Absence of spontaneous magnetism near the surface of 110-oriented $YBa_2Cu_3O_{7-\delta}$

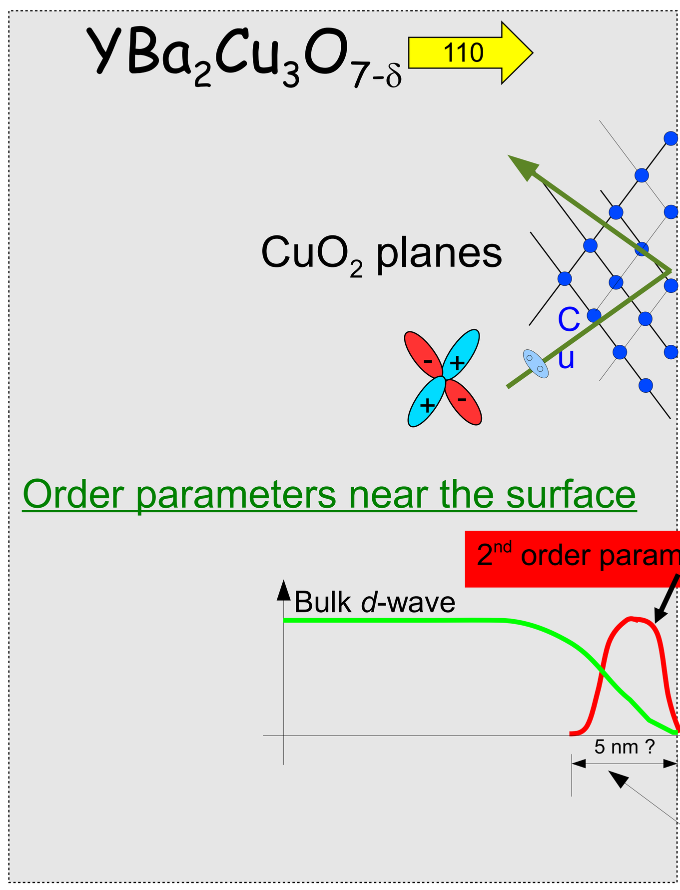
H. Saadaoui[1], Z. Salman[1], T. Prokscha[1], A. Suter[1], H. Huhtinen[2] and E. Morenzoni[1]

[1]Laboratory for Muon Spin Spectroscopy, Paul Scherrer Institut, CH 5232 Villigen, PSI Switzerland.
[2]Wihuri Physical Laboratory, Department of Physics and Astronomy, FI-20014 University of Turku, Finland.

Introduction

The $d_{x^2-y^2}$-wave order parameter of cuprates does not break time-reversal symmetry (TRS), but at the surface under special conditions an other order parameter may appear leading to broken TRS (e.g. d+is, d+id) [1,2]
This can happen due to surface scattering by a (110) surface in YBCO [3] but also near grain boundaries/junctions [4].
A TRS breaking (TRSB) order parameter is associated with spontaneous magnetism at the surface (in a region a few ξ_{ab} wide);
A depth-resolved magnetic probe such as low energy µSR is suitable to detect such fields.
In this work we present our investigations of internal fields near the surface of YBCO 110-oriented films.

Surface scattering by a (110) surface



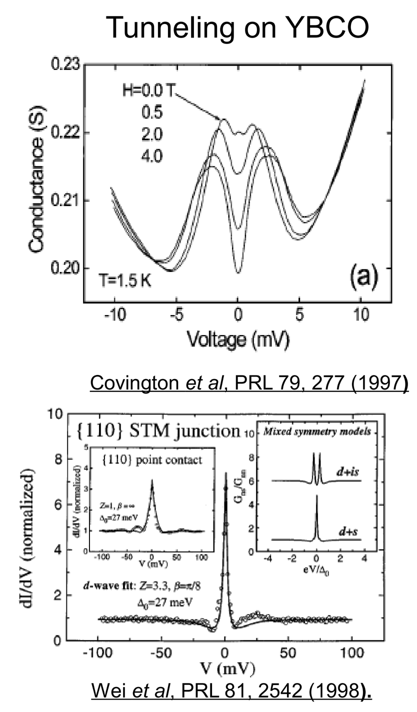
(110) surface: Formation of Andreev Bound States (ABS) (@ E_F) due to broken reflection symmetry of d_{x2-y2} OP (not present in 100, 010, or 001)

