New Approaches to Dark Matter and Neutrino Detection

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Abstract. Two new initiatives in astroparticle and neutrino physics are briefly reviewed. COUPP employs ultra-stable heavy liquid bubble chambers to search for WIMP dark matter. First results leading to improved limits on spin-dependent WIMP couplings are presented, together with the most recent progress and prospects. CoGeNT aims at the detection of very faint (~100 eV) signals in detectors massive enough (~1 kg) to allow searches for rare processes, using recently developed p-type point contact (PPC) germanium detectors. The broad range of applications (coherent neutrino scattering, light WIMP searches, double-beta decay) for these semiconductor devices is succinctly described. The implications from their first underground operation are discussed, as well as the status of an ongoing deployment at the San Onofre nuclear generation plant.

1. Preface

There is nothing new under the sky. The old adage fits quite nicely when applied to the "new" methods for particle detection briefly reviewed below. In the first case, the Chicagoland Observatory for Underground Particle Physics (COUPP), we have revisited that old shoe, the bubble chamber, to find new applications for it at the forefront of modern astroparticle physics. In CoGeNT (Coherent Germanium Neutrino Technology) we have taken devices tested and shelved by germanium detector manufacturers a quarter of a century ago (we find out only now!), realizing a plethora of exciting applications for them. Pausing to acknowledge that these projects could have been undertaken decades ago is a humbling exercise. But not nearly as much as being in Carolina celebrating the pioneering efforts of Frank Avignone and Ettore Fiorini. Their accomplishments, when paraded together as during the week of the CISNP, pretty much define the early days of what we would now call the intersection of neutrino, astroparticle and underground physics (Fig. 1).

2. COUPP: not your daddy's bubble chamber

COUPP uses CF_3I bubble chambers to look for particle dark matter, in particular Weakly Interacting Massive Particles (WIMPs) (Fig. 2). The operation of COUPP chambers at a modest superheat permits such searches for exotica in a detector otherwise known for its instability. The advantages of this approach are many, including an optimal target maximally sensitive to both spin-dependent and -independent WIMP couplings, an extreme intrinsic insensitivity to minimum ionizing backgrounds (Fig. 2), low cost and room-temperature operation.

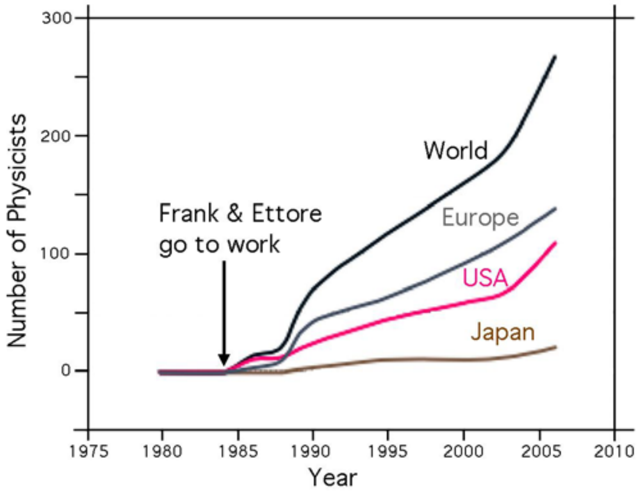

Figure 1. And this is just for the field of Dark Matter detection. Figure shamelessly stolen and adapted from an original by B. Sadoulet.

