Exploring Enhanced Magnetocaloric Effect in Low Dimensional Magnets as Potential Refrigerants to Lower Sample Temperatures in High Magnetic Fields

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Overview

In January 2018, the 36 T, 40 mm bore Series Connected Hybrid (SCH) Magnet became available. In 2019, the first of a couple of 32 T, 34 mm bore All-Superconducting (ASC) Magnets is expected to be ready and equipped with a specialized dilution refrigerator system providing minimum lattice temperatures down to nominally 20 mT.

These advances allow the possibility of pondering whether temperatures lower than typically available with dilution refrigerators can be achieved. This MagLab research report describes one plausible avenue of exploiting the enhanced magnetocaloric effect of low dimensional antiferromagnets as a means of refrigerating samples below temperatures afforded by the techniques presently being employed in magnetic fields above 20 T.

Motivation

In many instances, exploration of the underlying phenomena governing the electromagnet response of materials involves the completion between thermal and magnetic energies. Lowering the temperature usually reduces the phonons (lattice vibrations) that mask the subtleties, and an order of magnitude reduction in the temperature can result in three orders of magnitude reduction in the phonon density. In parallel, lowering the temperature allows the weaker magneto-lattice interactions to be probed at sufficiently high magnetic fields, which amplify these effects. In some instances, the magnetic field to temperature ratio ($\boldsymbol{B}/\boldsymbol{T}$) describes the competition between these two parameters, whereas in other cases, the phenomena possess a more sophisticated interplay between $\boldsymbol{B}$ and $\boldsymbol{T}$. Ultimately, the ultimate goal is high magnetic fields and lower temperatures.

The MagLab High $\boldsymbol{B}/\boldsymbol{T}$ Facility provides users access to magnetic fields up to 16 T and temperatures down to 1 mK while maintaining an electromagnetically quiet environment that allows low level signals to be detected. The technology employed to achieve the low temperatures involves adiabatic demagnetization of $PrNi_5$, which is cooled to dilution refrigerator temperatures. While maintaining fields up to 16 T on the sample, the $PrNi_5$ is demagnetized from 8 T after being disconnected from the dilution refrigerator through the use of a superconducting heat switch [1]. In the simplest description of this quasi-adiabatic process, the initial (i) and final (f) temperatures ($\boldsymbol{T}$) and magnetic fields ($\boldsymbol{B}$) are related,

$$\left(\boldsymbol{T}_{\mathrm{f}} / \boldsymbol{B}_{\mathrm{f}}\right) = \left(\boldsymbol{T}_{\mathrm{i}} / \boldsymbol{B}_{\mathrm{i}}\right) \quad . \tag{1}$$

This traditional approach is realized by the nesting of two superconducting coils that are specially designed to minimize the interactions and strong forces between them. The working hypothesis of present study is that this type of nesting of two powerful magnets is an implausible direction to purse with the aforementioned SCH and ASC magnets, so sample temperatures lower than those provided by dilution refrigerators will require alternative approaches.

Potential Alternative: Enhanced Magnetocaloric Effect

In 2004, Zhitomirsky and Honecker described the enhanced magnetocaloric effect in one-dimensional antiferromagnetic materials [2]. Due to the magnetic field induced level crossing of a high energy triplet state with the singlet ground state at sufficiently low temperatures, the relationship shown in Eq. (1) becomes highly nonlinear in the vicinity of the critical field $\boldsymbol{B}$c, and this effect is enhanced by systems with large magnetic anisotropy [2].

Several experimental studies have demonstrated the ability to exploit this enhanced magnetocaloric effect to realize lower temperatures by both demagnetizing when above $\boldsymbol{B}$c or magnetizing when below $\boldsymbol{B}$c [3,4].

Summary and Continuing Work

With the proper choice of material, the enhanced magnetocaloric effect may allow samples to be cooled from about 20 mK to 2 mK while demagnetizing from 32 T to 28 T or while magnetizing from 24 T to 28 T. The method will require a unique heat switch mechanism but only uses a single magnet. The operation will cause the magnetic field applied to the sample to vary in concert with the temperature, but quasi-equilibrium conditions will permit data acquisition in this unique low temperature, high magnetic field environment.

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