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Development of an Adiabatic Demagnetization Refrigerator for X-ray Microcalorimeter Operations

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Abstract.

An X-ray microcalorimeter is a non-dispersive spectrometer that measures the energy of an incident X-ray photon as a temperature rise. Operated at < 0.1 K, it achieves very high resolving power. We are developing X-ray microcalorimeters for future γ -ray burst observations, and are now setting up a compact adiabatic demagnetization refrigerator (ADR) for X-ray microcalorimeter operations. We fabricated a paramagnetic salt pill, and integrated it with a superconducting magnet and a heat-switch in a dedicated He cryostat. By applying a magnetic field of 2.6 T at the bath temperature of 1.8 K, it achieved 0.1 K. The attainable temperature and the hold time were, however, limited due to unexpected heat load. We also successfully measured a resistance–temperature characteristics of a superconducting transition edge.

Keywords: X-ray microcalorimeter, Adiabatic demagnetization

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INTRODUCTION

An X-ray microcalorimeter is a non-dispersive spectrometer that measures the energy of an incident X-ray photon as a temperature rise [1]. Operated at 50–100 mK, it achieves very high resolving power ($E/\Delta E > 1000$ at 6 keV). Using a superconducting transition edge as a high sensitivity thermometer (a transition edge sensor or TES), its energy resolution can be further improved [2, 3]. Observing γ -ray bursts (GRBs) with such X-ray microcalorimeters would enable us to determine metal abundance of host galaxies in the early Universe, as well as to detect warm-hot intergalactic medium (WHIM) using GRBs as a background candle. To achieve < 0.1 K in orbit (microgravity environment), an adiabatic demagnetization refrigerator (ADR) is a practical solution. The XRS instrument onboard Suzaku satellite utilized a single-stage ADR, and achieved 60 mK in orbit for the first time [4]. The SXS instrument onboard Astro-H adopts a 3-stage ADR for better cooling performance [5, 6].

We started X-ray microcalorimeter experiments in 2007, in collaboration with JAXA and Tokyo Metropolitan University groups. We are now developing a compact dual-stage ADR to operate X-ray microcalorimeters, with future γ -ray burst missions in mind [7]. So far, we fabricated the colder stage of the ADR and tested it.

IN-HOUSE FABRICATION OF PARAMAGNETIC SALT PILL

We fabricated a paramagnetic salt pill for the colder stage in our lab, using ferric ammonium alum (FAA) [7]. FAA is widely used in ADRs for 50–100 mK, because of its suitable properties [8]. We used a glass-epoxy cylinder as a salt container. It was designed determined to contain 70 g FAA, in order to achieve hold time of 10 hours at 100 mK under a bath temperature of 1.8 K and a parasitic heat load of $1 \mu\text{W}$. Since the thermal conductivity of FAA crystal is very low at ~ 100 mK, 260 gold wires of 0.1 mm diameter were installed in the container, and then the FAA crystal was grown. Net weight of the crystal was 67 g. After the crystal growth, the container was sealed with epoxy adhesive. Several thermal cycles were performed, and no leak was detected.

CRYOSTAT AND EXPERIMENTAL SETUP

A dedicated He cryostat for this experiment was prepared as shown in the left and the middle panels of Fig. 1. This cryostat has an experimental stage of liquid He temperature, large enough for mounting two sets of ADRs and a detector, and a radiation shield of the same temperature around it. It is possible to pump down the liquid He, and hence, the stage and the shield temperatures can be lowered. Around the He tank and the shield, there are two vapor-cooled radiation shields. Details are described in [7]. To reduce radiation into He, 10–20 layers of MLI (multi-layer insulation) were installed around the two vapor-cooled radiation shields. By introducing MLI, liquid He hold time doubled (~ 48 hours), which suggests that a parasitic heat load into the He tank was reduced to ~ 120 mW. This significantly lowered the attainable temperature by pumping (< 1.8 K).

The salt pill, a superconducting magnet (max 3 T with 9 A), and a mechanical heat-switch were installed on the He stage (middle panel of Fig. 1). The salt pill was suspended with Kevlar wires from support structures attached to the magnet. The mechanical heat-switch mounted on the He stage can be turned on and off manually from outside the cryostat, using a plastic rod.

PERFORMANCE TEST RESULTS

Cooling tests were performed at the bath temperature of ~ 1.8 K. A magnet current of 8 A was applied and a magnetic field of 2.6 T was generated as shown in the right panel of Fig. 1. Then the heat-switch was opened, and the magnet was demagnetized. As shown in Fig. 1, the salt pill temperature decreased to ~ 0.1 K. It was confirmed that the system works as an ADR. However, the attainable temperature was limited at ~ 0.1 K or higher. The hold time was about 1 hour, and was shorter than the designed value. Parasitic heat load on the salt pill was estimated from the temperature rise. It was $\sim 10 \mu\text{W}$, more than 10 times larger than expected, and this constrained the temperature and the hold time. We suspect that there existed heat leak from higher temperature region, due to incomplete close-out of holes for the mechanical heat-switch rod or wire harness.

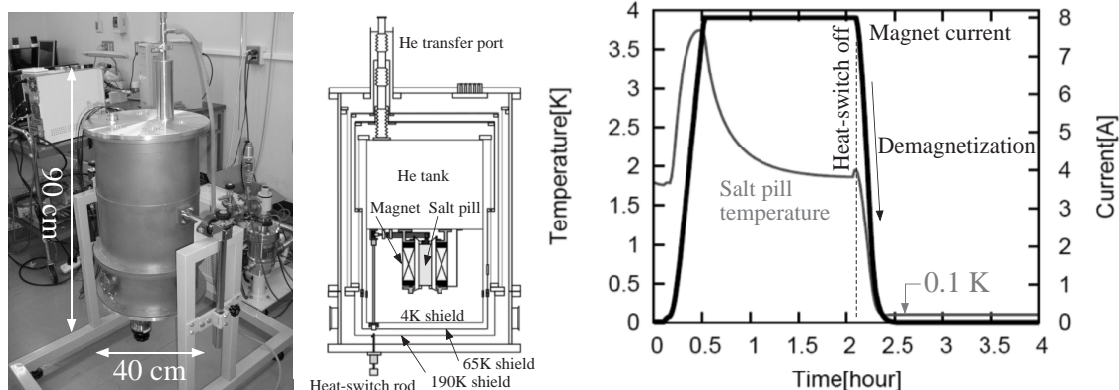


FIGURE 1. (Left and middle) Dedicated He cryostat for this experiment. (Right) Magnet current and temperature profiles during the cooling performance test.

A detector stage was attached to the salt pill, and a sample TES was mounted on it. After the salt pill reached the lowest temperature, a resistance-temperature (R - T) curve of the TES was measured, when the salt pill temperature was increasing. The measured curve was consistent with previous measurements in an dilution refrigerator, and the performance of our ADR was demonstrated.

We will improve the cryostat environment by completely blocking radiation from higher temperatures, and try to operate an X-ray microcalorimeter with our ADR. In parallel, we will develop the 2nd stage ADR, to improve the attainable temperature and hold time of the 1st ADR.

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