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The PICASSO Dark Matter Physics Program at SNOLAB

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Abstract: PICASSO is a dark matter search experiment currently operational at the SNOLAB International Facility for Astroparticle Physics, located 2 km underground in Sudbury, Canada. PICASSO is based on the superheated bubble technique. With good control of radiological backgrounds and a detector design that stabilizes the superheated liquid even when very close to the critical temperature, PICASSO has achieved very low nuclear recoil thresholds. This allowed the experiment to produce world-leading results with particular sensitivity to low mass WIMP signals in both spin-dependent and spin-independent interactions. The 2012 results and the future plans of the PICASSO collaboration are presented.

Keywords: Dark Matter, Superheated Droplet Detector, Bubble Detector, Spin Dependent, PICASSO, SNOLAB

1 Introduction

The past few years have been witness to great advances in the field of Astroparticle Physics. Through a variety of astronomical observations of very high precision, we have come to understand our Universe as one dominated by dark matter and dark energy. Despite the gravitational evidence for dark matter in galaxy and cluster halos, no irrefutable evidence exists for the direct detection of dark matter on earth. Experiments with increasing levels of sophistication and sensitivity are exploring the expected parameter space for dark matter.

A number of experiments now see a few events seemingly inconsistent with background models at low particle masses [1, 2, 3, 4], but these are in tension with other experimental results which appear to exclude them [5, 6, 7, 8]. To resolve these issues, experiments with significantly greater sensitivity are required. There is a major international effort afoot to accomplish this, with experiments employing a variety of techniques. Direct detection experiments search for evidence of dark matter in the form of some unknown Weakly Interacting Massive Particle (WIMP) expected to scatter weakly off nuclei in matter. In these experiments the recoiling nucleus is expected to have energies from a few KeV to order 100 keV, depending on the mass of the WIMP and the angle of scatter. The event rates could be as low as a few events per year per tonne of target material.

To detect such rare low-energy events, experiments need to be very large, must have ultra-low levels of radioactive backgrounds, and they typically operate for several years. They tend to be located in the deepest underground facili-

ties available to get adequate shelter from cosmic rays. It is not known if spin-independent or spin-dependent WIMP interactions are more likely. Nor is the mass very constrained. Hence there are a range of experiments currently operational, or planned, with different target materials, spin sensitivity, and strategies to mitigate against potential backgrounds. This has led to a significant world wide enterprise in the search for dark matter in direct detection experiments.

PICASSO is a direct detection experiment with very unique characteristics. It is one of only a few experiments with significant sensitivity to spin-dependent interactions, and the superheated liquid technique has the advantage of being largely insensitive to the backgrounds from gamma rays, electrons and minimum ionizing particles which plague most other detector types. In addition, the detection mechanism, low threshold, and use of ^{19}F as a target material make this experiment particularly sensitive to low masses, where there appear to be some hints for dark matter.

The PICASSO experiment has had a program of gradually increasing the sensitive mass, decreasing the backgrounds, and becoming ever more sensitive through a series of detector upgrades. Working in collaboration with COUPP, a next generation superheated liquid detector, with a mass or order 500 Kg is now being designed. The following sections will explain the principle of operation for PICASSO, the results obtained so far, the status of the current phase, and the ambitious plans for a joint COUPP/PICASSO program based on the superheated liquid technology.

2 Principle of Operation

The current form of the PICASSO experiment is 32 individual detectors, each 4.5ℓ in volume, containing tiny droplets of C_4F_{10} in a polymerized gel. The loading is limited to about 2% C_4F_{10} by weight in each detector, and this cannot be increased without damaging the gel as bubbles form. A version of the detector is shown in figure 1. When the detectors are active, the $\sim200\,\mu m\,\phi$ C_4F_{10} droplets are maintained in a superheated state by controlling the temperature and pressure of the detector. When a small, but sufficient amount of energy is deposited locally within the superheated droplets they undergo a rapid phase transition. The amount of energy required depends on pressure and temperature, and these can be varied to control the threshold sensitivity of the detectors.