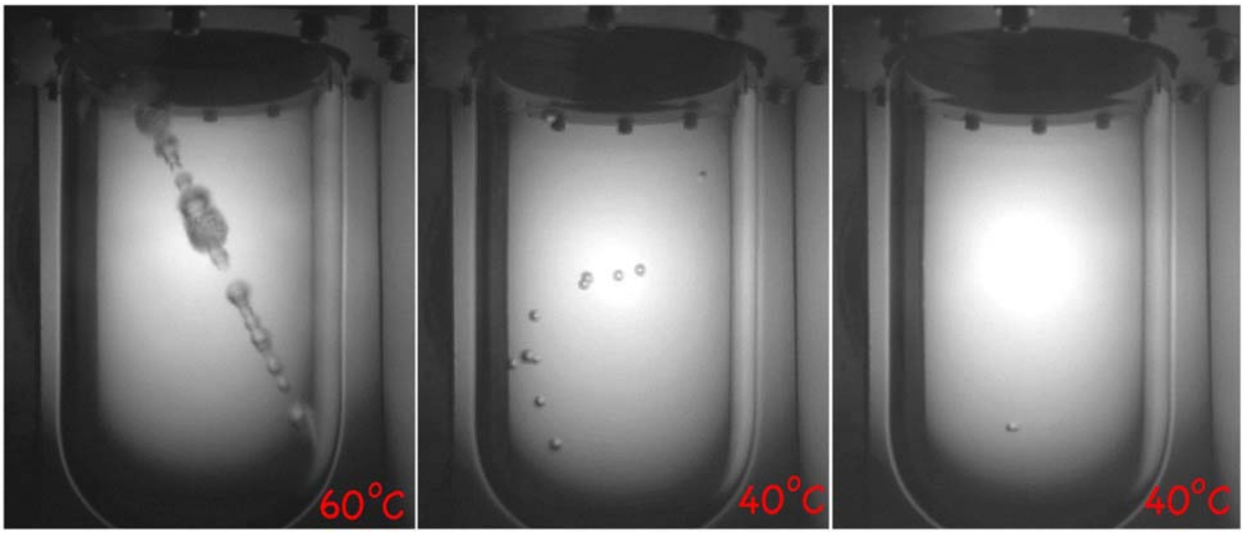

Figure 2. Left: at a high degree of superheat this bubble chamber containing 2 kg of CF_3I displays the typical sensitivity to minimum ionizing particles. The track from a cosmic muon traversing it looks rather robust, due to the relatively slow triggering of recompression in this device. Center: closer to equilibrium, only particles with high stopping powers such as nuclear recoils from WIMPs or neutrons can produce nucleations. The intrinsic background rejection against gamma-induced events has been shown to be better than 10^{-10} (the best in the field) in conditions that nevertheless lead to a full response to low energy recoils [1]. Simultaneous bubbles mark the sites of multiple neutron scattering. A WIMP can, on the other hand, produce single bubbles only (right panel).

COUPP released its first results during 2008 [1]. This analysis used engineering runs, where a majority of events was caused by alpha-recoils from radon penetration into the chamber. No effort was made at the time to control this source of background. The spin-dependent limits obtained are nevertheless some of the best anywhere (Fig. 3). These bounds exclude the possibility that the DAMA annual modulation effect [2] might originate in spin-dependent WIMP couplings. Radon control has since been implemented, resulting in a considerable reduction in event rate. The residual signal agrees with the expectations from muon-induced neutrons at the shallow depth of the NUMI gallery at FNAL, where COUPP currently operates (Fig. 4). A muon veto has been commissioned to tag these events, further reducing the background.

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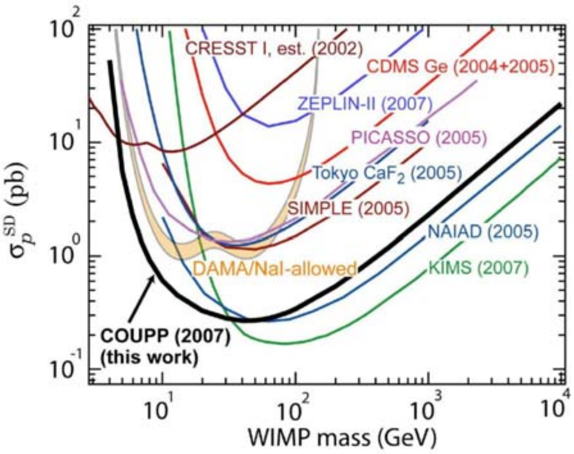

Figure 3. Improved spin-dependent limits from COUPP [1]. The last region of phase space allowing an interpretation of the DAMA annual modulation effect on the basis of spin-dependent WIMP interactions is eliminated by these bounds.

