Technical Report

Bubble Chambers for Dark Matter Detection

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Abstract

The use of superheated targets to detect dark matter has been expanding in recent years, taking a world-leading role in exploring the spin-dependent phase space. This trend will continue; however, there are groups investigating new versions of this technology which will cover entirely new regions.

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1. HISTORY OF BUBBLE CHAMBERS

1.1. Discovery

The bubble chamber has a long history of being used in particle physics experiments. In order to detect subatomic particles, several different technologies have been used, with many having led to the discovery of new particles. Using cosmic rays as sources, physicists used cloud chambers and nuclear emulsions in order to make many significant breakthroughs, including the discoveries of positrons, muons, and charged pions [1]. As acceleration techniques became more advanced; however, these technologies proved to be insufficient to keep up with the rate of events produced. It was in this environment that Donald Glaser worked to develop a solution to provide a high-density, large-volume detector capable of imaging the tracks of particles. The solution in the end was to use a superheated (or supercritical) medium in a state which is sensitive to the trajectories of ionizing particles. As bubble chambers grew in use, they led to many breakthroughs, including the discovery of particles such as the Σ_0, the Ξ_0, and the Ω^- [1].

One of the most interesting aspects of the bubble chamber is the flexibility to use a wide range of materials as the target. While developing this detection technique, Glaser worked with many superheated media including both liquid hydrogen (which became commonly used) and hydrocarbons such as ether and propane [2]. One of the most significant challenges concerned the triggering of the chamber when an event occurred in the target material. A great deal of effort was expended in this area, introducing a triggered strobe system which would take pictures of the particle track as it developed in the chamber. Many detectors of this type were tested at the Brookhaven Cosmotron, and within a few years, data was being analyzed from these chambers [3].

1.2. Use as Dark Matter Detectors

The use of bubble chambers to detect dark matter interactions specifically seems to have been prompted by the consideration that the majority of dark matter detection techniques relied on the ionization signal produced by the nuclear recoil [4]. Experiments using this method detect ionizing particles efficiently; however, this also leads to the inclusion of a great deal of background interactions combined with the signal. While there are several methods in which these backgrounds can be removed from the data stream during analysis, an ideal detector would be much less sensitive to the deposits from this ionization, removing the necessity of their removal later. The desire for this "background-free" detector spawned new investigations into the use of bubble chambers which, due to the difference in event generation for signal events (nuclear recoils, which are expected from WIMP interactions), can be much less likely to exhibit background events while maintaining sensitivity to the nuclear recoil signal. This does come at the cost of the collection of event-by-event information about the energy deposit lost. Bubble chambers operate strictly as threshold detectors, meaning the only energy information available is whether it was sufficient to create a bubble event.

2. BUBBLE CHAMBER BASICS

In order to achieve this sensitivity, the detector target medium must be in a metastable state. In this state, potential energy is stored in the medium such that the small deposit of energy from an incoming particle can be sufficient to cause a macroscopic effect—a bubble will be formed. One of the advantages of this type of chamber is that the threshold at which this happens can be tuned to, for example, be sensitive to the local deposit of energy from a recoiling nucleus simply by controlling the operational temperature and pressure.

The general concept of the generation of an event in the bubble chamber is easily explained, while the mathematical model is somewhat more challenging. In essence, a deposit of energy in the target medium causes a small quantity of fluid to vaporize, generating a "proto-bubble". If sufficient energy is deposited within a small volume, the proto-bubble will continue to grow into a full bubble large enough to be seen in the detector. If the threshold of energy deposited in the short distance is not met, the proto-bubble will collapse without achieving a detectable size.