As the energy (heat) must be deposited within a critical radius to begin bubble growth, the operating conditions can be set so that only heavily ionizing radiation creates a phase transition. This is one of the unique features of these detectors, as in contrast to most other detectors they are held blind to the troublesome background gamma, electron and minimum ionizing particles. The noise created by the phase transition can be detected using an array of 9 strategically located piezo-electric transducers mounted on the walls of the detector. Hence the data in PICASSO are digitized acoustic waveforms from particle induced bubble production collected over a range of temperatures.
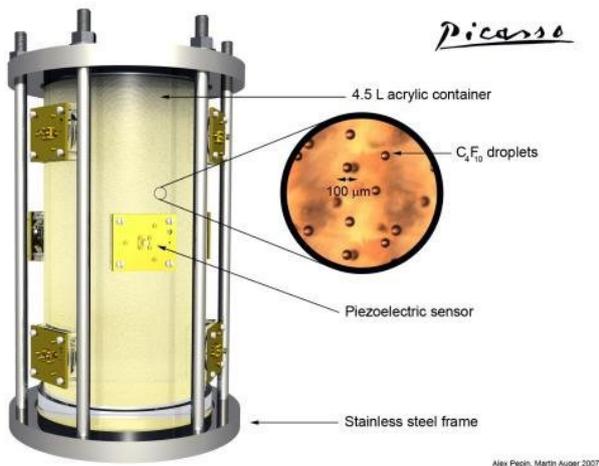

Fig. 1: An isolated 4.5ℓ PICASSO detector with piezo sensors mounted on the walls. The inset shows the droplets embedded within the gel matrix.

The PICASSO detectors are designed to be sensitive to low energy recoiling nuclei from WIMP-nucleus interactions. PICASSO has obtained thresholds as low as 1.6 KeV making it one of the most sensitive detectors for low mass WIMPs. The main backgrounds for these detectors are neutron-induced nuclear recoils (essentially indistinguishable from WIMP-induced nuclear recoils) and α-particles. Neutrons are avoided by locating the detectors deep underground in the SNOLAB facility where the number of neutrons produced by cosmic muon spallations is negligible for PICASSO. The main residual source of neutrons in the underground environment originate from (α,n) interactions in the surrounding rock. The detectors are shielded from

these by surrounding the entire apparatus with large tanks of water which effectively thermalize fast neutrons.

In the current configuration, the dominant source of background is due to α-particles in the materials of the detector. Although great advances have been made by fabricating the detectors from ultra pure materials, this is still the sensitivity limiting background for the experiment. Figure 2 shows the detector response as measured with γ, neutron, and α calibration sources, as well as the expected response of the detector to a 50 GeV/c^2 WIMP. By controlling the backgrounds and by measuring the bubble formation rate as a function of temperature, it is possible to distinguish a WIMP signal from the irreducible background.

Data are collected in runs of about 60 hours, followed by 15 hour compression periods where the detectors are reset by driving the bubbles back to the liquid phase and curing the gel matrix.
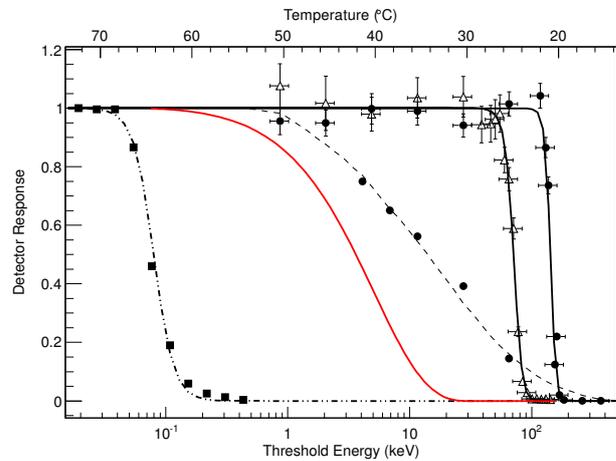

Fig. 2: Response to different kinds of particles in superheated C_4F_{10}. From left to right: 1.75 MeV γ-rays and minimum ionizing particles (dot-dashed) only observable at very high temperatures; ^{19}F recoils modeled assuming the scattering of a 50 GeV/c^2 WIMP (red); poly-energetic neutrons from an AcBe source (dotted); α particles at the Bragg peak from ^{241}Am decays (open triangles); and ^{210}Pb recoil nuclei from ^{226}Ra spikes (full dots). The last two correspond to α sources in the gel, and within the droplet, respectively.