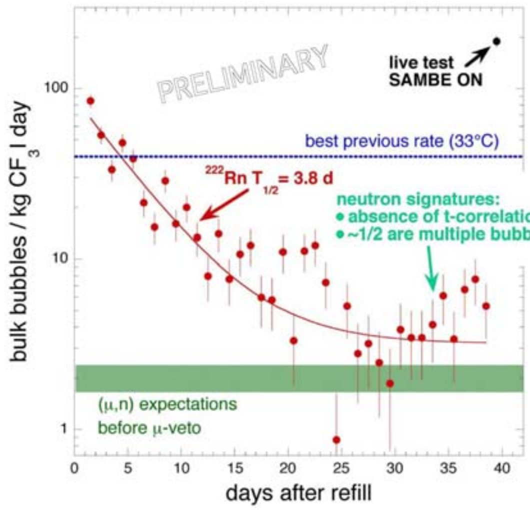

Figure 4. Observed reduction in event rate from radon control. The residual neutron-like rate is now tagged with a 4π muon veto, recently commissioned. The increase in rate resulting from a switchable Am/Be calibration source (SAMBE) is also visible in the figure.

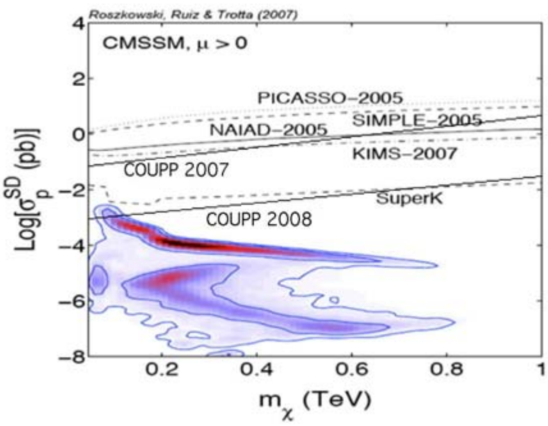

Figure 5. Sensitivity expected from COUPP during 2008, based on a preliminary inspection of recent data. The colored region shows theoretically favored spin-dependent couplings [3].

Figure 6. Images from a new 60 kg COUPP bubble chamber under construction at Fermilab.

Based on a preliminary analysis of recent data, we expect to reach the region of spin-dependent WIMP couplings favored by supersymmetric models very soon (Fig. 5). This would be a first, and particularly important since the supersymmetric phase space probed is complementary and different from that explored by CDMS and XENON [4]. The collaboration plans to commission two new chambers during the present year, one containing 20 kg of CF_3I in a new (windowless) simplified design, and a second conventional model containing 60 kg of active mass (Fig. 6). The first chamber is already operational and undergoing tests above ground. Footage of the "first light" (first bubble) from this large device can be found at [5]. After a short period of tests at 300 m.w.e., the chambers will be installed deep underground, Soudan and SNOlab being presently under consideration. A collaborative effort with Canadian members of SNO and PICASSO, specialists in fluid purification, has started. The collaboration is presently considering a preliminary design for a 500 kg chamber, a direct technical extrapolation from the devices already built and under test.

3. CoGeNT: the "neutrino radio" at last?

We recently reported on a new type of germanium detector [6] (Fig. 7). PPCs (p-type point contact), as we refer to them, feature an unprecedented marriage between large mass and low electronic noise, opening up more than a decade of low-energy (sub-keV) range to exploration with ultra-low background devices (Fig. 8). We have recently learned that Canberra Industries, our partners in crime in this (ad)venture, had actually experimented with such devices (minus the emphasis on ultra-low electronic noise) as early as in 1983, finding no immediate use for them. To make the situation even more strange, a quasi-planar version of this design, the so-called BEGe detector, has been commercially available from Canberra for about 15 years, finding a niche in very specific markets only. Good things can happen when industry and academia finally sit down to listen to each other. While our initial interest in the design was motivated by low-energy applications, we soon realized their strong potential for high-energy gamma background discrimination (Fig. 9) in next-generation double-beta decay projects such as MAJORANA.

The first PPC prototype [6] was operated early in 2008 in a shallow underground site (300 m.w.e.). This new laboratory is part of Chicago's Tunnel And Reservoir Project (TARP), sited 20 minutes from the UC campus (yes folks, we are talking them sewers). A full shield featuring a triple active veto was built around the detector. These runs revealed a low-energy background internal to the cryostat, now in the process of being addressed. The collected data have nonetheless allowed us to impose new limits on light WIMPs (Fig. 10), ruling out the very last possibility remaining for the DAMA modulation [2] to be caused by a standard WIMP halo. These results can be found in [7]. Besides their unmatched sensitivity to light WIMPs, PPCs are presently the only existing detector capable of testing the alternative hypothesis that light axion-like particles might be the cause for the DAMA effect. While TARP runs already constrain this hypothesis, the ongoing cryostat upgrade should allow us to confirm or deny this exciting possibility [7]. The detector is now taking data 25 m away from one of the reactors at the San Onofre Nuclear Generation Station (SONGS, Fig. 11). We expect to perform in this site a first observation of coherent neutrino-nucleus scattering, a process of great interest in fundamental and applied neutrino physics [6]. The large cross-section expected from this process can lead to a miniaturization in the mass of low-energy neutrino detectors by up to three orders of magnitude, enabling technological applications such as neutrino reactor safeguards.

