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Searching For Dark Matter With PICASSO

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Abstract

The Project In CAnada to Search for Supersymmetric Objects (PICASSO) at SNOLAB searches for Weakly Interacting Massive Particle (WIMP) interactions with ^{19}F. It is particularly sensitive to spin-dependent particle interactions. It uses a droplet technique, based on the principle of a bubble chamber, in which phase transitions in superheated liquids can be triggered by WIMP induced nuclear recoils. The detection process allows a highly efficient suppression of backgrounds from cosmic muons, γ rays and electrons. Recent results and progress are presented and future plans to scale this technique to large masses with the PICO collaboration are briefly discussed.

Selection and peer review is the responsibility of the Conference lead organizers, Frank Avignone, University of South Carolina, and Wick Haxton, University of California, Berkeley, and Lawrence Berkeley Laboratory

Keywords: Dark Matter, WIMPs, Superheated Liquids, PICASSO, SNOLAB

1. Introduction

The search for dark matter and the missing mass of the universe is one of the most important questions in modern astroparticle physics. The Project In Canada to Search for Supersymmetric Objects (PICASSO) located at SNOLAB in Canada uses a superheated liquid target of C_4F_{10} to search for Weakly Interacting

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Massive Particles (WIMPs). This detector complements other dark matter searches as the target of ^{19}F is the most sensitive (apart from a free proton) to spin dependent dark matter searches due to the favourable spin enhancement factor. Searching for spin dependent dark matter allows a more complete investigation of the full parameter space when combined with searches for spin independent WIMP interactions. The low detection threshold of the experiment (1.7 keV) allows the search for low mass WIMPs (below 20 GeV/c^2) in regions of parameter space which have caused much interest and possible discovery claims.

2. Detector Description

PICASSO uses droplets of a superheated target, where active mass is held in a metastable liquid state. If sufficient energy E_{min} is deposited within a critical radius R_{min} (where E_{min} and R_{min} are proportional to a temperature dependent superheat, surface tension, and critical length and energy efficiency factors) then a phase change can occur and the liquid droplet becomes a gas bubble [1]. The resulting explosion is measured acoustically.

The sensitivity of a superheated droplet is defined by a threshold which is dependent on operating temperature and pressure. The threshold has been measured and characterized with a mono-energetic neutron beam in the range of 0.86-800 keV. The detector response is particle dependent, with detection of internal α particle contamination fully efficient above threshold, leading to a flat α rate at all temperatures. WIMP interactions are expected to produce an exponentially increasing rate below 200 keV threshold energy. Electrons and γ rays have insufficient ionization energy to form bubbles except at threshold well below 0.2 keV, leading to suppression of rates from these particles by factors between 10^{-8} and 10^{-10}. The response for particles and γ rays is shown in Fig. 1.

