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Magneto-optical imaging of exotic superconductors

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Abstract. We have constructed a novel compact cryostat for optical measurements at temperatures below 2 K. The desktop cryostat, small enough to be placed under the objective of a standard commercial polarized light microscope, functions in a single shot mode, with a five hour autonomy at 1.5 K. Central to its conception are four charcoal pumps for adsorption and desorption of ^{4}He contained in a closed circuit, and novel thermal switches allowing for thermalization of the pumps and of the two 1 K pots. The latter are connected to the 1" diameter sample holder through braids. Sample access is immediate, through the simple removal of the optical windows. In this contribution, we shall present first results on magneto-optical imaging of flux penetration in the heavy-fermion superconductor $CeCoIn_5$.

1. Introduction

The control and understanding of inhomogeneity is a key issue in solid state physics and material science. A good example is the study of superconductors, in which the inhomogeneity of the material may mask the nature of the ground state [1], or, to the contrary, misleadingly suggest a multiplicity of ground states [2]. Recent measurements on the filled skutterudite $PrOs_4Sb_{12}$ have suggested multiple realizations of the superconducting order parameter [3], but a later, more precise study has cast doubt on the intrinsic nature of the observed double transitions [4]. In the same compound, low temperature anomalies in flux penetration have been detected [5,6], that may be due to a change of the superconducting order parameter symmetry, but that might also indicate changes in the structure of, or pinning of, the vortex lattice. The imaging of flux penetration may resolve the origin of anomalies in thermodynamic quantities, and reveal the length scale on which inhomogeneities occur. Conversely, in systems in which the (co-)existence of different superconducting phases has been proven [7,8], imaging may yield new physical information such as domain wall energies.

Direct imaging of flux penetration using the magneto-optical technique [9] has, in this respect, been proven extremely useful in the high temperature superconductors. Notably, the technique is able to identify the regions of the sample (*e.g.* bulk vs surface) in which dissipationless currents flow preferentially [10]. Magneto-optical imaging is also indispensable for selecting homogeneous crystals.

In an effort to transpose the technique to heavy-fermion superconductors, we have devised

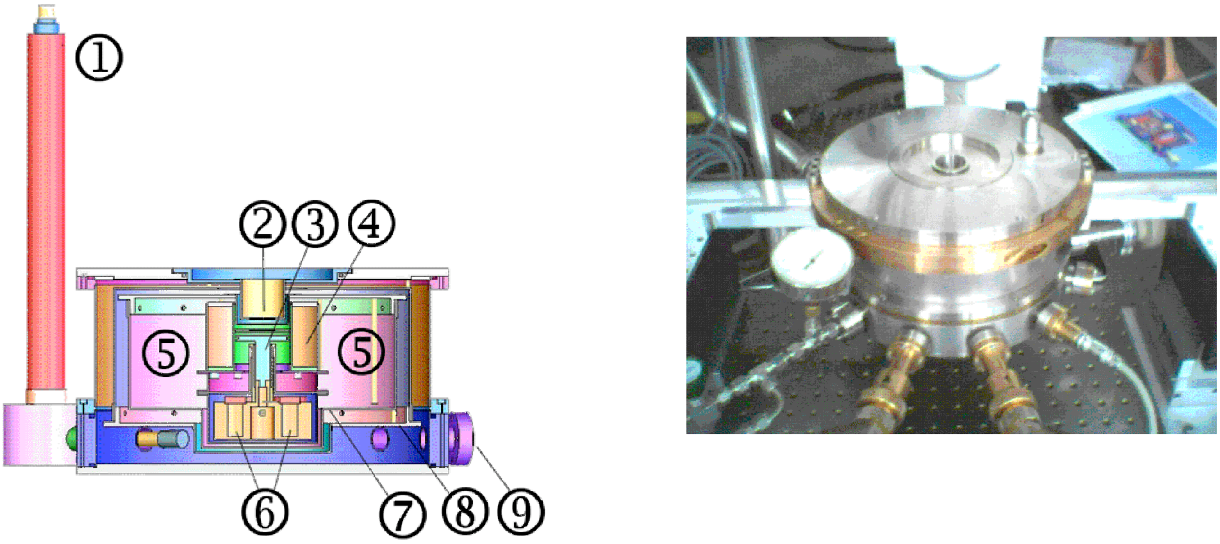

Figure 1. Left: Cross-section of the compact cryostat. 1 - ^{4}He transfer line. 2 - Sample access, optical windows. 3 - Sample holder. 4 - ^{4}He bath with superconducting magnet. 5 - Charcoal pumps. 6 - 1 K pot. 7 - 4.3 K screen. 8 - 50 K screen. 9 - Wiring Access. Right: photograph of the cryostat.

and built a compact cryostat with optical access, designed for operation below 4 K, and which fits under existing commercial polarizing light microscopes.