PPC detectors are becoming increasingly popular within MAJORANA. The planned MAJORANA 60 kg demonstrator will feature at least two-thirds of its target mass as PPCs. Several PPCs have been successfully developed within MAJORANA during 2007, demonstrating reproducibility in their manufacture. One more, featuring upgraded electronics and based on a BEGe crystal, is under construction for the University of Chicago group. A vigorous research program on improved front-end electronics is in progress: we envision realistic future energy thresholds lower than 100 eV. In other words, the energy resolution typical of a CCD, embodied in a large ($\sim$1 kg) germanium gamma spectrometer.

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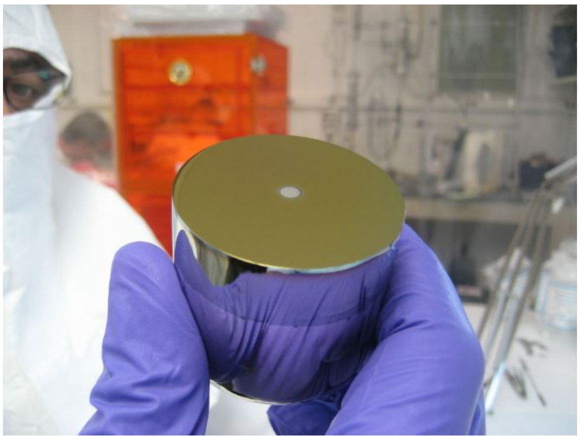

Figure 7. A view of the point contact region in a PPC germanium detector. Minutes after this photograph was taken, the author and his friends proceeded to rather nonchalantly maim this contact, "bricking" the detector.

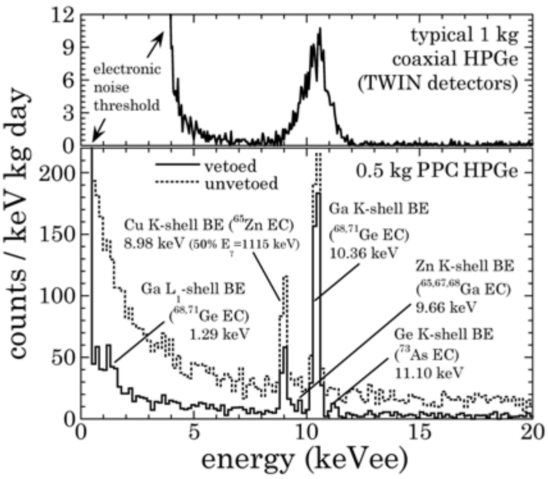

Figure 8. (from [7]) Improvements in threshold and resolution in a PPC design (bottom), compared to a typical coaxial HPGe (top). Cosmogenic peaks are clearly resolved in the PPC spectrum. BE stands for binding energy, EC for electron capture.

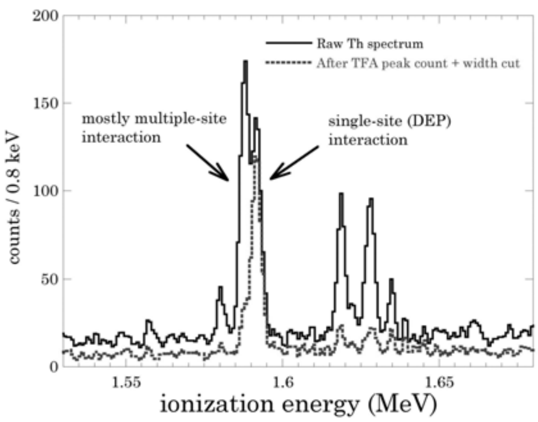

Figure 9. (from [6]) Natural Thorium irradiation of a PPC detector and effect of pulse-shape cuts on rejection of multiple-site events (see text). The energy resolution appears slightly degraded due to the limited resolution of the digitizer employed (8 bit).