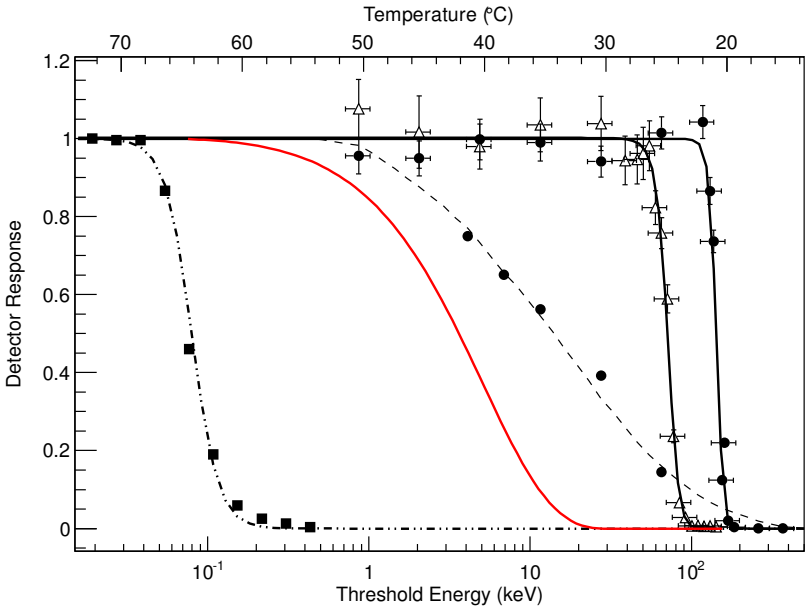

Fig. 1. Response to different kinds of particles in superheated C_4F_{10}. From left to right: 1.75 MeV γ rays and minimum ionizing particles (dot-dashed); ^{19}F recoils modeled assuming the scattering of a 50 GeV/c^2 WIMP (red); poly-energetic neutrons from an AcBe source (dotted); α particles at the Bragg peak from ^{241}Am decays (open triangles with error bars); and ^{210}Pb recoil nuclei from ^{226}Ra spikes (full dots with error bars).

The PICASSO detector consists of 32 individual modules containing C_4F_{10} droplets (~200 μm diameter) which are suspended in a polymerized aqueous gel matrix. Each module is a 4.5L acrylic cylindrical container (radius = 7 cm, height = 40 cm) containing active mass of ~ 85 kg of C_4F_{10}. On the external

surface of the container 9 piezoelectric transducers are spaced at regular intervals to record the sound of bubble formation. The modules sit in temperature and pressure control units and are surrounded by a 50 cm thick water shield, reducing external neutrons by a factor of 400. A full description of the detector is found in [2].

The detector data taking consists of regular runs of 30-50 hrs at a time, performed at temperatures between 25-50 °C. After each run the detector is pressurised for 11 hours to return the gas bubbles to the liquid droplet state. At regular intervals (~3 months) a calibration with a polyenergetic AmBe neutron source is performed.

PICASSO began operating in 2008 and ran continuously until 2010. The experiment was then moved to a new location within SNOLAB where data taking ran from 2011 until the end of 2013.

3. Analysis and Intermediate Results

Intermediate PICASSO results were published in 2012. This included a study of data in the first phase of PICASSO (up to 2010). A subset of 10 low background and high exposure modules were selected for analysis, giving a total target mass of 0.72 kg of ^{19}F with an exposure of 114 kg·days. The best detector had an average background rate of 20.0 ± 1.9 (stat.) ±1.3 (syst.) cts/kg(F)day.

Events were selected using variables derived from acoustic energy, frequency, signal rise time and correlation with other events in time. This allows a clear separation of particle induced events from electronic and acoustic noise events. After efficiency corrections event rates are calculated at all thresholds.

The data was compatible with no WIMP signal so a limit on the WIMP-^{19}F cross section was obtained for each detector by fitting a flat α particle background and a WIMP response curve. The results were converted to WIMP-proton cross section (σ_p) to allow comparison with other experiments. The best spin dependent proton cross section was found to be $\sigma_p^{SD} < 0.032$ pb (90% C.L.) at WIMP mass $M_W = 20$ GeV. This resulted in a factor 5 improvement on first PICASSO results and full exclusion of the spin dependent DAMA/LIBRA result. The exclusion curve is shown in Fig. 2. The limits were also calculated in the spin independent sector, where at $M_W = 20$ GeV/c^2 the cross section was found to be $\sigma_p^{SI} < 6.1 \times 10^{-5}$ pb (90% C.L.). At low WIMP mass the result excluded the majority of the allowed DAMA/LIBRA (no channelling) result region. These results are presented in full in [3].

4. Final PICASSO Results

PICASSO completed normal running at the end of 2013 and final analysis of results is currently underway. This includes an additional ~660 kg·days of exposure. During operation detector development was refined and high background detectors were removed; best final detector background rates are expected to be 1-2 orders of magnitude lower in rate than the detectors in the 2012 publication.

Improved analysis tools have been developed and refined. An event localization has been implemented, using the time differences between signal readout at piezoelectric transducers to reconstruct event position. This tool has been used to identify and remove radioactive hotspots in the detectors and to create fiducial cuts removing a class of background events found at the edge of the detectors. A wavelet analysis has been implemented to remove a non-particle related temperature dependent background found in some detectors. A number of signal shape variables have been developed to clean the analysis.

