Probing Microscopic Magnetic Properties of High-Temperature Superconductors with Muons

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Research Group

The group of Prof. Dr. H. Keller has a strong expertise in investigations of magnetic and thermal properties, and oxygen-isotope effects of high-temperature superconductors and related materials. Various complementary experimental techniques such as, SQUID and torque magnetometry, resistivity and specific heat measurements, as well as resonance techniques (NMR/NQR, EPR, µSR) are applied to investigate the same physical problems. The novel low-energy µSR method recently developed by PD Dr. E. Morenzoni and coworkers at PSI is a new very powerful tool in the research field of the group.

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The muon-spin rotation (µSR) technique has demonstrated to be a unique and powerful *microscopic* probe to investigate local magnetic fields in high-temperature superconductors (HTSC). Recently, a novel low-energy (LE) µSR method was developed at the Paul Scherrer Institute (PSI) which allows to explore local magnetic field profiles in HTSC near the surface of thin films and multilayer structures.

Bulk µSR technique

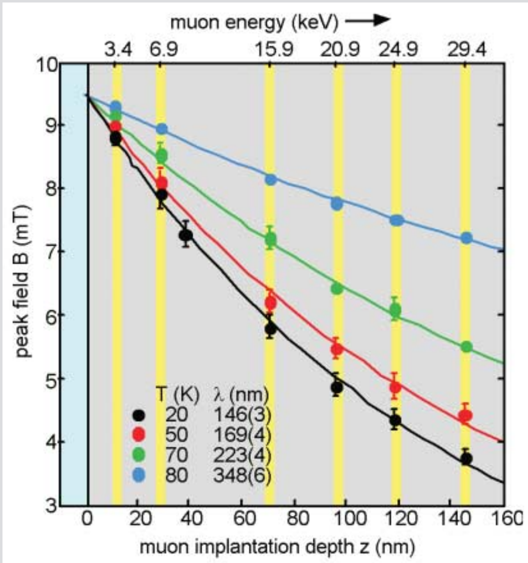
In a µSR experiment spin-polarized positive muons μ^+ serve as a *microscopic* magnetic probe of the local magnetic field distribution in the bulk of HTSC. In many cases µSR has provided important information on the complex vortex structure in HTSC, which is hardly obtained with other experimental techniques. Over recent years a collaboration between the Universities of Zurich, Birmingham, and St. Andrews has played a major role in applying µSR to many aspects of vortex physics in HTSC and other unconventional superconductors. Highlights of this work include the first microscopic observation of flux-lattice melting and disorder crossover in the highly anisotropic HTSC $Bi_2Sr_2CaCu_2O_{8+\delta}$ [1] and the microscopic observation of the suppression of vortex fluctuations in $Bi_2Sr_2CaCu_2O_{8+\delta}$ containing columnar defects [2], to give only two examples.

Low-energy µSR technique

So far µSR studies have been performed using μ^+ with energies of about 4 MeV, which require rather thick (≈1mm) samples. Recently, Morenzoni *et al.* [3] have developed a low-energy (LE) beam of spin-polarized μ^+ at PSI. Very slow muons with kinetic energy of about 10 eV are obtained from the moderation of high-energy μ^+ with an initial energy of about 4 MeV in a thin film of a condensed gas. These slow μ^+ of tunable energy between 0 eV and 30 keV can be implanted at very small and controllable depth below the surface of a sample. This allows to exploit all the advantages of bulk µSR in studies of local magnetic fields in thin samples, near surfaces, and as a function of depth below surfaces. The spectrum of possible applications of LE-µSR is broad, including superconducting thin films, magnetic/superconducting and normal-conducting/superconducting multilayers, nanostructured materials, and quasi two-dimensional magnetic systems.

Recent result

So far, the most beautiful demonstration of the power of LE-µSR is the first direct observation of the spatial variation of the magnetic field (magnetic flux penetration) beneath the surface of a superconductor in the Meissner state [4]. This was achieved by applying a magnetic field parallel to the CuO_2 planes of a c-axis oriented, 700 nm thick epitaxial $YBa_2Cu_3O_{7-\delta}$ film and then measuring the field profile inside the superconductor by implanting LE muons at various depths (~ 15 to 150 nm). The observed field profile is in excellent accordance with that expected for a thin film from London theory (see Figure).



Magnetic field profile B(z) in a 700nm thick c-axis oriented $YBa_2Cu_3O_{7-\delta}$ film in the Meissner state near the surface, measured in an external field of B_0 = 9.5 mT at various temperatures [4]. Using the London theory expression, the experimental data were fitted (solid lines) allowing to deduce a London penetration depth of 146±3 nm at 20K, in agreement with other experiments.

Outlook

Due to their layered structure and unusual electronic properties HTSC give rise to a much more exotic vortex structure than found in conventional superconductors. While HTSC have many potential applications, their usefulness depends crucially on the properties of the vortex state. A detailed understanding of these properties is thus relevant to applied superconductivity. A more fundamental interest of the physics of HTSC is in the exciting field of vortex matter. HTSC represent ideal model systems for the study of wider aspects of vortex matter. The unique advantage of LE-µSR is its ability to extend µSR studies of local magnetic fields in HTSC to thin films and various kinds of multilayer structures. This opens a completely new domain in vortex matter physics research. At present PSI is the only place in the world where LE-µSR experiments can be performed.

References

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A basic introduction on muons is given at the beginning of the Newsletter.