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CUTE - A Cryogenic Underground Test Facility at SNOLAB

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Abstract. The excellent energy resolution and low threshold of cryogenic detectors have brought them to the forefront of the search for low-mass Weakly Interacting Massive Particles. The next generation of large cryogenic detectors for dark matter search promises further improvements in sensitivity, yet it is difficult and in some cases impossible to test and fully characterize these detectors in an unshielded environment. Therefore, the Queen's SuperCDMS team is installing a well shielded Cryogenic Underground detector TEst facility (CUTE) at SNOLAB to support detector testing and characterization for SuperCDMS and future cryogenic rare event search experiments. Significant effort is put into achieving a very low background environment which may open the door for early science results with the first set of SuperCDMS detectors during the time the main experimental apparatus is being installed. We discuss some of the challenges and solutions implemented in the design of this facility as well as the status and schedule for the start of operations underground at SNOLAB.

1. Introduction

Cryogenic detectors have been at the forefront of direct searches for dark matter since almost two decades [1] and presently provide leading sensitivity for Weakly Interacting Massive Particles (WIMPs) in the range below a few GeV/c^2 [2]. Similarly, this technology plays an important role in the search for neutrinoless double beta decay [3]. As detectors with larger masses and lower thresholds are developed it becomes more difficult to conduct tests and characterize the detectors in an unshielded facility due to the overwhelming background from environmental sources. Thus, the Queen's group of the Super Cryogenic Dark Matter Search experiment (SuperCDMS) has designed a well shielded Cryogenic Underground TEst facility (CUTE) to perform such measurements in a low background environment under conditions that protect the detectors from contamination (dust, radon, cosmogenic activation) that would otherwise compromise their use in rare-event search experiments. CUTE is expected to be operational in spring 2018. During the initial phase, a large fraction of the available time will be devoted to detector testing and measurements for SuperCDMS SNOLAB which is under construction and will start operations in 2020. However, the facility is open to other projects with innovative detector ideas that require a low background environment.

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2. The CUTE Facility

The core of CUTE is a cryogen-free dilution refrigerator from CryoConcept (France) equipped with their proprietary *Ultra Quiet Technique* (UQT®) to minimize vibration transmission from the pulse-tube (PT) cooler to the payload of the cryostat (see section 2.2). It is designed to operate a payload of up to about 10 kg of detectors at temperatures as low as 15 mK. The present layout is optimized for the new SuperCDMS detectors which are mounted in stacks of six on a structure (*tower*) that provides a thermal and mechanical interface to the cryostat and includes all wiring required for detector operation and readout between the thermal stages of the cryostat from 4 K to base temperature.

The refrigerator is installed inside a drywell in the center of a 3.7 m diameter water tank which acts as shield against external neutron and gamma radiation. Additional lead and polyethylene further reduces the external and internal background (see section 2.1). A deck structure installed above the tank gives access to the top of the cryostat. In order to change the payload, the refrigerator is lifted by a 1-ton class mono-rail crane out of its measurement position and into a cleanroom (located next to the water tank) that will be supplied with air with low radon concentration ($\lesssim$ 3 Bq/m^3) to protect the detectors from contamination with radon daughter products. Figure 1 shows the layout of the facility.

