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The XENON dark matter experiment

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We report on progress of the XENON collaboration, which is developing a liquid xenon time projection chamber technology for use in a very-large-mass dark matter experiment. The collaboration is working towards demonstration of simultaneous ionization and scintillation measurement to provide strong background rejection. A 100 kg module will powerfully probe WIMP rates predicted by supersymmetry.

1. WIMP DARK MATTER

The nature of dark matter, which constitutes some quarter of mass-energy density of the universe [1], is one of the central questions in physics and cosmology today. Arguably the most attractive candidate for this dark matter is Weakly Interacting Dark Matter (WIMPs), particles frozen out of the big bang if their interactions have the strength of the weak scale of particle physics. They are also a generic prediction of supersymmetry. WIMPs in the Milky Way can be detected by their elastic scatters on nuclei in a terrestrial detector, but the interaction rate and deposited energy are small (for an overview, see [2]). The best published limits, from EDELWEISS [3] and CDMS [4], using detectors of roughly 1 kg, are just now gaining sensitivity to WIMPs with the largest interaction rates expected. Predicted interaction rates range at least 4 orders of magnitude lower than this, so that a fully comprehensive search requires much larger detectors.

2. A LIQUID XENON TPC

The newly formed XENON collaboration is developing a technology that promises to be readily scalable to very large size (tons or more), and takes advantage of the high purity and favorable scintillation and ionization properties of liquid xenon. This is a dual phase [5] liquid xenon time projection chamber (TPC). Particle interactions in liquid xenon create both ionization and (“primary”) scintillation. Electrons are drifted to the surface of the liquid via a high electric field and extracted into the gas phase, where they create copious amounts of proportional (“secondary”) scintillation and, potentially, undergo charge amplification. An array of PMTs measures both the primary and secondary scintillation light. The X-Y location of the event is reconstructed to ≈ 1 cm by the secondary light, and the event depth in the liquid is given by the time difference between the light pulses (typical electron drift speeds are 2 mm/μs).

This technology has several advantages. A combined ionization and scintillation measurement will give a powerful discrimination of

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background electron recoils from nuclear recoils caused by WIMPs; nuclear recoils suffer a strong deficit of ionization because of recombination in their high-charge-density, short-length tracks. Ionization has been measured by alphas [6], which have similar charge density to nuclear recoils, though it has not yet been demonstrated for nuclear recoils. Xe is also readily purifiable and therefore free of most troublesome radioactive backgrounds, with the exception of ^{85}Kr (see below). The materials of detector construction are all low in radioactivity, with the exception of PMTs. Finally, the construction techniques are inherently scalable to large size.

The primary challenge in this technology is the low thresholds needed for dark matter detection. For the ionization signal, proportional scintillation in the gas phase will allow measurement of single electrons. The efficiency of photon collection for the primary scintillation signal is maximized primarily by use of a CsI photocathode at the bottom of the detector [7]. It is also enhanced by a PTFE can which contains the liquid Xe and has 90-95% reflection [8] for the 175 nm scintillation light, and by using a high-transparency wire grid to define the electric fields.

3. CURRENT PROGRESS

Though most elements of the technology have been demonstrated separately by various groups, it remains a formidable challenge to bring all the necessary pieces together. The XENON collaboration brings a history of experience to attacking this challenge. The Columbia group is one of the world's mosted experienced with liquid Xe detectors, in particular with the LXEGrit gamma-ray astrophysics TPC [9]. Rice shares in this experience, and the Brown and Princeton groups have extensive experience in dark matter detector development [4] and low-background techniques.

Several prototype detectors have been constructed and tested at Columbia, with assistance from the collaboration. The goal is demonstration of nuclear recoils discrimination by making the first measurement of ionization for nuclear recoils.

Ionization and scintillation produced by gamma rays has been measured In a small dual phase detector (active liquid volume of 4 cm Ø and 1 cm deep) with a single PMT and a Teflon can. This system demonstrated electron transmission from liquid to gas and proportional scintillation in the gas phase.