2. Cryostat

Central to the cryostat is a copper liquid ^{4}He container with a 1 T superconducting coil (4 in Fig. 1). During operation, the container is kept at 4.27 K by continuous liquid ^{4}He flow. ^{4}He gas is absorbed from a 10 l expansion vessel into four charcoal pumps, in thermal connection with the central container. Cooldown below 4 K is achieved by the desorption of the gaseous ^{4}He to two 5 cm^3 1 K pots, and subsequent pumping using the charcoal pumps.

Critical to the correct operation are a set of two gas-gap thermal switches, that couple/decouple the charcoal pumps from the central container. A third thermal switch couples the sample holder to the central container during initial cooldown, and decouples it during the reduction of the ^{4}He pressure in the 1 K pots. Since the "on" state of the thermal switches is controlled by the operation of a set of (three) dedicated charcoal pumps, the cryostat has no moving parts. The sample holder is directly connected to the 1 K pots using copper braids.

Thermal insulation is achieved by a single vacuum space, pumped to 10^{-6} mbar before operation. There are two guilded radiation screens, one thermalized by the central container, and the other cooled to an intermediate temperature of 50 K by the cold ^{4}He gas leaving the container. Moreover, the second, external screen is wrapped in super-insulation.

The base temperature of the sample holder can be adjusted by mounting different, calibrated thermal resistors. During a typical run, a base temperature between 1.1 and 2.0 K can be held for 5 hours. Sample access is through the top of the cryostat, by simple removal of the three optical windows (one on the outer shell, and one for each thermal screen).

3. Experimental details

We have performed initial magneto-optical imaging experiments of flux penetration into Nb, Pb, KOs_2O_6 [11], and $CeCoIn_5$ [12]. Briefly, the sample is mounted with varnish on a small Cu

