Development of Adiabatic Demagnetization Refrigerator for Future Astronomy Missions

H. Jin\textsuperscript{1,2,3,4}, J. Shen\textsuperscript{1,2,3,4}*, C. Z. Li\textsuperscript{4}, C. Wang\textsuperscript{1,2,3}, F. Q. Yu\textsuperscript{1,2,3}, H. Y. Zu\textsuperscript{1,2,3}, P. Liu\textsuperscript{1,2,3}, J. Ding\textsuperscript{1}, K. Li\textsuperscript{1,2,3}, Y. N. Wang\textsuperscript{1,2,3}, W. Dai\textsuperscript{1,2,3}, Y. Zhou\textsuperscript{1,2,3}, W. Cui\textsuperscript{4}

\textsuperscript{1} Technical Institute of Physics and Chemistry, Beijing 100190, China University of Chinese Academy of Sciences, Beijing 100049, China; \textsuperscript{2} University of Chinese Academy of Sciences, Beijing 100049, China; \textsuperscript{3}CAS Key Laboratory of Cryogenics, Technical Institute of Physics and Chemistry of CAS Beijing 100190, China; \textsuperscript{4}Department of Astronomy, Tsinghua University Beijing 100084, China

\*j.shen@mail.ipc.ac.cn

Abstract The superconducting microcalorimeter provides astronomers with a new tool to probe the hot universe. This kind of detectors has superb energy resolution and high detection efficiency, which is important for diffuse X-ray detection. Astronomy missions, such as the Hot Universe Baryon Surveyor (HUBS) and Diffuse X-ray explorer (DIXE) proposed in China, is going to employ superconducting microcalorimeters. The superconducting microcalorimeter works in its superconducting transition region, which is at a very low temperature(<100 mK). Realization of such a low temperature in space is challenging. Adiabatic demagnetization refrigerator (ADR) is a good candidate for milli-Kelvin cooling system. Here we introduce our recent work on ADR design and construction. Most of the key components for building an ADR have been designed and fabricated. Recently we integrated all components and built a two stage ADR. Preliminary performance on each stages tes has been conducted separately. In its performance test, starting from 4 K, the FAA stage could cool down to 156.7 mK and the GGG stage could reach 768.4 mK. This result shows promise for future development.

1. Introduction
The superconducting microcalorimeter becomes a new tool for astronomers to probe the hot universe. The high energy resolution of superconducting microcalorimeter is an important feature for diffuse X-ray detection [1, 2]. The superconducting microcalorimeter needs to be operated at very low temperature (below 100 mK) to realize their potential of measuring the energy of individual X-ray photons with high precision. The microcalorimeters are the detector technology of choice for the proposed Hot Universe Baryon Surveyor (HUBS) mission [3, 4]. Besides the HUBS mission, the Diffuse X-ray Explorer (DIXE) is an experiment proposed for the Chinese Space Station that employs microcalorimeters to detect X-ray emission from hot gas in the Milky Way. In future, there might be other similar astronomy missions. Milli-Kelvin cooling system will become one of the key technologies for them.

It is challenging to cool down the detectors below 100 mK in space. Such kinds of milli-Kelvin cooling system require several stages based on different refrigeration principles [5, 6]. Mechanical coolers usually work as pre-cool stage. Recently, pulse tube coolers (PT) are well developed in China,
and multi-stage PTs are capable to reach 4 K [7]. The high-reliability of PT makes it a good option as the pre-cooling stage in milli-Kelvin cooling system. Regarding the milli-Kelvin stage, adiabatic demagnetization refrigerator (ADR) is a good candidate since it can operate in the gravity-free environment. Most of current astronomy missions choose to use ADRs as the milli-Kelvin cooling stage. In China, there is still no ADR available for astronomy missions such as HUBS and DIXE. Main goal of the research reported here is to build an ADR prototype which is able to cool down below 100 mK and verify the technical feasibilities of key components.

2. ADR Design and Construction

For a temperature below 100 mK, a two-stage ADR was designed considering the system complexity and cooling capacity. The schematic of the design is shown in Figure 1. In this design, GGG (Gd₃Ga₂O₁₂) and FAA (Fe(SO₄)₂(NH₄)2H₂O) are employed as the refrigerant separately. The GGG stage is the first stage. It is expected to cool down from 4 K to below 800 mK, while the FAA stage is expected to cool down from the first-stage temperature to below 100 mK. The GGG stage is thermally connected with 4 K heat sink with a gas-gap heat switch (GGHS) or a mechanical heat switch (MHS). The FAA stage is thermally connected with the GGG stage via a superconducting heat switch (SCHS).

![Figure 1. Schematic of the two stage ADR in development](image)

Except for the SCHS, which is still under development, all other components have been designed and constructed. We recently assemble the GGG stage and FAA stage on to a test bench, which provides a temperature of 4 K. For the performance tests, the GGG stage is thermally connected to the test bench via a MHS and the FAA stage is also thermally connected to the 4 K test bench via a GGHS; There is no thermal link between the two stages. As a first step, we tested the performance of two single-stage ADRs separately.

