Development of an adiabatic demagnetization refrigerator at Kanazawa for X-ray microcalorimeter operation

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Abstract

At Kanazawa University, we started X-ray microcalorimeter experiments in 2007. We are now developing a compact adiabatic demagnetization refrigerator (ADR) to operate X-ray microcalorimeters. The ADR will be composed of two stages, so that it can achieve large cooling capacity with a reasonable size. So far, we fabricated the colder stage, which consists of a salt pill of ferric ammonium alum (FAA), a superconducting magnet, and a mechanical heat switch. We operated it in a dedicated cryostat for this experiment, and achieved $\sim$ 100 mK.

Key words: X-ray microcalorimeter — ADR — salt pill

1. Introduction

An X-ray microcalorimeter is a non-dispersive spectrometer that measures the energy of an incident X-ray photon as a temperature rise (Moseley, Mather & McCammon 1984). Operated at 50–100 mK, it achieves very high resolving power. More importantly, its performance does not degrade even if the object is extended. It will bring a breakthrough to the X-ray astronomy.

To achieve 50–100 mK in orbit (microgravity environment), an adiabatic demagnetization refrigerator (ADR) is currently one of the most practical solutions. The XRS instrument onboard Suzaku satellite utilized a single-stage ADR, and achieved 60 mK in orbit for the first time (Kelley et al. 2007). The SXS instrument onboard Astro-H (Mitsuda et al. 2010) adopts a dual-stage ADR, to achieve an operating temperature of 50 mK under a detector heat load of 0.4 μW.

At Kanazawa University, we started X-ray microcalorimeter experiments in 2007, in collaboration with ISAS/JAXA and Tokyo Metropolitan University groups. We are now developing a compact dual-stage ADR to operate X-ray microcalorimeters, with future X-ray satellites and γ-ray burst missions in mind. So far, we fabricated the colder stage and tested it. In this paper, we briefly reports the status of our ADR development, and results of the cooling performance tests.

2. Salt pill fabrication

We fabricated a paramagnetic salt pill for the colder stage in our lab, adopting ferric ammonium alum (FAA; $Fe(NH_4)(SO_4)_2 \cdot 12H_2O$) as a paramagnetic salt material. FAA is widely used in ADRs for 50–100 mK, because of its suitable properties, i.e., a large angular momentum ($J = 5/2$), a low magnetic transition temperature (26 mK), etc. We used a glass-epoxy cylinder as a salt container (Fig. 1). Its size was determined to contain 70 g FAA, which corresponds to hold time of 10 hours at 100 mK under a bath temperature of 1.8 K and a parasitic heat load of 1 μW. Since the thermal conductivity of FAA crystal is very low at $\sim$ 100 mK, we installed 260 gold wires of 0.1 mm diameter 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 (Stycast 2850FT). Note that, from the reliability point of view, a combination of a stainless steel container and welding is better. However, we took this approach because we can seal the container after crystal growth is finished. We performed several thermal cycles, but no leak occurred so far.

3. Cryostat and experimental setup

We prepared a dedicated cryostat for this experiment, following Shinozaki et al. (2008). This cryostat has an experimental stage of liquid He temperature, large enough for mounting two sets of ADRs and a detector,

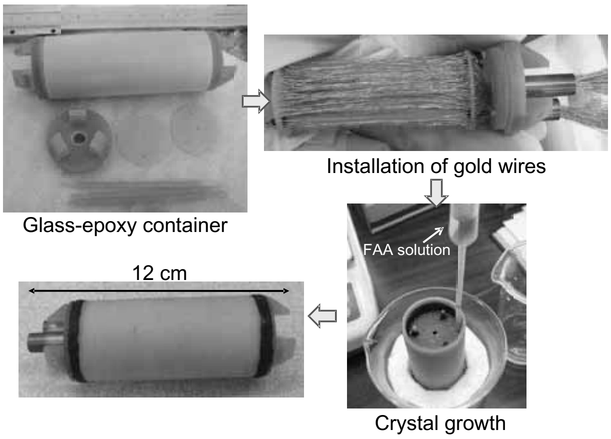

Fig. 1. Fabrication of FAA salt pill.

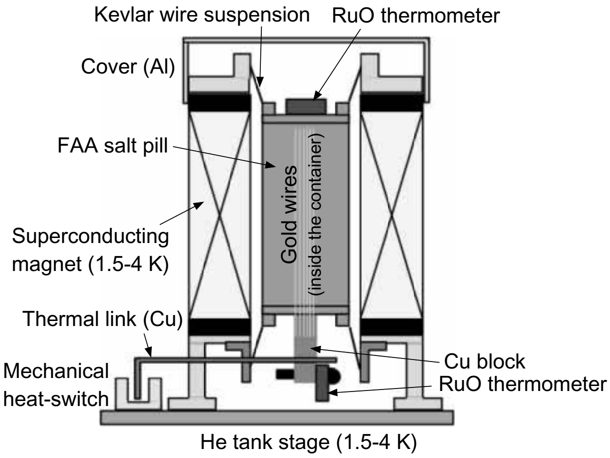

Fig. 2. Setup of the salt pill

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.

To reduce radiation into He, we installed 10–20 layers of MLI (multi-layer insulation) around the two vapor-cooled radiation shields. By introducing MLI, liquid He hold time doubled ($\sim$ 48 hours), which suggests that a parasitic heat load into the He tank was reduced to $\sim$ 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 (Fig. 2). 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.

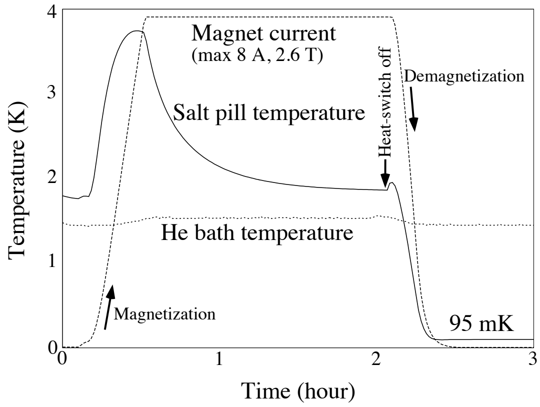

Fig. 3. Profiles of magnet current and temperatures

4. Cooling test results

We performed a cooling test, at the bath temperature of 1.5 K. A magnet current of 8 A was applied and a magnetic field of 2.6 T was generated as shown in Fig. 3. Then the heat-switch was opened, and the magnet current was ramped down. As shown in Fig. 2, two thermometers were attached, one on the Cu block at the bottom of the salt pill, and the other on the container at the top. Since the gold wires are connected to the Cu block, the former reflects the crystal temperature, while the latter shows the container temperature. After demagnetization, read of the bottom thermometer reached 95 mK (Fig. 3). Note that this thermometer was not calibrated, but even if its uncertainty is considered, the crystal temperature must have been lower than $\sim$ 150 mK. On the other hand, the salt pill container temperature measured at the top was $\sim$ 210 mK. This discrepancy implies that there still existed unexpected heat input.

Since the temperature reached $\sim$ 100 mK, we now try to establish temperature control, and to operate X-ray microcalorimeters with our ADR.

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