3 Results from PICASSO 2012

The most recent results from PICASSO [7] were published in 2012 based on a set of 10 "golden detectors" - ones which had lower backgrounds and reproducible behavior. The data set corresponded to 114.3 kg-days. To monitor the stability and response of the detectors, they were calibrated every 3 months, on average, using an AmBe neutron source. The analysis proceeds by examining the power and frequency spectra and the timing of the acoustic signals to identify real bubble nucleations and remove acoustic noise. In this way the true bubble rate for each detector at each temperature is determined. In the temperature range of operation, the α background rate is observed to be constant as the detectors are fully efficient at detecting them. A hypothetical WIMP signal would be observed as a departure from the flat background, appearing at a particular temperature (threshold)

according to the mass assumed for the WIMP. Hence the fitting procedure is to fit the data with the probability distribution functions for WIMP induced recoils as a function of WIMP mass and cross-section. In all cases, the WIMP amplitudes were consistent with zero, and hence we determine a limit (at 90% C.L.) in the mass- cross-section plane.

Figure 3 shows the results obtained, as published in 2012, for spin-dependent interactions on ^{19}F [7]. At this time PICASSO had the best limits in the low mass region and they were in tension with the Dama/Libra interpretation, even with channeling [9, 10]. To facilitate comparison between experiments the results are normalized to the cross-section for WIMPs on protons.
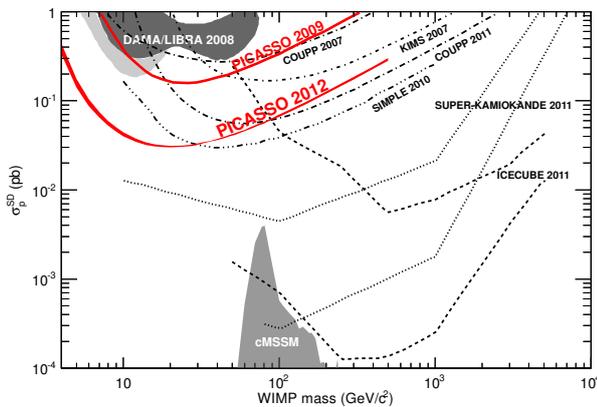

Fig. 4: PICASSO limits in the spin-independent sector (90% C.L.). Only the region with low WIMP masses is shown, and this is the only area in the spin-independent sector where PICASSO has sensitivity. The allowed regions of DAMA/LIBRA, CoGeNT and CRESST and the exclusion limits by XENON100 and CDMS are also shown. The broadening of the PICASSO exclusion limit is due to the uncertainty in the energy resolution at low threshold energies. See [7] and references therein for further detail.

Fig. 3: PICASSO upper limits (at 90% C.L.) on spin-dependent WIMP-proton interactions. The PICASSO limits were shown as full lines. Additional curves were from KIMS, COUPP and SIMPLE. The DAMA/LIBRA allowed regions were also shown (light grey: with ion channelling). Also shown were the spin-dependent search results in both soft and hard annihilation channels from SuperK and AMANDA-II/IceCube; and some theoretical predictions in the grey shaded area at low cross-sections. See [7] and references therein for further detail.

Since this figure was produced, new results from SIMPLE [11], KIMS [12] and COUPP [8] have been reported. Although these newer results have an improved sensitivity compared to PICASSO over much of the mass range, PICASSO still has the best limits at the lowest masses, a consequence of the very low threshold obtainable with C_4F_{10}.

With detectors of low atomic mass, PICASSO is not very sensitive as a spin-independent search experiment. Fortunately, the low threshold capability allows PICASSO to play a role at the lowest of masses, precisely in the interesting region where there are several hints for dark matter or misunderstood backgrounds. Figure 4 shows the results obtained, as published in 2012, for spin-independent interactions [7]. At this time PICASSO showed that it had potential to contribute to the understanding in this range of masses. Again, PICASSO is in tension with the DAMA/LIBRA results, almost completely ruling them out.

With the 2012 data release PICASSO demonstrated that it was competitive with the rest of the community, that it had world leading results at the lowest masses, and that the technology produced robust detectors with good sensitivity.
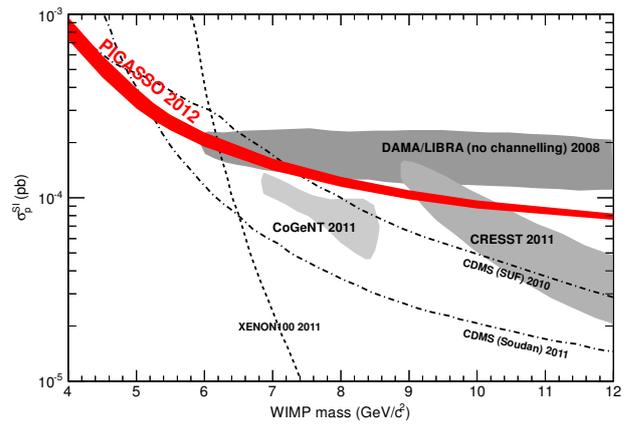
4 Current Status of PICASSO

PICASSO is currently operational with 32 detectors. To improve on the 2012 limits, significant enhancements had to be made. The main improvements are as follows:

- The radio-purification procedures were improved, and the previous generation of detectors have been gradually replaced with newer, lower background detectors.