This model then suggests that there are two important quantities to define when determining the threshold of the detector—the critical radius and the necessary energy deposit. The mathematics of this were developed by Seitz [5] and can be summarized in the following equations, involving the surface tension σ, the pressures of the bubble (P_b) and liquid (P_l), the enthalpy of vaporization ΔH, and the irreversible work in the process W_{irr}. Also required are the vapor density in the proto-bubble ρ_b, and the vapor pressure and density (P_v and ρ_v, respectively) at which saturation is achieved at the operational temperature T. In this "hot spike" model, the critical radius is defined as

$$r_c = \frac{2\sigma}{P_b - P_l}, \tag{1}$$

and the necessary energy deposit is

$$E_{\text{seitz}} = \frac{4\pi}{3} r_c^3 \rho_b \Delta H + 4\pi r_c^2 \left(\sigma - T\frac{d\sigma}{dT}\right) - \frac{4}{3}\pi r_c^3 \left(P_b - P_l\right) + W_{\text{irr}}. \tag{2}$$

This model has been used for nuclear recoil calculations, though it is worthy of note that an update has been made to the electron-recoil model. This states that the nucleation of bubbles by gammas is driven through δ-electron production instead of the temperature spike model [6]. This can also explain the insensitivity of bubble chambers to electron-recoil events, which will be further discussed in Section 3.2. Other methods used by dark matter experiments to detect particle interactions may not include the restrictions detailed in these equations, allowing electron recoils to trigger events. This insensitivity is then one of the advantages of the bubble chamber.

The energy deposit as described in equation (2) provides a good model for the detector response, in particular with relation to the experimental parameters of pressure and temperature. There are improvements to the efficiency of the nucleation based on calibrations [7] which more accurately detail the relationship between E_{seitz} and the nuclear recoil energy.

Since the pressure is the more easily (and quickly) controlled variable, the operation of these chambers involves a cycle through the pressure. With a stable temperature, the equilibrium pressure is lowered to put the target material into a metastable (superheated) state. The detector can remain in these conditions until an event is detected, necessitating a pressurization stage in which the newly formed bubble is compressed back into a liquid. Following a short pause to allow the conditions to stabilize, the pressure can be lowered again to return the detector to an active state. For bubble chambers used in rare event searches, the event cycle then can be summarized as follows:

(1) Maintaining a fixed temperature, the pressure in the active region is lowered until the fluid is superheated and then held constant
(2) A bubble is created and viewed on the camera system (with the images being stored for offline analysis)
(3) The pressure is raised until the bubble is forced back into the liquid state, held for a short pause for stability, and the cycle can recommence.

2.1. *Monolithic vs Droplets*

When considering the chambers used for dark matter detection, two slightly different strategies have been deployed. The first, used by the PICASSO [8] and SIMPLE [9] collaborations, is to disperse the target material throughout an inert gel matrix in the form of small droplets. Detectors employing this technique are known as Superheated Droplet Detectors (SDDs). These have the advantage that the nucleation of one droplet does not affect the others, so the detector can remain in a "live" state for a much longer period of time, generally a matter of hours. The fact that the droplets of active material are surrounded by the gel matrix also addresses the challenge of providing a container surface which is free of defects that could lower the effective bubble nucleation threshold due to macroscopic sharp points. Detectors employing this strategy cannot have as much target material per container volume as those that do not distribute their active material throughout a nonreactive gel and so have restrictions concerning their total active mass. The operational cycle also differs slightly, as the nucleation of one droplet will not expand to engulf all the active material. The active fluid is repressurized after a fixed period of time regardless of the number of events. This time is generally on the order of hours.

The second strategy is to maintain the target material as a monolithic entity, filling the entire container. This design has been employed by the COUPP [10] and PICO [11] collaborations. While this style of detector requires a compression cycle following every event, the use of the available volume is much more efficient. The material used to contain the active material must be chosen carefully, however. Similar to the discussion above, the container must not provide nucleation sites, and must be radioactively very clean, which has generally meant that fused silica has been the material of choice for these experiments.

One of the additional difficulties associated with operating the monolithic detector is the necessity of frequent compression of the chamber. There have been several strategies employed to accomplish this pressurization, primarily hydraulically using either a water buffer (as in early PICO detectors) or nested jars connected with bellows (as in later PICO detectors). One other tactic is to connect areas at different temperatures (and therefore different degrees of superheat) through plumbing. This has been referred to as the "geyser" method, and was employed by the MOSCAB collaboration. This style removes much of the difficulty associated with the pressurization of the fluid following an event, but the manufacture of the detector itself is more challenging. The MOSCAB [12] collaboration has successfully operated detectors of this style.

