Magnetic cooling

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Energy production, saving and conversion and the search of energy alternatives are topics of extreme importance in politics, education and science [1, 2]. Even though most of the activities in our Institute are dedicated to fundamental research, some of materials we discover find rapid application in technical areas which are often related to energy conversion. In searching for alternatives to ^{3}He-based refrigeration techniques for achieving temperatures below 2 K, because of the recent shortage and high price of the rare helium isotope ^{3}He, we have discovered the first metallic material with a large magnetocaloric effect: $YbPt_2Sn$. This material is capable of converting magnetic to thermal energy and allows adiabatic demagnetization cooling from 2 K down to 0.2 K. Other materials, for example paramagnetic salts, are commonly used for the same purpose but none of them is metallic, a severe limitation for low-temperature applications. The volumetric entropy capacity of $YbPt_2Sn$ is three times larger than that of paramagnetic salts and it can be easily cast into any shape, making it the perfect material to be used in any adiabatic demagnetization refrigerator or for zero-gravity space applications.

Standard techniques for cooling below room temperature involve the use of cryogenic fluids like nitrogen N_2 or both isotopes of the noble gas helium, ^{4}He and ^{3}He. Although nowadays efficient cooling down to 2 K (-271.15 °C), can easily be achieved with techniques like pulse-tube cryogenic cooling or pumping of liquid ^{4}He, temperatures below 2 K can only be reached with ^{3}He-based cryostat or adiabatic demagnetization refrigeration (ADR) cooling with paramagnetic salts [3].

Pure ^{3}He is, however, currently in limited supply on a market that can no longer satisfy the demand for its many various uses, and costs are extremely high. Low-temperature physicists required only 1.3 % of the available ^{3}He between 2004 and 2010 [4, 5].

The adiabatic demagnetization refrigerator (ADR) is a smart alternative. This device makes use of the entropy change in magnetocaloric materials, which are essentially paramagnetic compounds with a strong magnetocaloric effect (MCE), i.e., the capacity of changing their temperature T with an applied magnetic field B, reversibly, in adiabatic conditions [6]. To cool down the system, a heat-switch is operated while controlling the magnetic field. This technique is also used at room temperature, as an alternative to standard domestic refrigerators [7] or

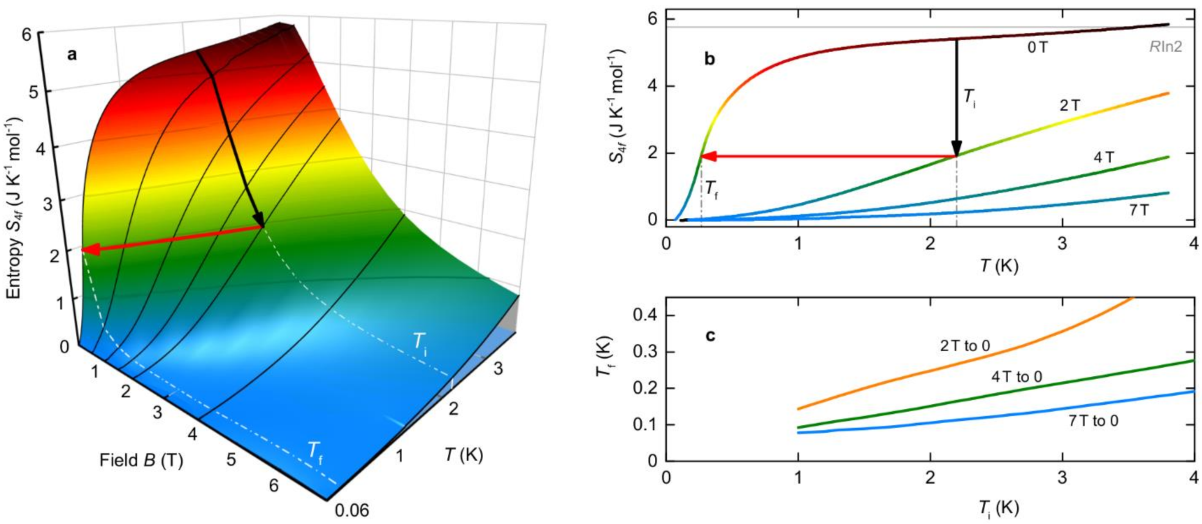

Fig.-1: (a) Color map of the 4f-electron magnetic entropy, S_{4f} (T,B) of $YbPt_2Sn$ calculated from the measured specific heat C_{4f} (T,B)/T. Regions with the same color are isentropic. The black arrow designates the isothermal suppression of the entropy, and the red arrow designates the adiabatic demagnetization, revealing a clear MCE. (b) Projection into the S–T plane of the data. The grey line marks Rln2, which is the saturation entropy of the ground state doublet. (c) Initial temperature T_i dependence of the final temperature T_f for different adiabatic traces or isentropic contours (Figure taken from Ref. 10).

in space projects where zero-gravity cryostats are required [8].