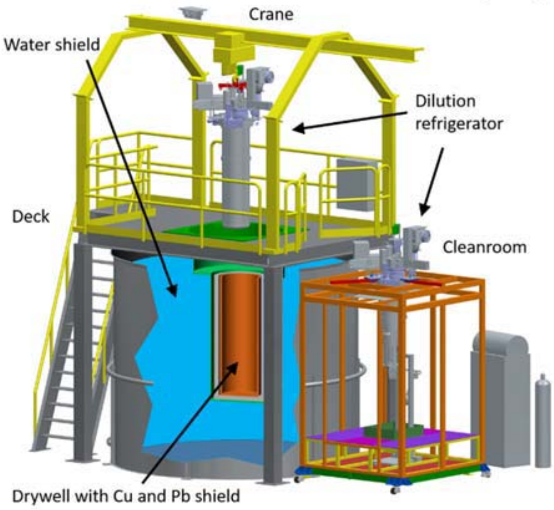

Figure 1: Layout of CUTE. While in operation, the dilution refrigerator with the detector payload will be located inside the drywell in the center of the water shielding tank. Additional lead and copper shielding directly surrounding the cryostat further reduces the external gamma radiation and a 15 cm thick polyethylene layer (not shown) will cover the setup from the top to reduce the neutron flux from above. The monorail crane lifts the cryostat out of the drywell and places it in the cleanroom located next to it for changing the detector payload. The cleanroom is supplied with radon reduced air to avoid contamination of the detector.

2.1. Shielding and Background

A key consideration for the design of CUTE is the radioactive background. According to early Monte Carlo simulations, the water tank (water thickness ~1.5 m on the side and ~1 m at the bottom) reduces the external radiation by about a factor of 20 [4]. The remaining background is very strongly dominated by radiation entering the setup from the top where the drywell generates a hole in the shielding. To close this gap for gammas, and to shield the detectors from potential contamination inside the dilution refrigerator, a 15 cm thick layer of lead is installed inside the cryostat, between the detectors and the cooling unit. The lead is not very effective for neutrons; therefore, an additional layer of ~15 cm of polyethylene is installed above the cryostat once it is put in place. An additional gamma shield will be installed inside the drywell to further reduce the residual environmental gamma radiation that penetrates the water shield. This shielding is composed of lead (9 cm on the sidewall and 15 cm on the bottom) and copper (2.5 cm, side and bottom). Between the two layers a magnetic shield will be installed to reduce the magnetic flux to a level that is acceptable for the operation of the SQUID based preamplifiers used in SuperCDMS. The air gap between the cryostat and the external shielding will be flushed with air with a low radon content.

To minimize the internal radioactivity, the thermal shields inside the cryostat are produced out of low-activity copper. The brazing material used to produce the thermal shields has unfortunately a high activity (400-640 Bq/kg of ^{210}Pb) and even though the total amount of material is very small, it still contributes about 10 % of the total expected background. The outer vacuum can of the cryostat consists of 316L stainless steel (~10-30 mBq/kg of ^{60}Co) as a compromise between cost and low activity. The internal and external lead shield is produced out of low-activity lead (a few Bq/kg of ^{210}Pb). The expected background in a SuperCDMS style germanium detector has been determined with GEANT4 Monte Carlo simulations based on measured or estimated contaminations. In the described configuration, external radiation entering through the gap between the internal and external lead shield gives the dominant contribution (~40 %) to the background in the low energy range of interest (0-1 keV). Contamination in the external lead and the outer vacuum can together contribute at a similar level, while the contributions from the inner cans, the inner lead and radon in the water and the air gap between the cryostat and the shield are subdominant. Table 1 summarizes the contributions from these sources. The expected total background of < 5 events/keV/kg/day should be compared e.g. to the measured rate in CDMSlite Run 2 (~5 events/keV/kg/day between 70 and 100 eV [2]) or the expected rate for SuperCDMS SNOLAB Ge detectors in the same range (~0.1 events/keV/kg/day [7]).

Background source	Material	Contributing isotopes	Induced detector rate [evts/keV/kg/d] below 1 keV
External Environment	Cavern walls	^{208}Tl, ^{40}K, n	1.10
Radon in water	Water	^{222}Rn	0.05
Lead shield, external	Low act. lead	U/Th, ^{210}Pb	0.65
Radon in air gap	Rn reduced air	^{222}Rn	0.04
Cryostat vacuum can	SS, 316L	U/Th, ^{60}Co	0.58
Cryostat inner shields	Copper, CuC2	U/Th, ^{60}Co	0.10
Brazing	AgSn	^{210}Pb	0.25
Lead shield, internal	Low act. lead	U/Th, ^{210}Pb	0.10
Total			**2.87**

Table 1: Major contributors to the expected background in a SuperCDMS Ge detector in CUTE.