It was observed by the PICASSO collaboration that α particle signals are louder than neutrons. This is now understood as being due to nuclear recoils having point like bubble nucleation sites, while α particles have track like nucleations due to both a nuclear recoil and energy deposited at the α Bragg peak. Studies of this has shown that α particle tracks fully contained within a superheated droplet can be fully separated from neutrons, but α particle backgrounds near the edge of the droplet (inside or outside) can not be clearly separated from nuclear recoils. Ongoing work in PICASSO is being performed to improve resolution and perform partial or full discrimination. Upgrades have included: use of event localization for distance and angle corrections; fiducial volume cuts; wavelet analysis variables; corrections for time of event during run; pulser for gain stability corrections; double speed electronics; gain optimization of electronics; and new variables based on event shape.

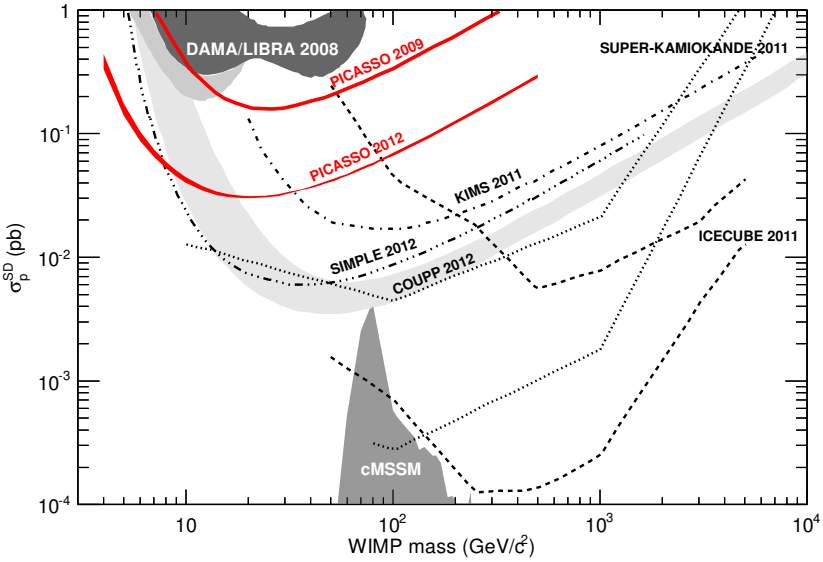

Fig. 2. Upper limits at 90% C.L. on spin dependent WIMP-proton interactions. PICASSO limits are shown as full lines. Additional curves are from KIMS [4], COUPP [5] (light grey band) and SIMPLE [6]. The DAMA/LIBRA [7, 8] allowed regions are also shown (light grey: with ion channelling). Also shown are the spin dependent search results in both soft and hard annihilation channels from SuperK [9] and AMANDA-II/IceCube [10]; and theoretical predictions discussed in [11, 12].

5. Ongoing Work

Research and development work to build a large scale detector is underway, with the aim to improve active mass by using a bulk superheated liquid. A condensation chamber technique is being investigated where bubbles are collected above the chamber and cooled, condensing them back to a liquid state. This technique minimizes detector dead time and the use of bulk liquids allows to neglect the effect of α events at the edge of the droplet. Tests with a condensation chamber filled with ethanol have already shown full α-neutron discrimination.

The PICASSO and COUPP collaborations have recently joined to study large scale superheated detector options as the PICO collaboration. The current projects include PICO-2L (presented by Russell Neilson at this conference), a bubble chamber filled with C_3F_8 running since Fall 2013. This will provide a low energy threshold and excellent α-neutron discrimination, with large sensitivity in the spin dependent sector. Plans to develop this to large scale (PICO-250L) are under investigation.

6. Conclusions

PICASSO is a leading experiment searching for low mass WIMPs, particularly in the spin dependent regime. It has published best spin dependent WIMP-proton cross section limits at $\sigma_p^{SD} < 0.032$ pb (90% C.L.) at WIMP mass $M_W = 20$ GeV (though subsequently improved limits from COUPP and SIMPLE have overtaken PICASSO). Final results will be published in 2014 with a factor ~ 6 increase in exposure and improvements in background reduction and α-neutron discrimination. Research and development using bulk superheated liquid detectors continues, exploring condensation and bubble chambers in the framework of the PICO collaboration.

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