2.2. *Target Material*

The flexible nature of the bubble chambers also lends itself to investigations using many different target materials. This has allowed different aspects of dark matter to be investigated. For example, dark matter interactions with nuclei may couple to, among other things, the number of nucleons ("spin-independent coupling") or to the spin of the nucleons ("spin-dependent coupling"). The former type of interaction would scale in cross section with the square of the number of nucleons in the target nucleus, while the latter is only possible if the target nucleus has nonzero net spin. The COUPP collaboration used CF_3I [10] as a target material with the intent of exploring both spin-dependent and spin-independent dark matter (exploiting the large spin-independent cross section from the iodine due to the large A^2 and the spin-dependence from the fluorine). Other examples, such as the PICASSO detector, focused on the spin-dependent coupling with the proton using the large cross section on ^{19}F and employing C_3F_8 and C_4F_{10} as targets. The SIMPLE collaboration followed a similar strategy using C_2ClF_5 in order to incorporate the large spin-dependent enhancement due to the odd number of protons in the fluorine.

The flexibility of the target material can also allow for some intentional specialization in the area of the dark matter phase space explored. One potential advantage could be to include hydrogenated targets in order to emphasize lower-mass targets, an under-explored area of dark matter phase space to this point. This could be accomplished by employing $C2H_2F_4$, for example. The thermodynamics of the target material (and particularly the boiling point) could be the only challenge, potentially requiring operation significantly below (or above) easily achievable values around room temperature; however, this can be overcome through a more advanced detector design.

Throughout the history of bubble chambers, there has been discussion around the use of scintillators as target materials. In particular, bubble chambers superheating noble elements (most commonly argon and xenon) have been built multiple times [2]. These are particularly attractive as the ability of the target to scintillate provides an additional channel through which deposited energy can be measured. This dramatically improves the insensitivity to electron-recoil interactions, allowing lower thresholds in these chambers (see Section 5.1). This is a path that is currently being investigated by the Scintillating Bubble Chamber (SBC) collaboration [17].

3. ADVANTAGES AND CHALLENGES

The use of bubble chambers as dark matter detectors is motivated primarily by the advantages offered in the removal of background signals from the data stream. The challenges associated with two of the most significant backgrounds, electron recoils and alpha particles, have unique solutions offered by this technology.

3.1. *Alpha-Induced Recoil Rejection*

Controlling alpha contamination in any dark matter detector relies on the careful screening of materials along with sophisticated cleaning procedures. The bubble chamber, however, has an additional technique of information collection which can be used to discriminate alpha-induced recoils from other signals.

First exploited by the PICASSO collaboration [8], the acoustic signature of alpha-induced events differs from others. This is attributed to the different way in which the events are created. Alpha particles tend to nucleate multiple proto-bubbles along their track which then coalesce to form the bubble, a process which has a different signature than the growth of a single proto-bubble. This effect has been well characterized and can be used to effectively separate alpha-induced events from those involving neutrons as shown in Figure 1.

