Expected Performance of CryoArray

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WIMP-nucleon cross sections $\sigma \lesssim 10^{-9}$ pb may be probed by ton-scale experiments with low thresholds and background rates $\sim 20$ events per year. An array of cryogenic detectors (“CryoArray”) could perform well enough to reach this goal. Sufficient discrimination and background suppression of photons has already been demonstrated. Reduction of neutron backgrounds may be achieved by siting the experiment deep enough. Removal of the surface-electron backgrounds alone has not yet been demonstrated, but the reductions required even for this troublesome background are quite modest and appear achievable.

1. Introduction

Direct detection of supersymmetric WIMP dark matter in the coming decade appears possible. As shown in Fig. 1, experiments under construction should probe a large fraction of parameter space allowed by minimal supersymmetric theory and experimental constraints \cite{2–4}. Interestingly, if the sign of $\mu$, the Higgs mixing parameter in the superpotential, is positive, the WIMP mass must be $< 500$ GeV c$^{-2}$, and the WIMP-nucleon cross section must be $\gtrsim 10^{-9}$ pb \cite{3,4}, possibly making the entire parameter space accessible to a ton-scale WIMP-detection experiment. CryoArray would be a 1-ton deployment of semiconductor cryogenic detectors, of a type similar to that in use in CDMS II \cite{6}. This experiment would be sensitive to a WIMP-nucleon cross section $\sigma \approx 6 \times 10^{-10}$ pb, corresponding to a signal of a few WIMP interactions per 100 kg years.

The detectors of CDMS or CryoArray measure phonons and charge carriers separately for each interaction in order to allow rejection of the otherwise dominant electron-recoil background events. The background discrimination of these detectors has already been demonstrated to be so good \cite{1,6} that instrumenting a one-ton detector is fully justified. Below, we review in detail the expected performance of CryoArray, and conclude with a short discussion of the challenge to build such an experiment at a reasonable cost.

Figure 1. Comparison of theoretical expectations and experimental sensitivities for spin-independent WIMP-nucleon cross section vs WIMP mass. Curves indicate experimental limits for CDMS I \cite{1} (solid), and projected sensitivities for CDMS II at Soudan (dashed) and for CryoArray (dotted). The region outlined in dashes \cite{2} and the lightest shaded region \cite{2} each shows the results from calculations under an effective supersymmetry theory. The medium-gray and darkest regions \cite{2} arise from more constrained frameworks. These and other results and projections are available via an interactive web plotter \cite{5}.
Table 1
Mean single-detector event rates and counts (#) between 15–45 keV recoil energy in the Ge detectors of CDMS I, CDMS II, and CryoArray. Rates are listed in units of mdru (10⁻³ keV⁻¹ kg⁻¹ day⁻¹). Values listed for CDMS I and preliminary rejection efficiencies listed for CDMS II at the Stanford Underground Facility (SUF) have been achieved; values listed for CDMS II at Soudan and for CryoArray (at Soudan or at a potential deeper site) are projections.

| Site      | Event Rate (1000 kg day) | Exposure Rate (mdru) | Rejection Efficiency (%) | After Rejection (mdru) |
|-----------|--------------------------|-----------------------|--------------------------|------------------------|
| CDMS I SUF | 16 800 0.016             | 384                   | 99.96% 0.1 0 0            |
| CDMS II SUF | 16 800 0.04              | 960                   | 99.97% 0.3 0 0            |
| CDMS II Soudan | 2080 260 2.50          | 19500                  | 99.97% 6.5 5 0.07         |
| CryoArray | 13 500 195000            | 99.97% 65 15 0.001    |

| Site      | Event Rate (1000 kg day) | Exposure Rate (mdru) | Rejection Efficiency (%) | After Rejection (mdru) |
|-----------|--------------------------|-----------------------|--------------------------|------------------------|
| CDMS I SUF | 16 300 0.016             | 145                   | 95.00% 7 7 15            |
| CDMS II SUF | 16 80 0.04              | 96                    | 95.00% 5 5 4             |
| CDMS II Soudan | 2080 20 2.50            | 1500                  | 95.00% 75 15 0.2         |
| CryoArray | 1 500 15000              | 99.50% 75 15 0.0004   |
| Neutrons produced in shield |
| CDMS I SUF | 16 2200 0.016           | 1000                  | 99.90% 1 0 0             |
| CDMS II SUF | 16 1000 0.04            | 1200                  | 99.95% 0.5 0 0           |
| CDMS II Soudan | 2080 0.5 2.50         | 38                    | 99.90% 0 0 0             |
| CryoArray | 2080 0.5 500             | 7500                  | 99.90% 8 6 0.0004        |
| CryoArray NUSL | 4500 0.020 500        | 300                   | 99.90% 0 0 0             |
| Neutrons produced in cavern rock |
| CDMS I SUF | 16 50 0.016              | 24                    | ~ 50% 12 8 17            |
| CDMS II SUF | 16 22 0.04              | 26                    | ~ 50% 13 8 7             |
| CDMS II Soudan | 2080 0.22 2.50         | 16                    | ~ 50% 8 6 0.08           |
| CryoArray | 2080 0.22 500             | 3300                  | ~ 50% 1650 80 0.005      |
| CryoArray NUSL | 4500 0.01 500         | 150                   | ~ 50% 75 18 0.001        |
| CryoArray NUSL | 7200 0.0004 500       | 6                     | ~ 50% 3 3 0.0002         |

2. Expected Backgrounds

Table 1 lists photon, electron, and neutron background event rates in the energy range 15–45 keV for actual exposures of CDMS I and CDMS II at Stanford, and for projections for CDMS II at Soudan and for CryoArray. The goals of CryoArray reflect a factor 20 improvement in backgrounds, and a factor 10 improvement in electron discrimination, over the goals for CDMS II. The low-energy threshold is at 15 keV (rather than 5 or 10 keV) to avoid the contributions of the cosmogenic activation peaks and tritium beta spectrum in Ge near 10 keV.