If the need arises, further improvements to the background level are possible by replacing the vacuum can by one made out of copper, building new inner vacuum cans avoiding the high activity of the brazing material and partially closing the gap between the inner and outer shield.

2.2. Vibrations

Mechanical vibrations can affect the operation of massive cryogenic detectors in several ways. The most likely way for vibrations to couple into the detector signal is either mechanically through the detector support or capacitively through vibrating wires. While the latter primarily affects readout circuits with high impedance, the former will couple through friction directly into the phonon system of the detector. CDMSlite measurements conducted at the previous SuperCDMS setup in the Soudan underground lab were limited at low energy by vibrations transmitted into the system from a Gifford-McMahon (GM) cooling system used to intercept the heat from the readout cables. PT coolers as used by the refrigerator for CUTE to cool the 50K and 4K thermal stages produce less vibrations than GM coolers, but still pose a danger to sensitive measurements if no precautions are taken.

CryoConcept has developed the Ultra-Quiet Technology (UQT®) where the traditional copper-braid coupling between the cold-stages of the PT cooler and the cryostat are replaced by a gas coupling which takes advantage of the low-pressure gas return of the dilution unit that provides cooling to the colder stages of the cryostat. This approach has been shown to significantly reduce vibrations at the detector level [5].

The CUTE design includes modifications to further reduce the transmission of vibrations from the PT and other external sources to the detectors. In the standard assembly from CryoConcept, the vacuum connection between the PT and the cryostat is provided by a compact 10 mm long edge-welded bellows with a low axial stiffness (4 N/mm) but high radial stiffness (~5 kN/mm). This high radial stiffness couples the vertical motion of the PT to a lateral motion of the cryostat and excites a pendulum mode of the system. For CUTE, this bellows is replaced by a hydro-formed bellows with a much lower radial stiffness of only 167 N/mm. This reduces the resonance of the coupling to ~7 Hz which is well below the estimated 40 Hz resonance frequency of the pendulum mode.

The PT is mechanically connected to the deck structure. The cryostat, however is mounted on three elastomer dampers (Newport Model ND-20A) with a stiffness of only 5 N/mm, decoupling it also from environmental vibrations. Figure 2 compares the transmission of the CUTE design to the standard configuration.

Ambient pressure in the underground lab can vary significantly (up to about 10 %) due to changes in ventilation or mining activity in the active mine hosting SNOLAB. This, together with the soft mounting of the cryostat and the large cross-section bellows between the PT and the cryostat, could lead to significant displacement exceeding the small tolerance set by the gas coupling of the UQT. Therefore, the dampers are mounted on motorized tables equipped with optical position sensors. A slow feedback loop assures that the cryostat stays at its nominal position to within ±0.05 mm.

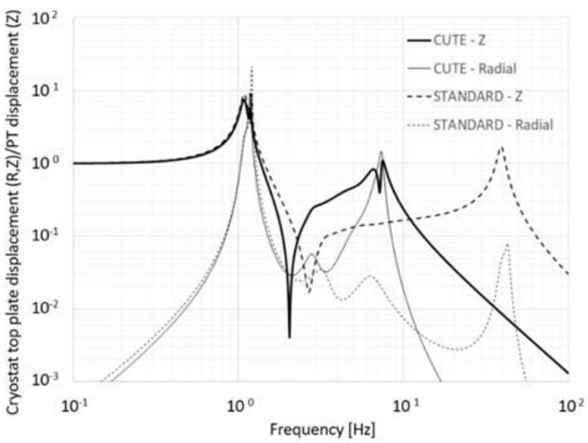

Figure 2. Vibration transmission from the PT to the top plate of the cryostat. The dashed and dotted lines show the transmission from a z-displacement of the PT to a z- and a radial displacement of the cryostat top plate, respectively for the standard configuration. The thick and thin solid lines show the z- and radial displacements for the CUTE design with the softer bellows between PT and cryostat. The transmission is stronger at very low frequencies, but at the frequency of the first internal mode (~40 Hz) it is reduced by more than an order of magnitude