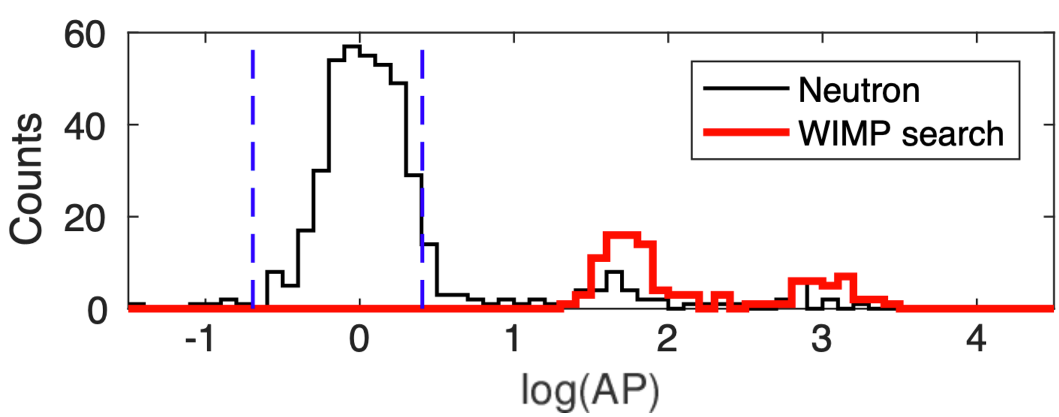

FIGURE 1: Acoustic parameter (AP) distributions for neutron calibration (black) and detector data (red) showing the parameter used to provide a distinction between nuclear recoils and alpha-induced events. Taken from [15].

Plotted in Figure 1 is the "acoustic parameter" (AP) used by the PICO collaboration. The AP value is calculated using the data collected by the piezoelectric sensors mounted on the PICO detectors and measures the power contained in specific frequency bands of the acoustic signal. For the PICO-60 data, the power contained in a frequency range from 55 to 120 kHz range was used, with corrections applied for both the position of the event and the temperature of the detector.

The efficiency of these cuts at removing background events has been shown to be extremely good [15] while retaining the signal events. This has been the motivation for the inclusion of piezoelectric sensors in all subsequent bubble chambers.

3.2. Electron-Recoil Insensitivity

For the majority of dark matter detection projects, the identification of events induced by electron recoils presents a challenge as they can deposit an amount of energy that is similar to that associated with the desired signal from a WIMP-induced nuclear recoil. Due to the unique method of detecting energy deposits in bubble chambers, the magnitude of this challenge is greatly reduced, depending on the operational conditions. Where the Seitz model requires a threshold deposit of heat within a critical radius [5], a new analysis models the nucleation of bubbles by electron recoils to be driven instead by ionization [6]. This model can be used to predict the probability of gamma interactions producing a bubble signal in bubble chambers. Combined with the measured gamma flux in the experimental location, the rate of gamma-induced nucleations as a function of threshold can be produced as shown in Figure 2.