2.1. GGG Stage Construction

GGG is a kind of rare-earth oxides, commonly used in some optical experiments and magnetic refrigerators. It is chemically stable and doesn’t need any special protection in vacuum environment. The thermal conductivity of GGG crystal is fairly good [8, 9], so temperature gradient inside the crystal is not a big problem. The contact resistance between GGG crystal and copper plate poses a potential problem. In our design, a hole was dug in the centre of GGG crystal. A thin-wall stainless steel tube goes through the hole and pulls the GGG crystal onto the copper plate tightly, as shown in Figure 2. N-grease is applied on the interface between GGG crystal and copper to enhance heat transfer. The copper plate is supported by four G10 posts, which reduce the heat leakage from the 4 K stage to the GGG refrigerant. The cold end of the MHS is installed on the GGG copper plate.
2.2. FAA Stage Construction

2.2.1 Fabrication of FAA Salt Pill

FAA and CPA (CrK(SO₄)₂·12H₂O)) are two kinds of paramagnetic salts commonly used in ADRs for lower temperature. The ordering temperature of both salts are well below 50 mK (FAA 26 mK and CPA 9 mK) [10, 11]. FAA could provide more cooling power than that of CPA under the same operating conditions, and is chosen here. FAA dehydrates when exposed to a vacuum environment, so it has been carefully sealed in a hermetic enclosure which is made of stainless steel (SS) and is made leak-free with laser welding.

The thermal conductivity of FAA is quite low at low temperature, leading to significant temperature gradient inside the crystal during the heat transfer process. A common way to solve this is to add thermal bus with high thermal conductivity. FAA solution is corrosive to copper and silver. Gold becomes the only choice for thermal bus fabrication. The thermal bus in the form of a bundle of gold wires is shown in Figure 3. These gold wires go through two SS plates in parallel and was brazed onto a copper rod.

The FAA crystal has been grown directly on the gold wires in this enclosure, following a similar process reported previously [12]. The experimental setup is also shown in Figure 3. Briefly speaking, saturated FAA solution is injected into the SST enclosure, with its temperature maintained at 33 °C. As the temperature is lowered to the room temperature, crystallization happens inside the solution. After crystallization, the remaining solution is discarded. The process repeats, with fresh saturated FAA solution filled every 24 hour. The solubility of FAA is quite high, so the growth process does not take too long (about 2 weeks).

The wire diameter and distance between the wires are important for heat conduction at low temperatures. In our case, the diameter of gold wires is 0.25 mm and the distance between adjacent wires is 2 mm. These are the optimal values, as determined by heat transfer simulation (see Figure 3 right). In the simulation, we assume a 1 μW heat load flowing from thermal bus to the FAA crystal. The temperature difference between the thermal bus and FAA crystals is generated due to the limited thermal conductivity of the crystals and the boundary resistance between FAA crystals and the wires. The parameter of gold wire minimized the number of gold wires and keep the temperature difference below 3 mK, which is acceptable at this temperature.

Figure 2. GGG and copper plate assembly (left) and MHS (right)
2.2.2 Gas Gap Heat switch
GGHS is free from moving parts and the ON/OFF status can be easily switched. It is a good choice for ADRs operated in space. In this work, the FAA stage is thermally connected to the 4 K stage with a GGHS. This GGHS shown in Figure 4 is temporarily filled with $^4$He gas (a $^3$He charged GGHS will replace it in future). The thermal conductivity of GGHS is tested at the temperature of 4 K. In the test, the end of GGHS which is connected with getter chamber is fixed with 4 K stage and the temperature of the other end was measured after it is heated. The thermal conductivity of this GGHS was determined to be 8.85 uW/K and 7.19 mW/K for the off and on states, respectively, corresponding to a ON/OFF ratio of about 812.

2.3. Integration of ADR
A test bench was built for ADR integration and performance test. A commercial PT from Sumitomo provide a 4 K heat sink for the ADR. Figure 5 shows the FAA stage and GGG stage, assembled on the test bench. A ruthenium oxide thermometer was installed on the FAA stage and a Cernox 1010 thermometer was installed on the GGG stage for temperature measurements. A superconducting power supply was used for charging the magnets. The temperatures and magnetic fields were recorded in a data acquisition computer.

3. Result and Discussion
For a quick test, Carnot cycle is not performed here. After cooled to 4 K, the FAA and GGG stage were magnetized with the respective heat switch at on state and demagnetized adiabatically. The refrigeration processes of both stages are shown in Figure 6. It can be seen from the figure that during the
magnetization process, the temperature rises and heat is released. After the superconducting magnets were charged to the maximum field, the temperature began to decrease. When the thermal equilibrium was reached, the heat switches were opened and the adiabatic demagnetization process began. The temperature of each stage went down with the magnetic field accordingly. The GGG stage could reach down to 768.4 mK and the FAA stage to 156.7 mK.

**Figure 5.** The integrated ADR (left) and test bench schematics (right)

The FAA stage was only able to reach 156.7 mK, partly because the maximum magnetic field is limited to 2.2 T and it runs as a single-stage ADR with the 4 K heat sink (as opposed to about 800 mK in a two stage design). We observed that the temperature of FAA stage went up quickly after the demagnetization process ended, indicating a marginal heat leak through the GGHS, which is approximately calculated to be 35.4 μW. A further investigation on how to reduce this heat leak is needed.

**Figure 6.** Performance of the GGG stage (left) and the FAA stage(right)

4. Conclusion
To develop ADRs for future astronomy missions employing superconducting microcalorimeters, a two stage ADR was designed. This paper introduces the preliminary experimental work by testing both stage separately on a test bench. The FAA stage could cool down to 156.7 mK when it is demagnetized from 2.2 T. The GGG stage could cool down to 768.4 mK. Key technologies of ADR, including GGHS, MHS, salt pill, suspension mechanism have been tested. After the SCRS is ready, these two stages will be integrated and form a two-stages ADR. Current result shows a feasibility for future ADRs development. We have a path forward in the development of ADR technology for future astronomy missions.
5. References

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