The first columns of the table show the radioactivity event rates and the total numbers of events expected during the tabulated exposures. The other columns show how event-by-event discrimination can be used not only to reject most of the background, but also to subtract part of the residual background if the detector response is well enough understood. The results of this background subtraction include the effects of a 5% systematic uncertainty in the detector discrimination. A muon veto provides the neutron rejection (see Section 2.3). However, the neutron subtraction is performed based on the observed population of multiple-detector neutron events.
2.1. Photon Background

As shown in Fig. 2, the original CDMS II and CryoArray goals [8] for rejection of photons have already been exceeded. Based on the demonstrated rejection, the original photon-background goal for CDMS II (15 events after subtraction) has already been met, even without the expected 3× reduction in rate from increasing the experiment’s depth. Furthermore, the rejection efficiencies in Table II are statistically limited lower limits, and are probably overly conservative.

Based on the demonstrated rejection, CryoArray’s post-subtraction background goal for photons is achievable merely by reducing the raw photon rate to 13 mR/hr, only 2× lower than that currently achieved by IGEX [9] in HPGe detectors in the same energy range. This modest improvement is expected due to the increased detector self-shielding and multiple-scatter rejection from increased mass and many detectors.

2.2. Electron Background

The beta electron background represents a greater challenge. The current observed background rate for CDMS II at SUF is 80 mR/hr, 4× above the CDMS II Soudan goal of 20 mR/hr. Some of the current beta contamination may be due to exposure of the detectors to a leaking calibration source during testing. Use of such sources has been restricted. Moving to the deeper site at Soudan will remove essentially all cosmogenically produced betas, potentially the dominant beta background. Furthermore, the discrimination performance of the new detectors (see Fig. 2b) may well be sufficient even if CDMS II does not reach the absolute beta background goal.

For CryoArray, self-shielding will eliminate the beta backgrounds from materials surrounding the detector stacks. Nevertheless, improving the beta background by a further factor of 20 will require sensitive screening of the detectors and nearby materials. While screening to the required level of 0.02 counts keV$^{-1}$ m$^{-2}$ day$^{-1}$ for betas with $E > 50$ keV appears achievable [11], cleaning the materials may require new techniques. Improving the electron discrimination to 99.5% appears achievable through improvements of the signal-to-noise of the detectors.

2.3. Neutron Background

The low-energy (<10 MeV) neutrons from ($\alpha$,n) and fission processes in the rock are trivially stopped by hydrogenous shielding. Such shielding reduces the low-energy neutron flux by $\sim 10^4$ per 10 cm of material, so 70 cm of such shielding should make this neutron flux negligible.

Other neutrons arise from muons interacting inside the experiment’s shielding or in the cavern rock. The former can be tagged using a local active muon veto directly around the passive shielding. A muon veto efficiency of 80% is adequate at Soudan (2080 mwe) to ensure that these “shield” neutrons contribute negligibly to the CDMS II background. The demonstrated CDMS II muon veto efficiency of 99.95% would even be sufficient to limit this neutron background to a small enough rate at Soudan for CryoArray. A deeper site such as Gran Sasso (at $\sim 4$ kmwe) would reduce the neutron flux by $\sim 25^\times$, making the muon-veto requirement very modest.

The high-energy neutrons generated in the cavern rock by spallation processes of high-energy
muons are difficult both to veto and to stop. With the CDMS II polyethylene shielding sandwiching Pb shielding, ∼8 secondary neutrons from these “punch-through” neutrons should scatter in single detectors during the 2500 kg-day exposure, based on extensive Monte Carlo studies [11,8]. Because this neutron flux for deep sites is approximately proportional to the muon flux [12], increased depth is the easiest way to reduce this neutron background. Siting CryoArray at a depth of 4 kmwe would likely reduce this background sufficiently, while siting it at 7 kmwe should essentially remove this background. If the experiment were sited at <2000 mwe (e.g. WIPP or Soudan), either a much thicker liquid-scintillator buffer would be required around the detector in order to tag high-energy neutrons, or the cavern rock itself (or an outer heavy shield) would need to be instrumented with additional veto detectors in order to catch some part of the shower associated with the muon that generated the neutron.

3. Conclusions

CryoArray should work well enough to probe WIMP-nucleon cross sections σ < 10^{-9} pb once it is built. The most significant challenge at this point is determining how to build it at a reasonable cost. For CDMS II, the 42 detectors are being built using university facilities and technicians under the close supervision of CDMS physicists. Detectors are tested at least twice in batches of ≤ 3 in university dilution refrigerators. This time-consuming and physicist-intensive procedure is not practical for CryoArray’s ∼ 500–2000 detectors. An industrial approach is needed.

In order to “out-source” this effort, we will need to engineer and specify a stable and reliable high-yield process. Since it is not feasible to test each individual module prior to deployment in the array, the yield must be ≥ 90%. This goal is ambitious; current detector yields are ∼50%. We expect to continue to make gains in understanding pathologies in the processing steps during the remaining CDMS II construction period, which is scheduled for completion at the end of 2003. In 1–2 years we will have substantially more experience in fabricating and operating CDMS detectors. The knowledge gained will be essential for establishing a realistic plan for building CryoArray and assessing its likely performance. This knowledge will likely point the way to additional laboratory work to be carried out before a full-scale proposal is considered.

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