Frustrated magnet for adiabatic demagnetization cooling to milli-Kelvin temperatures

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Generation of very low temperatures has been crucially important for applications and fundamental research, as low-temperature quantum coherence enables operation of quantum computers and formation of exotic quantum states, such as superfluidity and superconductivity. Recently, the development of quantum computers and sensors for dark matter detection rendered low-temperature refrigeration an important technological challenge [1,2]. One of the viable methods for reaching milli-K (mK) temperature range is adiabatic demagnetization refrigeration (ADR) using paramagnetic salts. Its main advantages over the currently dominant technique, ^{3}He-^{4}He dilution refrigeration, are the simple construction of a cooling device and its operation without the usage of expensive ^{3}He. The recent crisis of ^{3}He, which was caused by the increased demand due to construction of neutron detectors for defense against nuclear terrorism, raised serious concerns about the strong dependence of the current technology on such a scarcely available and ever more expensive gas [3]. This triggered renewed interest in ADR.

The only advantage of ^{3}He-^{4}He dilution refrigeration is its capability of continuous cooling, while conventional ADR is a single-shot technique, which heats up once after reaching its lowest temperature. This makes the ^{3}He-^{4}He dilution refrigeration more commonly used than ADR. However, the situation may change thanks to recent developments of continuous ADR cooling [4,5] and availability of commercial continuous refrigerators based on ADR. Therefore, ADR has the potential of becoming the main cooling technology already in near future, at least in the mK temperature range.

In ADR, fluctuations of magnetic moments absorb heat from surroundings. Usually a magnet orders magnetically below some temperature, which is about equal to strength of interaction between magnetic moments. Below such ordering temperatures magnets cannot cool by ADR process anymore because magnetic moments stop fluctuating. This sets a limit for the final temperature which refrigerant materials can achieve.

A key to overcome this limitation is quantum fluctuations. In classical thermodynamics, magnetic moments or particles like atoms are completely stationary at absolute zero temperature. However, according to quantum mechanics, magnetic moments or particles fluctuate even at absolute zero. This is called quantum fluctuations. For example, Helium does not solidify and remains to be fluid even at absolute zero temperature because of quantum fluctuations, although most of materials solidify at low temperatures because of reduction of thermal fluctuations. For magnets, geometrical frustration of magnetic interaction suppresses ordering of magnetic moments and may lead magnets to fluctuating states even at zero temperature (Fig.1). Therefore, such "frustrated magnets" may be able to reach very low temperature even below the limitation.

We demonstrate the effective refrigeration with an frustrated magnet $KBaYb(BO_3)_2$ that shows excellent ADR performance on par with conventional paramagnetic salts, and achieve an end temperature T_f of 22 mK, starting from a temperature of 2 K at a magnetic field of 5 T (Fig.2) [6]. In this compound, magnetic Yb^{3+} ions, forming frustrated triangular lattice, are responsible for magnetic properties. From Curie-Weiss behavior of magnetic susceptibility, the strength of magnetic interaction of Yb^{3+} moments is estimated to be 40 mK, below which magnetic ordering is usually expected. From our measurements, however, magnetic ordering is absent down to 22 mK, well below the strength (Fig.2). This is due to suppression of magnetic ordering because of geometrical frustration. We believe that this study will pave a road for usage of frustrated magnets for ADR, cooling even below the conventional limit for magnetic refrigeration.

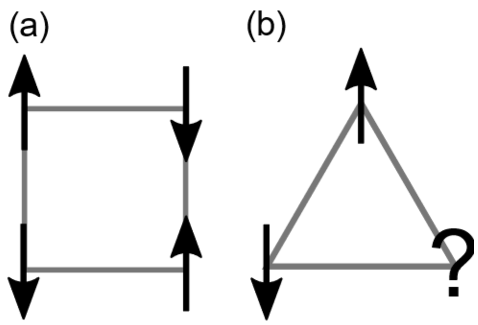

Fig. 1 (a) Antiferromagnetic ordering on square lattice. (b) Frustrated antiferromagnetic interaction on triangular lattice.

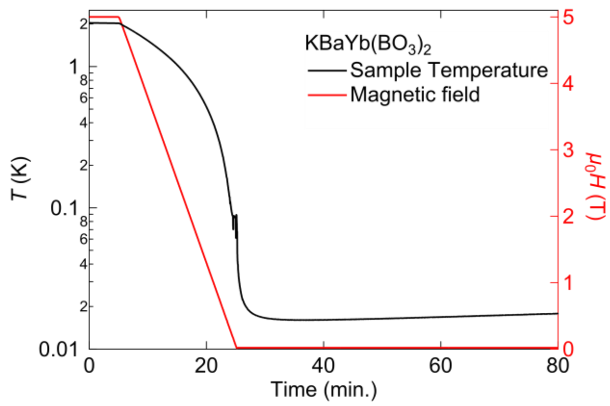

Fig. 2 Refrigeration test under nearly adiabatic conditions. The black and red lines are temperature (left axis) and external magnetic field (right axis), respectively. The final temperature is 22mK [6].

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