A larger detector, with liquid Xe only, have been used to study charge collection and operation of PMTs in liquid, using a variety of gamma ray sources. Charges were measured with a charge-sensitive amplifier, while two PMTs at either end of the drift space measured scintillation. The drift length is given by the time between photon and ionization signals. Electron liftetimes of $\approx$ 1 ms (equivalent to $\approx$ m drift lengths) have been demonstrated at kV/cm fields. In addition, several different PMTs were successfully operated in liquid Xe. A key element of this chamber is a recirculating Xe purification system: liquid xenon is removed from the bottom of the chamber, separately evaporated, purified with getters, and recondensed in a continuous process.

We have been testing PMTs from Hammamatsu that meet the twin requirements of low radioactivity and capability of operating at LXe temperatures. This work builds on development of a LXe capable PMT, the R6041 that was done for the LXeGrit TPC [9], and development of low background PMTs for the XMASS experiment [10]. The current model R8778 has a K/U/Th radioactivity of 140/18/7 mBq/2 PMT, substantially better than previous low-background PMTs. Ceramic bases that are compatible with use in ultra-pure liquid Xe have been demonstrated.

We are now constructing a 13 cm Ø, 10 Kg module with 7 PMTs, for which we will have a CsI photocathode. The cryostat uses a pulse tube refrigerator, and it has been successfully operated with $\leq$ 50 mK temperature stability. When the device is operated with the CsI, proportional scintillation in the gas will cause an electron pulse that must be gated to avoid runaway feedback. We are developing a gating system based on fast switching of the electric field used to extract charges from the liquid. We are also developing precision measurement and control of the liquid Xe level.

There are also several long-range developments. Two aim to use charge multiplication and measurement in the gas phase. Combined with the CsI photocathode, this eliminates the PMTs which by far are the most radioactive elements in the current design. Standard charge multiplication on a multi-wire grid is being studied at Princeton, and initial results with room temperature gas look promising. The Rice group is studying charge multiplication use GEMs, which also hold the possibility of having a CsI surface on the first GEM, aiding in the primary scintillation measurement. Both Princeton and Rice have constructed LXe cryostats. The Brown group is studying a new photomultiplier tube based on a micro-channel plate, which holds the promise of very low radioactivity segmentation, and favorable geometry.

Radioactive ^{85}Kr is the most problematic of all potential contaminants, as it is chemically very similar to Xe. We are developing a technology for the separation of Kr from Xe based on charcoal column chromatography [11]. Kr, in a helium carrier gas, propagates 20 times more slowly than Xe in an adsorption column, allowing separation. Preliminary chromatographic measurements indicate that technique is promising.

4. TOWARDS A 100 KG DETECTOR

We have completed a preliminary design of a 100 kg detector. The inner LXe volume is 50 cm, 30 cm deep with 180 kg material, of which the inner 120 kg is fiducial. A key feature is a 5 cm thick active LXe shield that completely surrounds the central detector, serving as an effective veto of gamma radiation from the PMTs. The separation is made by a UV reflective PTFE can, and closes with metal end caps. Only those photons that penetrate to the inner fiducial volume, Compton scatter at low angle, and then escape through the inner detector and shield are a potential background. The added thickness of the active shield reduces this rate significantly. The simulated background in fiducial volume, assuming a 99.5% rejection of electron recoil backgounds, is below 1x10^{-5} counts/kg/keV/day. This 100 kg module could operate for three months with negligible background, setting a WIMP-nucleon cross-section limit of $\sigma = 2x10^{-45}$ cm^2. As shown in figure 1, this is some 3 orders of magnitude better than the current best, and it is deep into the expected interaction rates from supersymmetry. A 10 module array would, also with negligible background, be able to measure 20 WIMP events at $\sigma = 2x10^{-46}$ cm^2

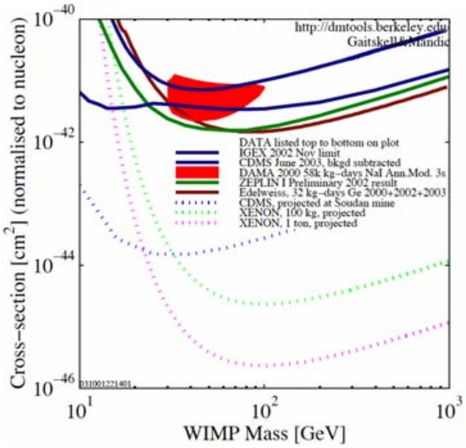

Figure 1. Current WIMP limits and the expected performance of 100 Kg and 1 ton version of the XENON experiment

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