [7, 17]. This breakdown is attributed to the relatively large size of carbon and fluorine recoil tracks in CF$_3$I, as bubble nucleation only occurs if the energy deposition is contained within a critical bubble size. Iodine recoils in CF$_3$I have much shorter tracks and have been shown to more closely match the Seitz model predictions [12]. Simulations of nuclear recoil track geometries using the Stopping Range of Ions in Matter (SRIM) package [18] as well as measurements in
C$_4$F$_{10}$ [19] indicate that fluorine recoils in C$_3$F$_8$ are also in the regime where the Seitz model is a close approximation for bubble nucleation.

To confirm this expectation, we performed neutron calibrations in-situ in the PICO-2L chamber with an AmBe neutron source. We also deployed a ~30-ml C$_3$F$_8$ bubble chamber at the Tandem Van de Graaff facility at the University of Montreal, using well-defined resonances in the $^{51}$V(p,n)$^{51}$Cr reaction to produce mono-energetic 61- and 97-keV neutrons. Each of the three neutron calibration experiments is simulated in MCNP [20] using updated differential cross sections for elastic scattering on fluorine [21].

A single calibration point, i.e., a bubble rate measured at a given thermodynamic threshold and produced by a single spectrum of nuclear recoil energies, can in general be fit by a family of possible nucleation efficiency curves. In this analysis, the fluorine and carbon efficiency curves at each threshold are fit by monotonically increasing, piece-wise linear functions to allow for a variety of different efficiency shapes, with no reference to the Seitz theory except that bubble nucleation cannot occur for recoil energies below $E_T$ (subject to the experimental uncertainties). In addition, the carbon efficiency is assumed to be less than or equal to the fluorine efficiency at a given recoil energy from track geometry considerations. Fig. 3 shows the observed rates of single and multiple bubbles for the AmBe and test beam sources compared to the best-fit efficiency model at a thermodynamic threshold of 3.2 keV. The best-fit efficiency curves for fluorine and carbon at 3.2 keV are shown by the solid lines in Fig. 4.

We take a conservative approach when determining the sensitivity of PICO-2L to dark matter. For each WIMP mass and coupling, we select the pair of fluorine and carbon efficiency curves giving the worst sensitivity for that particular WIMP that is consistent with the calibrations at $1\sigma$. As an example, the dashed lines in Fig. 4 show the actual efficiency curves used to determine the sensitivity of the experiment for a 5 GeV SI WIMP for the $E_T = 3.2$ keV dataset. For this case, where most of the sensitivity to WIMPs comes from the lowest energy fluorine recoils, our conservative approach uses a weaker response to fluorine relative to the best fit case (e.g. the turn on is shifted to slightly higher energies). Because the total rate in the calibration data is unchanged, the fit compensates for the weaker fluorine response by assuming a larger contribution from carbon. The difference between the solid and dashed lines is small, attesting to how well the calibration data constrain the C$_3$F$_8$ response.

As shown in Table I, WIMP search data were taken at four different thresholds, with most data coming at thresholds of 3.2 keV and 6.1 keV. There are 9 candidate events within the AP acceptance region at 3.2 keV and 3 candidate events at 6.1 keV, with no candidate events observed at 4.4 keV and 8.1 keV. All 12 candidate events were hand-scanned and found to be well-reconstructed, bulk events.

In [7], WIMP-candidate events were observed exhibiting correlations with events in previous expansions, and the candidate events in PICO-2L exhibit similar correlations. To explore this anomaly further, simulated events with random timing are populated into the actual data to model the expected timing distribution of a potential WIMP signal. Fig. 5 shows the cumulative distribution function (CDF) of the time-to-previous-non-timeout (TPNT) for a randomly distributed sample, along with the TPNT for each candidate event at 3.2 keV. A Kolmogorov-Smirnov test comparing the two samples returns a p-value of 0.04 that they are drawn from the same distribution. Given these results, the candidate
events are not treated as evidence for a dark matter signal but instead as an unknown background. Studies are now underway to test hypotheses for the source of these events.

The correlation of the candidate events with previous bubbles can be used to set a stronger constraint on WIMP-nucleon scattering by applying a cut on TPNT. Since there is no valid basis for setting the cut value \textit{a priori}, a method based closely on the optimum interval method [22] is used to provide a true upper limit with TPNT cuts for each WIMP mass optimized simultaneously over all four operating thresholds. The optimum cuts remove all 12 candidate events at each WIMP mass, while retaining 49–63\% of the efficiency weighted exposure, with the range due to changes in the relative weighting of the four threshold conditions for different WIMP masses. If the optimum cuts had simply been set \textit{a posteriori}, without applying the tuning penalty inherent in the optimization method, the cross section limits would be a factor of 1.2–2.4 lower than reported here, with the bigger factor applying to higher WIMP masses.

The limit calculations assume the standard halo parameterization [23], with $\rho_D = 0.3$ GeV cm$^{-2}$ cm$^{-3}$, $v_{esc} = 544$ km/s, $v_{Earth} = 232$ km/s, $v_0 = 220$ km/s, and the spin-dependent parameters from [24], and the resulting 90\% C.L. limit plots for spin-independent WIMP-nucleon and spin-dependent WIMP-proton cross-sections are presented in Figs. 7 and 6. Using the same parameters as in [23] would yield approximately 5–20\% stronger limits depending on the WIMP mass. The results shown here represent the most stringent constraint on SD WIMP-proton scattering from a direct detection experiment and the first time supersymmetric parameter space of the CMSSM model of [30].

The CMS and ATLAS limits assume an effective field theory, valid for a heavy mediator. The purple region represents parameter space of the CMSSM model of [30].
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