3. Measurement Program

CUTE is designed to host one full tower of six SuperCDMS detectors. SuperCDMS SNOLAB will be deploying two types of detectors: iZIPs [6, 7], which are optimized for background discrimination, and HV detectors [7] which sacrifice background discrimination for the ability to reach considerably lower thresholds. Both detector types will be built using germanium as well as silicon substrates. The initial CUTE measurement campaign will focus on detector tests for SuperCDMS. Test will include basic functionality tests to confirm that the detectors are still fully in tact after transportation to SNOLAB and noise performance tests of the new SuperCDMS electronics in the SNOLAB environment. These tests have to be performed at SNOLAB but would not require particularly low background.

More demand on the facility comes from planned tests of the intrinsic noise performance of the new detectors, which may critically depend on the overall interaction rate. Another measurement that requires moderately low background ($\mathcal{O}$(100 events/keV/kg/day)) is the demonstration of the background discrimination power of the new iZIP detectors.

Next, measurements of the intrinsic background of the detectors are planned. This includes the determination of the ^{32}Si contamination (or an upper limit thereof) in the silicon detectors and a confirmation of the tritium production rate in germanium. These measurements require the lowest achievable background for the best possible precision. They will confirm that there are no major issues with the procedures for handling (during detector production and testing above ground) and shipping of the detectors.

Finally, if the background goal of CUTE is achieved and the detector rate is of order of a few events/keV/kg/day in the lowest energy range (from a few keV down to threshold), the facility can be used for early dark matter science. While the expected background is still considerably higher than what can be achieved within the new SuperCDMS setup at SNOLAB, it is still low enough that we can take advantage of the very low energy threshold of the new SuperCDMS detectors to explore new parameter space in a WIMP mass range below a few GeV/c^2.

SuperCDMS has been in discussions with other cryogenic dark matter search experiments (EDELWEISS, CRESST) about possible collaborations. CUTE is available to test new detector implementations from these experiments using a SuperCDMS-like detector tower. This would open the door to install these detectors in the SuperCDMS SNOLAB setup for future measurement campaigns. Also proposals from other groups that are developing innovative detectors that are in need for a low-background environment for testing will be considered.

4. Status

The CUTE dilution refrigerator will be delivered to Queen's in November 2017 for confirmation of performance and then sent to SNOLAB in early 2018. The infrastructure at SNOLAB is presently under construction. Installation and commissioning at SNOLAB is planned for winter and early spring 2018. Detector testing will start in late spring or early summer 2018. A first attempt at pushing the sensitivity for very low mass WIMPs could be possible in 2019.

5. Conclusion

Typical cryogenic detector test facilities have cycle times of a few days and typical background rates of hundreds of events/keV/kg/day, providing flexibility but prohibiting tests and investigations that require low rates, in particular if testing massive detectors. On the other hand, facilities designed for rare event searches such as SuperCDMS SNOLAB achieve extremely low background rates, but have cycle times of several weeks or months. CUTE lives in a unique range between the two extremes; with a cycle time of order of a week, it provides reasonable flexibility for detector testing, but at the same time is anticipated to achieve a background that is low enough to test the low-rate behaviour of detectors and even perform competitive rare event searches, at least until the next generation of experiments comes online. The start of operations in early 2018 is thus very timely. On a longer timescale, CUTE will provide the unique opportunity to test new detectors for SuperCDMS SNOLAB in a low background environment to ensure that the experiment interrupts its measurements only for the implementation of detectors that have a confirmed performance and are likely to improve the sensitivity of the experiment. In addition, CUTE is open to other groups who need a well shielded environment for testing innovative cryogenic detector concepts.

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