The most popular materials used below 2 K are paramagnetic salts which were first introduced 80 years ago. But the use of salts has significant disadvantages: Sensitivity to humidity, long thermal response, thermal insulation at low temperature and low entropy volume density. Up to now, metals were thought to be poor magnetocaloric materials because of their tendency to leave the paramagnetic state via magnetic or superconducting phase transitions. We have recently discovered that a remarkable exception to this behavior is $YbPt_2Sn$ [9]. Although it is a good conductor, it has the extraordinary quality of remaining paramagnetic down to 0.25 K. Its volumetric entropy capacity is three times larger than that of common paramagnetic salts [10]. This is illustrated in Fig. 1 in which we have plotted the *T*- and *B*-dependence of the entropy of $YbPt_2Sn$. The maximum entropy is *Rln2* (with *R* the gas constant) which is the entropy of the ground state magnetic doublet of the Yb atoms. The black and red arrows in Fig. 1 illustrate the AD cooling process while sweeping a magnetic field of 2 T to 0 T, resulting in a temperature change from an initial temperature T_i to a final temperature T_f.

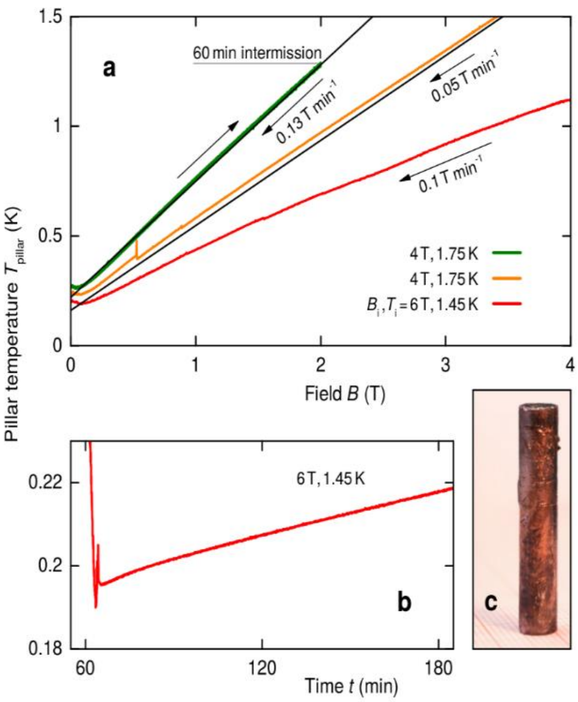

Fig.-2: (a) Measurements of the MCE by means of quasi-adiabatic demagnetization. The temperature of the $YbPt_2Sn$ ingot pillar (photograph), T_{pillar}, is shown for various paths. Current record of the lowest temperature is 0.19 K, which was reached starting from 6 T and 1.45 K. (b) Increasing of T_{pillar} with time: about 0.01 K/ h. (c) The ingot pillar (10 g) of $YbPt_2Sn$ (Figure taken from Ref. 10).

An ADR we built ourselves was in fact powerful enough to cool 30 g of metallic brass structure down to 0.2 K, starting from 2 K, with only 10 g of $YbPt_2Sn$. This is illustrated in Fig. 2 and the photo shows the $YbPt_2Sn$ cast into a 10 g rod. The record temperature was 0.19 K in our ADR set-up with a field of 6 T. Since this metal can easily be cast in any shape it can be used in ordinary commercial cryostats, like the Physical Properties Measurement Systems (PPMS) by Quantum Design, more specialized cryostats based on pulse-tube coolers, like those produced by Entropy GmbH or even in small cryostats for space applications. Our discovery provides a new, practicable alternative to and ^{3}He-based refrigerators and could trigger the search for new and better metallic magnetocaloric materials.

External cooperation partners

K. Mitsumoto (Niigata University, Japan); C. Krellner (Universität Frankfurt, Germany)

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