- The experiment was moved to a new location in S-NOLAB where there was sufficient room to add more water shielding for improved neutron mitigation and to provide additional space for testing new detectors.

- PICASSO discovered that it was possible to distinguish between α-particles and recoil events when they were contained in the active material. Physically, this is a consequence of the difference in acceleration for a single expanding proto-bubble (in the case of recoils) or multiple proto-bubbles along a track, in the case of contained α particles. To fully exploit this capability required upgrades to both the electronics and the data acquisition systems in order to most accurately record the bubble initiation phase. While this is sometimes a useful tool for PICASSO, in most detectors the majority of α-particles originate in the gel and this technique does not help in those cases. In contrast, it has proven to be very useful when applied to experiments like COUPP where all of the α radioactivity of concern is found in the active material.

PICASSO is now working on the analysis of the next data set which includes the full set of 32 detectors, most of which have significantly lower backgrounds and longer exposures than the previous detectors. The expectation is for this analysis to be complete by summer, 2013, and this should produce a much better limit, particularly at low masses, compared to the 2012 data set.

5 Longer Term Plans

The current detector technology is reaching its limits. The purification systems have been very successful in developing the detectors this far but with 98% of the detector volume comprised of the difficult to purify gel matrix, further gains will be marginal. In addition, the discrimination technique developed by PICASSO works when the contamination is in the active material. When an α-particle straggles into the active material from the gel, the remaining track is short, and the recoiling nucleus is not present, so these behave like nuclear recoil events and the discrimination power is weaker. Finally, operating an array of detectors, each of which behaves slightly differently, and so requires individual calibration and analysis techniques, makes scaling up to a tonne scale detector quite difficult.

What has been learned from PICASSO to date is very valuable and will help guide the development of the next phase. In particular, robust purification techniques have been developed, the acoustic discrimination technique has been discovered, the capability of C_4F_{10} and similar gases for low threshold measurements has been demonstrated, very accurate measurements have been made to characterize the detector performance using mono-energetic neutrons from the Montreal tandem Van de Graff and world leading dark matter exclusion curves have been produced.

PICASSO is exploring design ideas for the next generation detector. They have joined forces with the COUPP collaboration for this exercise which brings together much of the world expertise in this field. The ultimate goal is a detector of order 500 kg or more. Two different technologies for this are being explored. The default plan is a scale up of the current COUPP style bubble chambers, with the Picasso style discrimination, and likely C_4F_{10} or a similar gas characterized by PICASSO. This detector is in a reasonably advanced state of design. COUPP and PICASSO are jointly working on a prototype that will test the COUPP bubble chamber technology with the known PICASSO fluids, to see if that eliminate some of the background issues experienced by COUPP. In parallel, COUPP have begun operation of a 60 Kg chamber which is sufficiently large that rapid measurements can be made to test background hypothesis while still making a solid physics measurement.

The other technology being investigated is known as a Geyser. These are similar to bubble chambers in that they contain a single large volume of active liquid, but they are self regulating. By providing cooling at the top of a large sealed flask, it is possible to have droplets which form in the superheated liquid rise upwards to the neck. In doing so, they build pressure, the fluid is no longer superheated, and the expansion stops. The bubbles then cool in the neck and condense. This drops the pressure and the bulk fluid becomes active again. The main advantage of this technique over a COUPP style bubble chamber may be the possibility of operating at much lower pressures (and hence less materials and sources of radioactivity) . Testing began with small prototype geysers, and so far they have demonstrated that they work well at detecting neutron sources, and the discrimination between recoil and α-particles is extremely good.

Hence there are two similar, and very promising technologies that might be employed in the ultimate 500 kg detector. The choice of technology will be made in 2013 with plans to construct and have the detector operational by 2015. The detector will be designed, built and operated by the joint COUPP/PICASSO collaboration. Such a detector will improve the current sensitivity by many orders of magnitude over current limits, and will probe most of the expected parameter space thought to be available for dark matter WIMPs.

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