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 ~ 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 achieveable.

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 [2–4]. Interestingly, if the sign of μ, 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 [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 [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 [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.

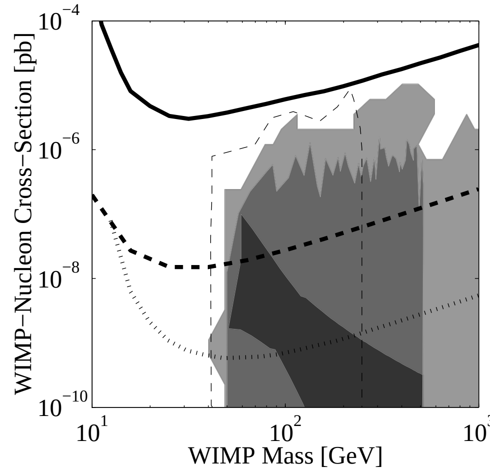

Figure 1. Comparison of theoretical expectations and experimental sensitivities for spin-independent WIMP-nucleon cross section vs WIMP mass. Curves indicate experimental limits for CDMS I [1] (solid), and projected sensitivities for CDMS II at Soudan (dashed) and for CryoArray (dotted). The region outlined in dashes [2] and the lightest shaded region [3] each shows the results from calculations under an effective supersymmetry theory. The medium-gray and darkest regions [4] arise from more constrained frameworks. These and other results and projections are available via an interactive web plotter [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	Depth (mwe)	Event Rate (mdru)	Exposure (1000 kg day)	Raw Events (#)	Rejection Efficiency	After Reject (#)	After Subtraction (#)	After Subtraction (mdru)
Photons									
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
Electrons									
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	0.001
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	Soudan	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	$\sim 50\%$	12	8	17
CDMS II	SUF	16	22	0.04	26	$\sim 50\%$	13	8	7
CDMS II	Soudan	2080	0.22	2.50	16	$\sim 50\%$	8	6	0.08
CryoArray	Soudan	2080	0.22	500	3300	$\sim 50\%$	1650	80	0.005
CryoArray	NUSL	4500	0.01	500	150	$\sim 50\%$	75	18	0.001
CryoArray	NUSL	7200	0.0004	500	6	$\sim 50\%$	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 [1] and CDMS II at Stanford [6], 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 [7]. 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 1 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 mdru, 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 mdru, 4× above the CDMS II Soudan goal of 20 mdru. 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 [10], 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.

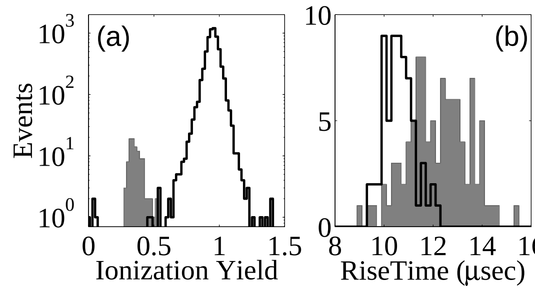

Figure 2. Discrimination of background events in the energy range 10–100 keV as demonstrated with CDMS II calibration data [6] from sources of photons (unfilled histograms) and neutrons (filled histograms). (a) Discrimination of photons is $> 99.97\%$ efficient, limited by statistics. (b) Applying a cut based on phonon risetimes can remove $> 97\%$ of the low-ionization-yield events (mostly electrons) while keeping $> 50\%$ of the neutron events.

2.3. Neutron Background

The low-energy (<10 MeV) neutrons from (α,n) and fission processes in the rock are trivially stopped by hydrogenous shielding. Such shielding reduces the low-energy neutron flux by ∼10× 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 ∼4 kmwe) would reduce the neutron flux by ∼25×, 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 $\lesssim 2000$ 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 $\sigma \lesssim 10^{-9}$ 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 $\sim$ 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 $\gtrsim 90\%$. 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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