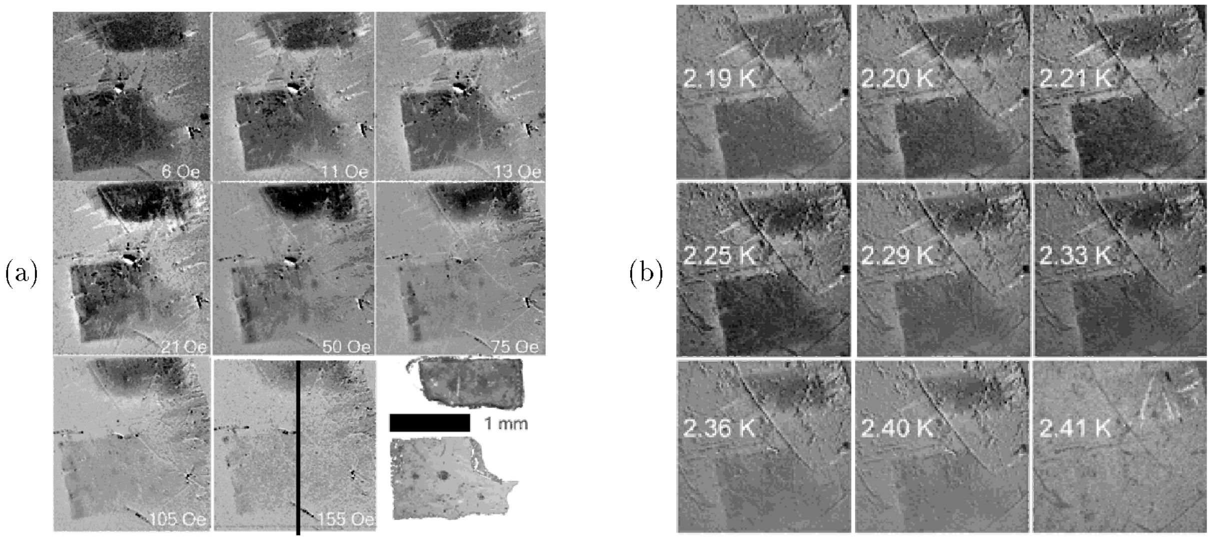

Figure 2. (a) Magneto-optical images of magnetic flux exclusion and inhomogeneous flux penetration into two $CeCoIn_5$ crystals (bottom right image) at 1.88 K. Bright areas correspond to high magnetic flux density, dark areas represent low flux density. The Bean critical state in the top crystal testifies of moderately strong bulk [13] or surface [15] flux pinning, while the bottom crystal shows inhomogeneous screening, mainly by a surface barrier [10]. (b) Flux penetration upon warming the two $CeCoIn_5$ crystals in a field of 1 Oe. Sawtooth-like features are domain walls in the garnet indicator.

support, which is fixed to the Cu sample holder using Apiezon N grease. A ferrimagnetic garnet film with in-plane (negative) magnetic anisotropy, and thickness 4 μm, covered by an Al mirror of thickness 1 μm, is placed directly onto the sample top surface. After closing the cryostat and cooling, the garnet "indicator" is observed using a polarizing light microscope with nearly crossed polarizer and analyzer. Images are aquired using a 16 bit CCD camera with 500 ms exposure time.

4. Results

Fig. 2 shows results on two $CeCoIn_5$ crystals grown by the flux method [12]. The topmost crystal was cut into a rectangular bar and slightly abraded as a result of polishing. The bottom, larger crystal had a large flat surface exposed after cleaving. Magneto-optical imaging of flux exclusion in an applied magnetic field of 1 Oe showed that both crystals have a $T_c = 2.41$ K [Fig. 2(b)]. Nevertheless, both crystals behave quite differently in the superconducting state. Fig. 2 (a) shows magneto-optical images taken at 1.88 K at successive values of the applied magnetic field. Clearly, the polished crystal shows better magnetic screening. This screening is due to bulk [13] or surface pinning [15] of magnetic flux vortices, as testified by the Bean-like straight flux profiles [13] (left side of Fig. 3). The flux density profile of 0.35 G/μm corresponds to a critical current density of 2.8×10^7 Am^{-2}, in good agreement with Ref. [14]. In contrast, the bottom crystal shows very weak screening, that disappears at fields of approximately 150 Oe. This value indicates that flux exclusion is mainly due to Meissner currents at the crystal edge and surface. Nevertheless, (vertical) streaks of stronger flux pinning can be seen, these are presumably related to the varying velocity of the growth front during synthesis. All in all, the main features of flux penetration in the layered heavy fermion superconductor $CeCoIn_5$ are very similar to those encountered in the high temperature superconductor $Bi_2Sr_2CaCu_2O_8$ [10].

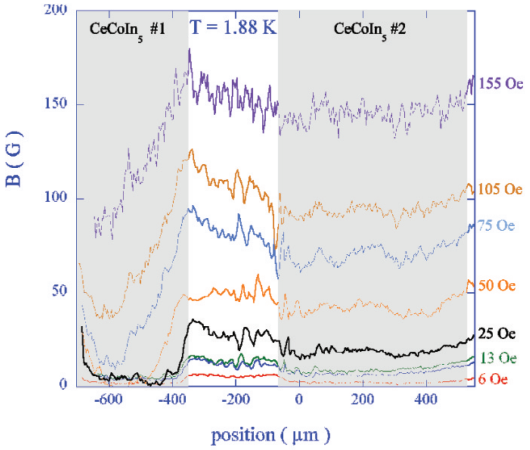

Figure 3. Flux profiles along the vertical line crossing the two CeCoIn$_5$ crystals in the bottom central panel of Fig. 2. The gray bands correspond to the extent of the crystals.

5. Concluding remark

We have demonstrated the feasability of magneto-optical imaging of flux penetration into heavy-fermion superconductors. With future development, this seems a promising route for the resolution of outstanding physical problems related to disorder, inhomogeneity, phase coexistence, and, possibly, spontaneous magnetization in these compounds.

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