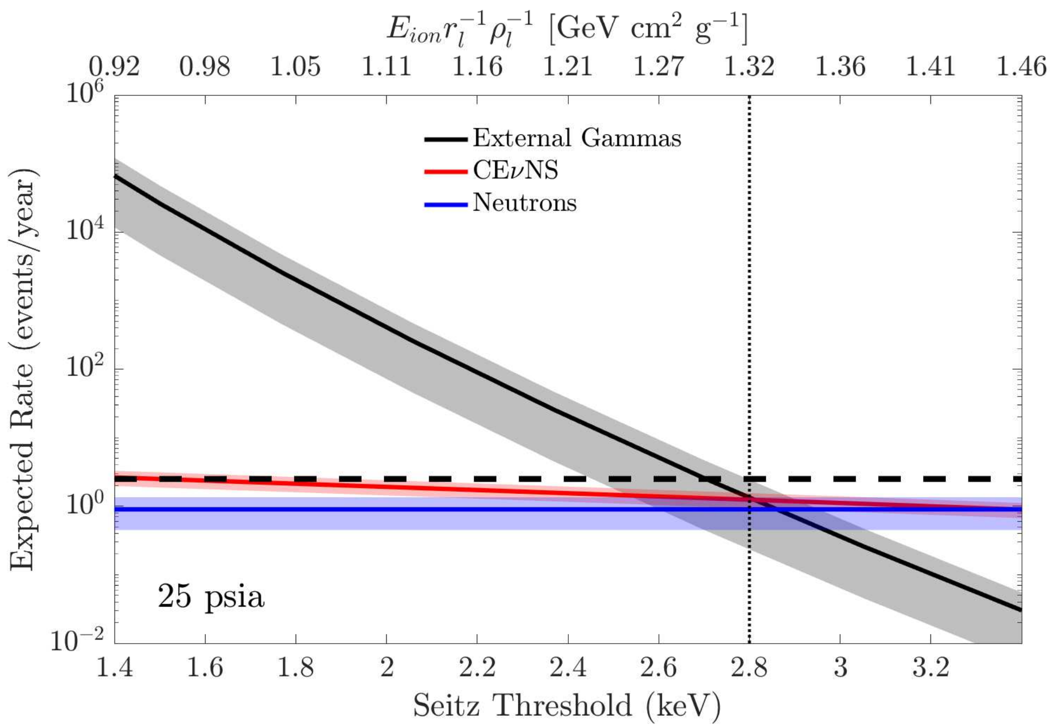

FIGURE 2: The predicted background rates for the PICO-40L C_3F_8 detector operating at 25 psia as a function of both the Seitz threshold (bottom: nuclear recoils) and the ionization stopping power threshold (top: electron recoils). The horizontal black dashed line shows the target rate of two events per year. Taken from [6].

As shown in Figure 2, the PICO-40L detector (used in this example, though the results are similar for the widely used targets), the rate of gamma-induced recoils is very low down to a Seitz threshold (as defined in equation (2)) of roughly 2.8 keV. This insensitivity to electron recoils for a significant range of thresholds is one of the primary motivations for the dark matter search. The increase of gamma sensitivity as the threshold is lowered is a challenge which will be discussed.

3.3. Energy Information

One of the challenges associated with the use of bubble chambers is the lack of event-by-event energy information. The only available energy information is whether the deposit was above the threshold, generating a bubble. This is not an insurmountable disadvantage—the energy spectrum of events can be determined by collecting data while changing the operational conditions (the temperature and the pressure) in order to vary the threshold. In this way, the energy spectrum can be reproduced with the difficulty that the changes necessary to carry this out (particularly changes in temperature) can require time delays on the order of days to stabilize sufficiently to allow detector operation.

3.4. Operating Condition Instability

As described above, the operational conditions of the detector can have a large impact on the threshold for the energy deposit. These conditions include both the temperature and pressure in the active area of the detector, which can be prone to instabilities. As an example, the operational goal for the temperature stability of a bubble chamber is generally $\pm 0.1°C$. This requires a great deal of effort to be expended to ensure that the temperature is stable and constant throughout the entire active area, which can require significant heating and cooling control. Bubble chambers can therefore require large amounts of insulation very close to the active area, bringing along challenges not only with design but also with potentially increased background events due to the materials required. The pressure is less challenging, although the variation between the top and bottom of a large detector can be significant.

3.5. Scalability

One final challenge to be discussed is the scalability of the bubble chamber concept. In the current form, these chambers require an active area capable of compression to several hundred psi contained within a vessel sufficiently free of surface defects where spontaneous nucleation due to geometric effects does not impact the live time. The solution employed by the COUPP, PICO, and SBC collaborations is to use fused silica jars. These have been shown to be sufficiently smooth on a level that affects the nucleations while being largely free of radioactive contaminants. They also have the advantage of being optically transparent, allowing the bubble signals to be detected using cameras located outside of the active medium.

The limitation comes in the difficulty associated with producing larger fused silica vessels. The PICO collaboration has undertaken the construction of the next generation of dark matter bubble chambers in PICO 500 [16]. The active volume for the PICO-500 detector is limited at 260 L due to manufacturing constraints associated with fused silica [16]. Research into the use of alternative materials has been ongoing, including the use of flexible materials (effectively eliminating difficulty in manufacture) and the removal of the camera systems, allowing for nontransparent chambers. Progress in this research will be required to increase the active mass of the bubble chamber further.

4. CURRENT GENERATION

The development of bubble chamber technology for dark matter detection has been pursued by several collaborations, with a few continuing to produce world-leading sensitivity in some dark matter models.

4.1. PICO

Created from (and named for) the merger of the PICASSO and COUPP collaborations, PICO was created with the intent of using the best aspects of these two detectors. The monolithic nature of the COUPP detector, along with the use of fused silica jars, was continued in the joint group. From the PICASSO detectors, the use of piezoelectric sensors to distinguish alpha-generated nucleations was maintained in the new detectors. In this way, the PICO collaboration strove to use the best of all worlds.

