Study of Anisotropic Superconductors by Angle-resolved Specific Heat

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Related references:
T. Park, M. B. Salamon, E. M. Choi, H. J. Kim, and S.-I. Lee, Phys. Rev. Lett. 90 (2003) 177001; K. Deguchi, Z. Mao, H. Yaguchi, and Y. Maeno, Phys. Rev. Lett. 92 (2004) 047002; H. Aoki et al., J. Phys.: Condens. Matter 16 (2004) L13.

Recommended with a Commentary by Al Migliori, Los Alamos National Laboratory.

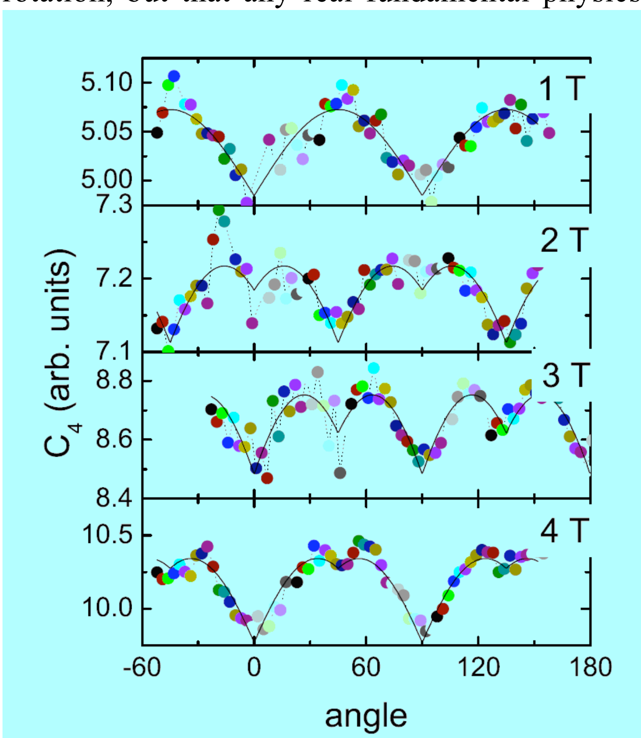
One of the wonderful things about heat capacity is that it is a scalar whenever thermal equilibrium can be achieved in times shorter than the measurement—which is usually all circumstances. The heat capacity, of course, reflects the number of accessible states at a given energy (temperature). Anharmonic processes “mix” all the excitations including electronic, spin, lattice, disorder etc. These processes are typically thrown into a bucket and ignored, but their effect is profound: at any given temperature, the change in the total number of excitations with temperature, each of which can hold kT worth of energy, determines a nice scalar number—the heat capacity, no direction in space needed. Thus heat capacity does not depend on “angle” unless some external field can modify the properties of the material, and that these modifications affect the total density of states (DOS) accessible at a given temperature.

A “simple” system in which direction and magnetic field interact with entropy is Tb_2PdSi_3, and some related compounds where ferromagnetism is locked in monocrystal samples to the crystallographic axes. Thus for fixed magnetic field, the “amount” of spin polarization depends on the direction of the field, and, therefore, so does the magnetocaloric effect and the specific heat. But the origin is no mystery. The system itself defines a “magnetic” direction and, therefore, the system changes as the angle between the internal magnetic direction and applied field changes.

The properties of anisotropic superconductors also change with magnetic field direction, but the effects remain controversial and somewhat obscure to me. The pieces involved are the crystallographic axes, the directional dependence of Hc2 (negligible at low fields), the Doppler shift in quasiparticle gap energy, the change in relaxation time, and the normal core of vortices. The big trouble is that if the DOS and relaxation time both change (true) then the thermal conductivity (very popular) produces ambiguous results that are difficult to separate into fundamental sources.

The idea then, is to use heat capacity because it only depends on DOS. If the anisotropy in the gap in momentum space is fixed to the crystal axes, it induces an anisotropy in the current response around vortices because quasiparticles and supercurrent are coupled. The magnetic field determines the plane of the current loops. Therefore, if we have, say, a d-wave superconductor, then there are four directions with nodes in the gap. A field with the obvious direction perpendicular to the d-wave propeller will not change the physics as the sample is rotated around the field. But if the field is in the plane of the propeller, then as the field is rotated in that plane, vortices have supercurrents that see locally varying gaps, and hence, the equilibrium quasiparticle DOS ought to vary. How it varies still remains a hot topic, but the measurement of the variation has certainly come of age. Although conventional relaxation calorimetry (buy it off the shelf from Qunatum Designs) and adiabatic calorimetry (Aoki) have been used to observe angle-resolved effects in unconventional superconductors, Park and Salamon used AC calorimetry, a popular, hard to calibrate, but extremely sensitive technique.

It is worth reading (but the figure captions and flow of the paper will take some patience to deal with) how they separated the effects of the change in the AuFe thermocouple heat capacity (basically a Kondo thermoelectric) by showing that two thermocouples placed differently would produce signals out of phase with the sample rotation, but that any real fundamental physics must produce signals independent of thermometer location. They also observed this in tests of the system.



They also convincingly observed important physics in $LuNi_2B_2C$. The figure at above shows some of the measurements, with a not-too-bad model, and 2% variation in heat capacity with angle. It is clear that this technique should be pushed hard and the results studied. As with any new technique, one expects that it will be worthwhile and successful to get another factor of ten in signal/noise. It would also be nice to do this in 45T fields where the easier-to-understand effects of anisotropic Hc2 on DOS could be measured as a test of both experiment and theory.