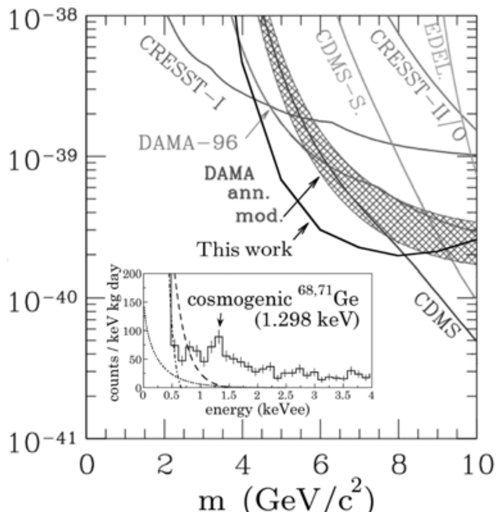

Figure 10. (from [7]) New limits on spin-independent couplings from light WIMPs, from a shallow underground run of the first PPC prototype (see text).

4. Afterword

Here's to Frank and Ettore, with the desire, perhaps certainty, that the many exciting fronts of research they opened up for the rest of us should bear fruit very soon. May we all get to meet during the next CISNP to discuss some discoveries. Exclusion plots and improved limits are nice, but how about a little signal now and then? Patience comes to those who wait...

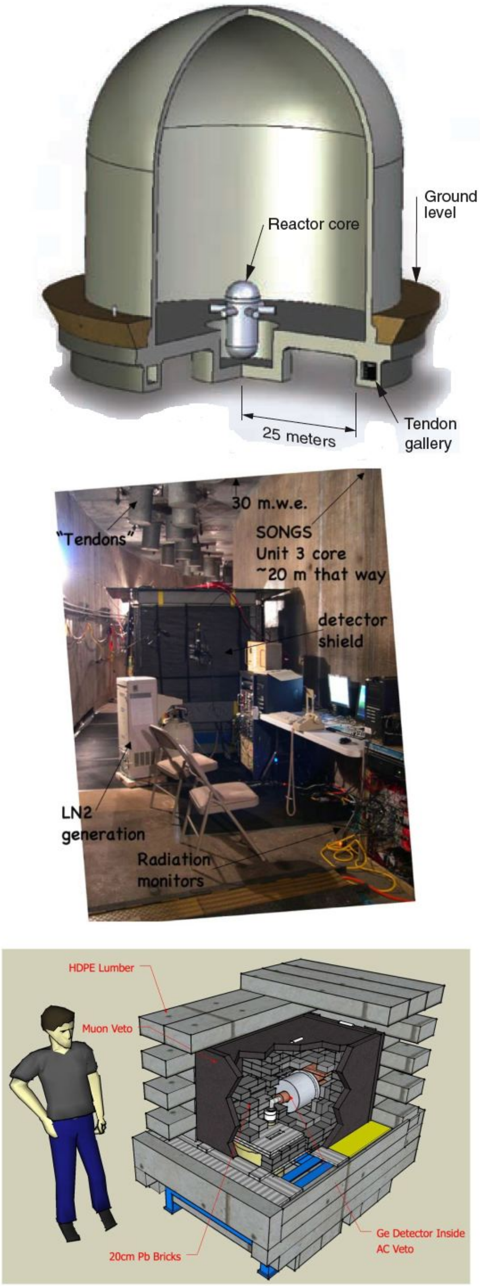

Figure 11. Top: "Tendon" galleries are commonly found along the periphery of power reactor containment domes. The term makes reference to the endings of the steel reinforcement cables that criss-cross the structure. Middle: the experimental setup for our ongoing attempt at coherent neutrino detection. Galleries like these combine a high (anti)neutrino flux ($\sim 10^{13}\ \nu/\mathrm{cm}^2$ s) with the background reduction benefits from a ~30 m.w.e. overburden. Liquid nitrogen is generated from air in situ. Bottom: shield design. A triple active veto is combined with several layers of passive shielding. A low-efficiency external muon veto is not shown in the diagram, but visible in the photograph.

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