There have been several generations of detectors produced by the PICO collaboration. The first notable PICO detector operated in the low-background environment at SNOLAB [13] (the low background lab roughly 2 km underground in Lively, Ontario, Canada) was called PICO-2L [14]. Several operational changes were made to the detector, comprising a 2 L active volume, during its operation including a change of the target material from CF_3I to C_3F_8. The final results were reported in 2016, achieving peak sensitivity to the spin-dependent dark matter interaction [14], with the detector being retired the same year.

The next generation PICO detector operated at SNOLAB was the PICO-60 detector, taking data from 2013 to 2017. The active material used in this generation was also changed from CF_3I to C_3F_8 during detector upgrades which additionally involved the deployment of an upgraded camera system which increased the amount of the active region visible.

The current generation PICO detector at SNOLAB is approximately the same volume as PICO-60 but employs a different strategy for the containment of the active material, particularly for compression. The PICO-40L detector uses two nested fused silica jars, connected by a bellows, to contain the active material as shown in Figure 3. This removes the water buffer previously required to compress the target material and instead allows the pressure to be increased using a hydraulic fluid surrounding these jars. This strategy has the advantage of limiting contamination associated with the water while maintaining fused silica as the only material in contact with the superheated target. Specifically, the location of the water buffer above the active area means that small particles in the water can cross the boundary between the water and the target material, creating nucleation sites. To remove this buffer, the temperature profile of the active area must be well defined with only the target material visible to the cameras being superheated and the remainder maintained at a colder temperature, therefore being insensitive to energy deposits producing nucleations. The active material in contact with the bellows is of particular importance state since the relative roughness of the material surface can make this area susceptible to nucleations.

4.2. SBC

The Scintillating Bubble Chamber (SBC) collaboration is constructing a novel bubble chamber having a target material of 10 kg of liquid argon doped with xenon [17]. Liquid argon is chosen as the target primarily due to its availability, but the wavelength of the argon scintillation light is outside the high-efficiency range of the silicon photomultipliers. To increase the amount of light detected, the argon is doped with xenon, acting as a wavelength shifter. This chamber operates in much the same manner as the PICO-40L detector though at the significantly colder temperatures necessitated by the use of liquid noble elements as the target. In addition

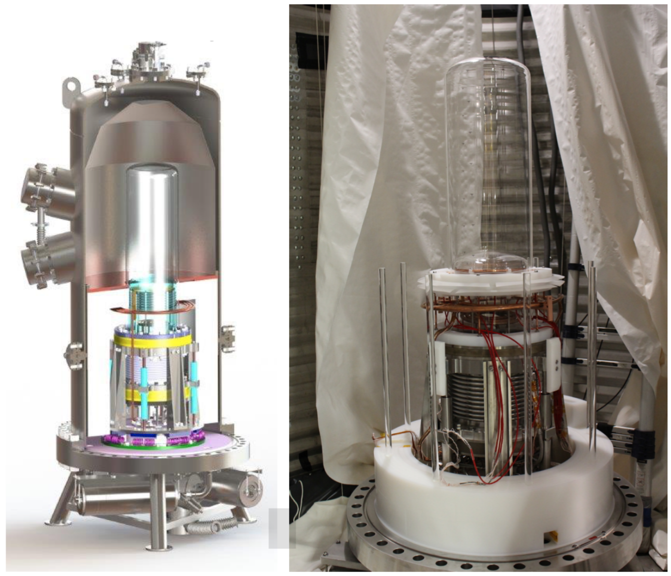

FIGURE 3: Left: a schematic view of the PICO-40L detector. Of particular note are the nested jars containing the target material and connected by a bellows. Right: a picture of the PICO-40L detector during construction. Taken from [18].

to the data collection methods employed by these chambers (cameras, pressure sensors, and acoustic sensors), the SBC detectors collect the scintillation light using silicon photomultipliers (SiPMs). The mounting structure, along with the active area, is shown in Figure 4.

FIGURE 4: Left: view of the active area of SBC with the fused silica vessels connected by a bellows. Right: mounts for the SiPMs which surround the active area of SBC. Taken from [19].

The collaboration has chosen to build two functionally identical chambers—one to be located at Fermilab and one at SNOLAB. The Fermilab chamber will prove the viability of the concept and provide information concerning operation at the lowest thresholds (approaching 100 eV). It will also be operational first, with the knowledge gained during the construction and commissioning feeding into the SNOLAB chamber. The second detector will operate in the low-background environment and provide the dark matter search data.

4.3. *Dark Matter Exclusion Limits*

The results of recent experiments searching for signals from WIMP-proton spin-dependent couplings are shown in Figure 5. Curves indicate that a given experiment has excluded the parameter space above the curve with $\geq$90% confidence. As PICO-60 is one of the only experiments using a target nucleus having excess proton spin (as opposed to excess neutron spin), it provides the most sensitive and robust search for this signal.

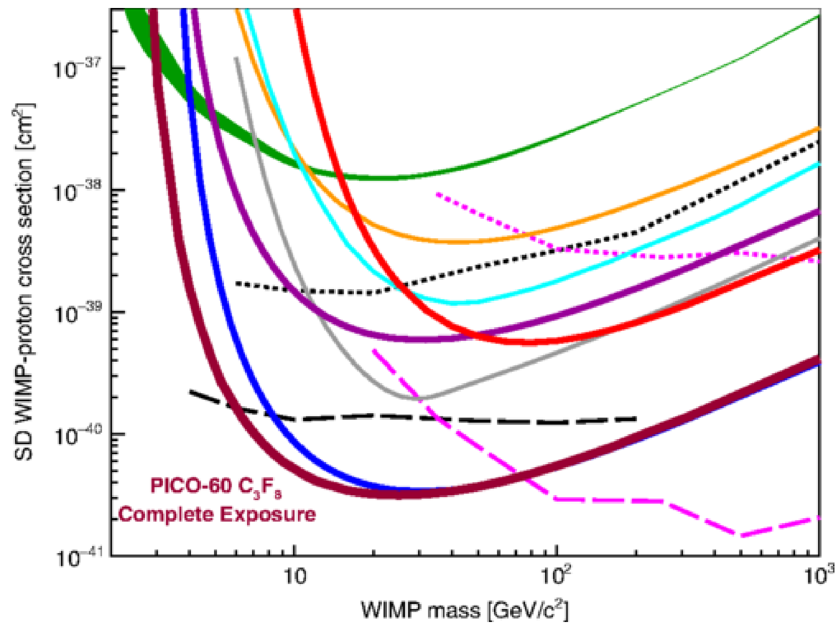

FIGURE 5: The 90% CL on the spin-dependent WIMP-proton cross section. The final analysis of PICO-60 data is indicated, with the previous result in blue. Other experiments are shown for comparison. Taken from [11].

The projections for the sensitivity of the SBC detectors to spin-independent GeV-scale dark matter, along with projections and limits for other experiments, are shown in Figure 6 taken from [19].

5. FUTURE AND NEW CHALLENGES

While bubble chambers have been used as dark matter detectors for many years, the field is still vibrant. The PICO collaboration anticipates the next generation detector to be active soon [16], and construction is underway on the SBC detectors. This operation of these chambers will further increase the reach into dark matter phase space, though this gain does come with associated difficulties, which will also be discussed.

5.1. Lower Energy Thresholds

One area of particular focus is the lowered energy thresholds. As discussed in Section 3.2, a decreased threshold has traditionally come with a significant increase in electron-recoil-induced signals. This lower limit of the threshold directly corresponds to a limit in the ability of the detector to probe dark matter candidates of lower mass. This has been addressed through the use of different target materials, particularly noble elements as in the SBC detectors. Prototype-scale detectors have been operated and calibrated [20] which indicate that the lack of electron-recoil energy-loss mechanisms that nucleate bubbles significantly diminishes this issue. The model for this is that the energy which, in other target materials, would become heat instead becomes scintillation photons, providing excellent discrimination from nuclear recoils. The effect of the significantly lowered threshold can be seen by comparing the low-mass performance of the PICO and SBC detectors in Figure 6.

5.2. CEνNS Background

As the operational thresholds are lowered, additional signals become important. This presents a new opportunity to study the parameters associated with a different scattering signal, in this case coherent elastic neutrino-nucleus scattering (CEνNS). The scattering of neutrino from nuclei has been observed, first by the COHERENT collaboration using neutrons from stopped-pion and -muon decays at Oak Ridge National Laboratory [21]. There is additionally excellent justification to search for CEνNS signals from reactor neutrinos, primarily due to the lower energy range of the incident neutrinos producing fully coherent scattering. In addition, the higher flux of neutrinos allows for the statistics required to improve the uncertainty on the scattering parameters, and the pure $\bar{\nu}_e$ beam is a complementary measurement to that which has been conducted.

Neutrinos arising from the ^{8}B decays in the center of the sun and neutrinos arising from cosmic-ray interactions in the Earth's atmosphere will present background signals via the CEνNS process which will mimic that of dark matter in the next generation of experiments. The next generation of dark matter bubble chamber detectors will be forced to contend with this signal, but it will open a new area of physics for which these detectors will be uniquely suited. Several studies have been conducted using the SBC chamber as a model, providing a demonstration of the reach of this type of experiment [22, 23].

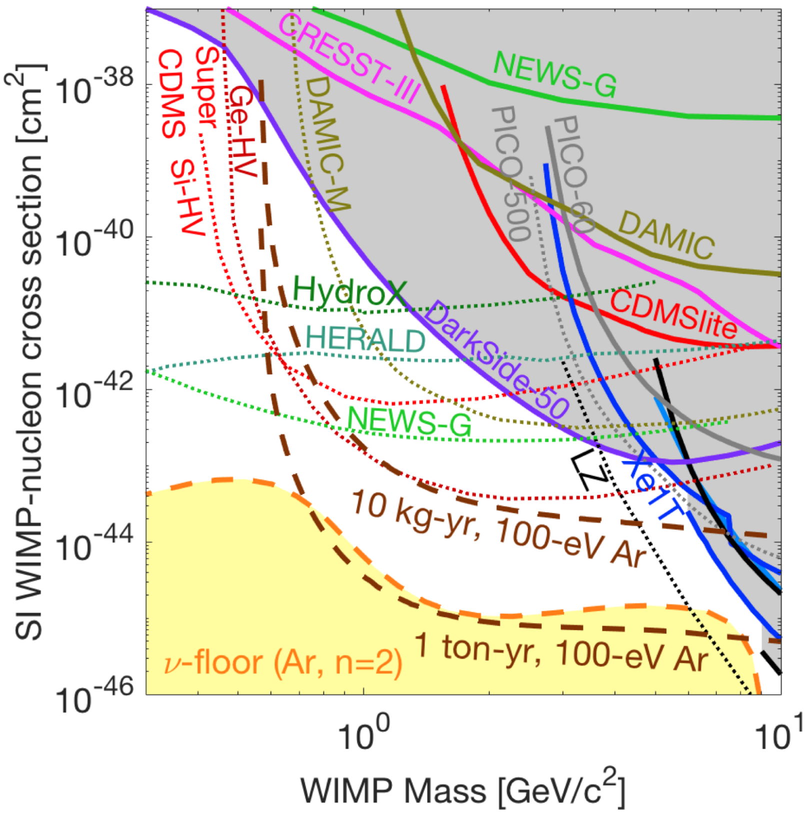

FIGURE 6: The projections and limits for GeV-scale dark matter experiments, all limits at 90% CL and projections in the absence of a dark matter signal. The brown, dashed curves are for SBC, with both 10 kg-yr and 1 ton-yr shown using a 100 eV threshold. Taken from [19].

6. CONCLUSION

The use of bubble chambers has evolved considerably throughout the years since their invention. Following on from its successes with accelerators, this technology has been applied to the search for dark matter particles, primarily due to its effective insensitivity to a major source of backgrounds. Excellent results have been achieved, particularly in the search for dark matter which couples in a spin-dependent manner, and the development of new detectors with lower thresholds holds promise for lower-mass dark matter candidates.

CONFLICTS OF INTEREST

The author declares that there are no conflicts of interest regarding the publication of this paper.

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