ABS can carry currents along the surface (in a region few ξ_{ab} wide) and lead to suppression of the d-wave OP and appearance of a subdominant complex order parameter, e.g. is

d±is breaks time reversal symmetry and spontaneous magnetic fields may appear near the surface

Examples of TRSB studies

Techniques such as SQUID, tunneling, bulk µSR... have been used to study TRSB. SQUID detected magnetism in YBCO below T_c, while tunneling detected it below 7K. These experiments have reached different conclusions.



Spontaneous splitting of Andreev Bound States (ABS) below ~ 7 K in ab-plane tunneling spectroscopy as evidence of TRSB in YBCO.

ABS splitting confirmed in some experiments; in other not or found under unexpected orientations (100) (faceting)

Search of magnetic fields above the surface (0.001 T -1 T) gave also conflicting results

LE-µSR can search for fields within the surface region

Experiment

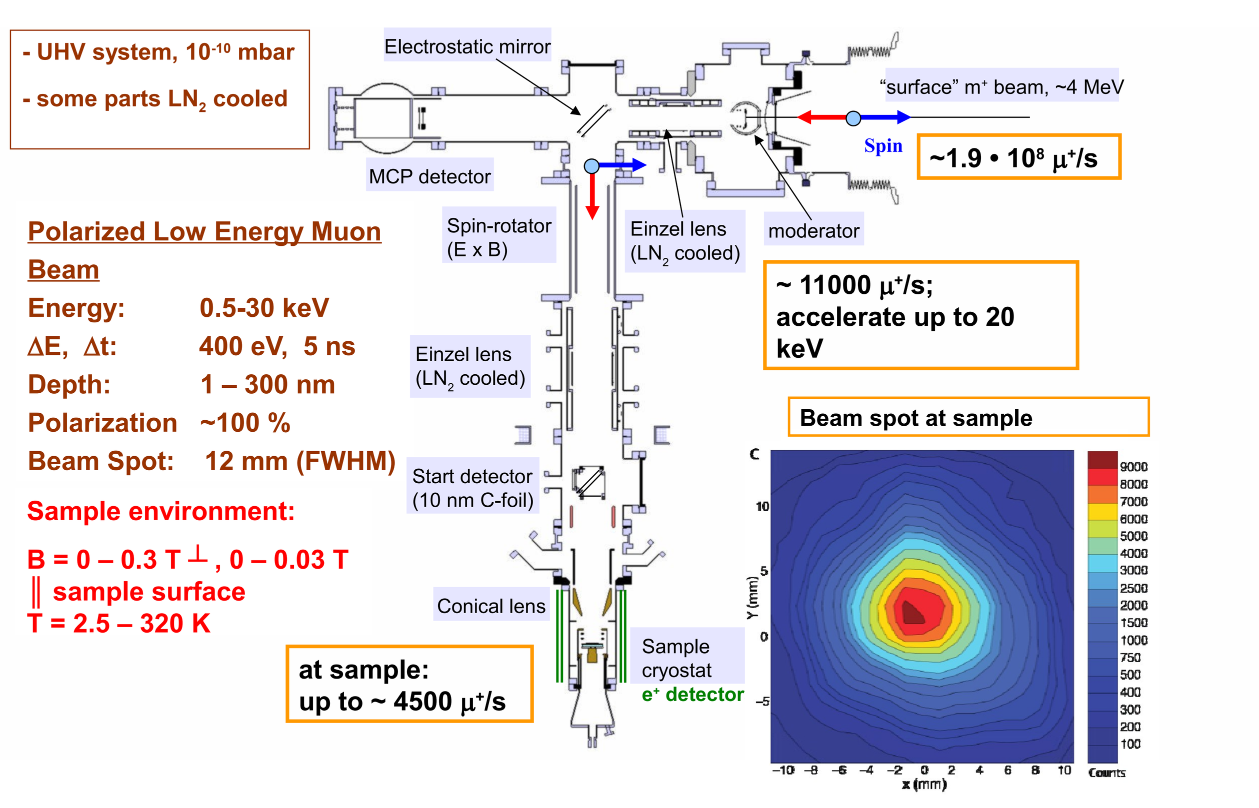
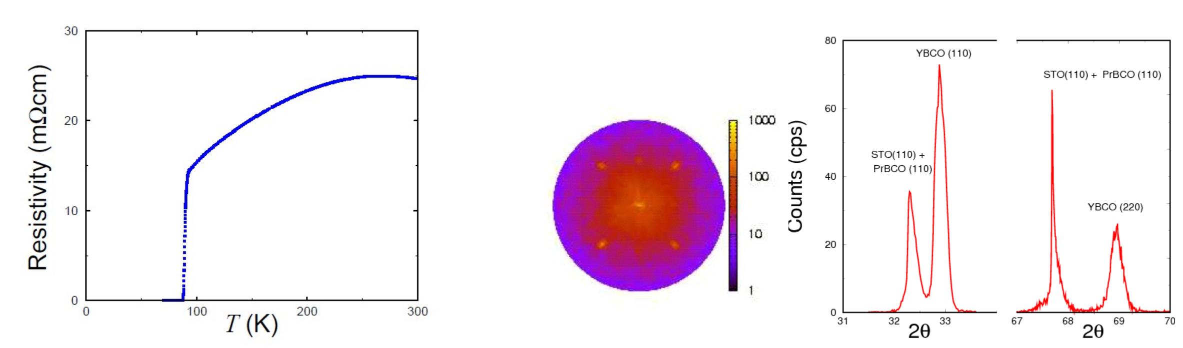
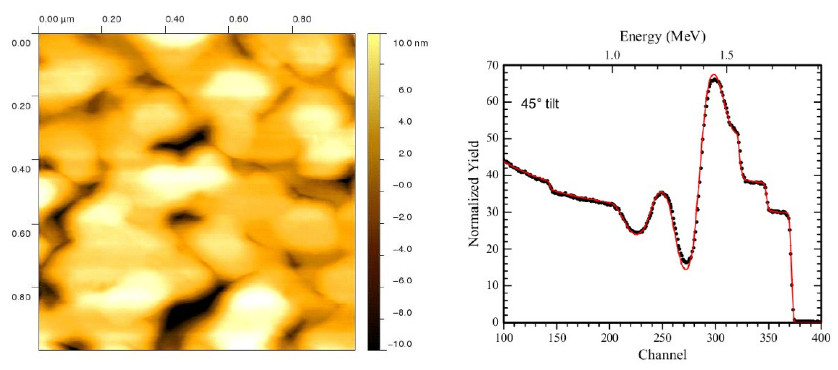


Figure: Low energy μ^+ beam and set-up for LE-µSR.

Sample Characterization

XRD Bragg peaks (and pole picture) show clearly the 110 orientation and absence of other orientations
Also resistivity corresponds to the expected orientation





AFM and RBS characterization

Measurements

We performed ZF measurements with muons implanted near the surface and
TF measurements in the Meissner state of the 110-oriented film with external field parallel or perpendicular to the c-axis (Fig. 1).

In the Meissner magnetic field profile we observe no anomalies, which may be associated to a spontaneous field at the surface and which should be shielded within the penetration depth (Fig. 2).

The measurement of the ZF muon spin relaxation as a function of temperature gives a stringent upper limit of spontaneous fields (Fig. 3).

Results

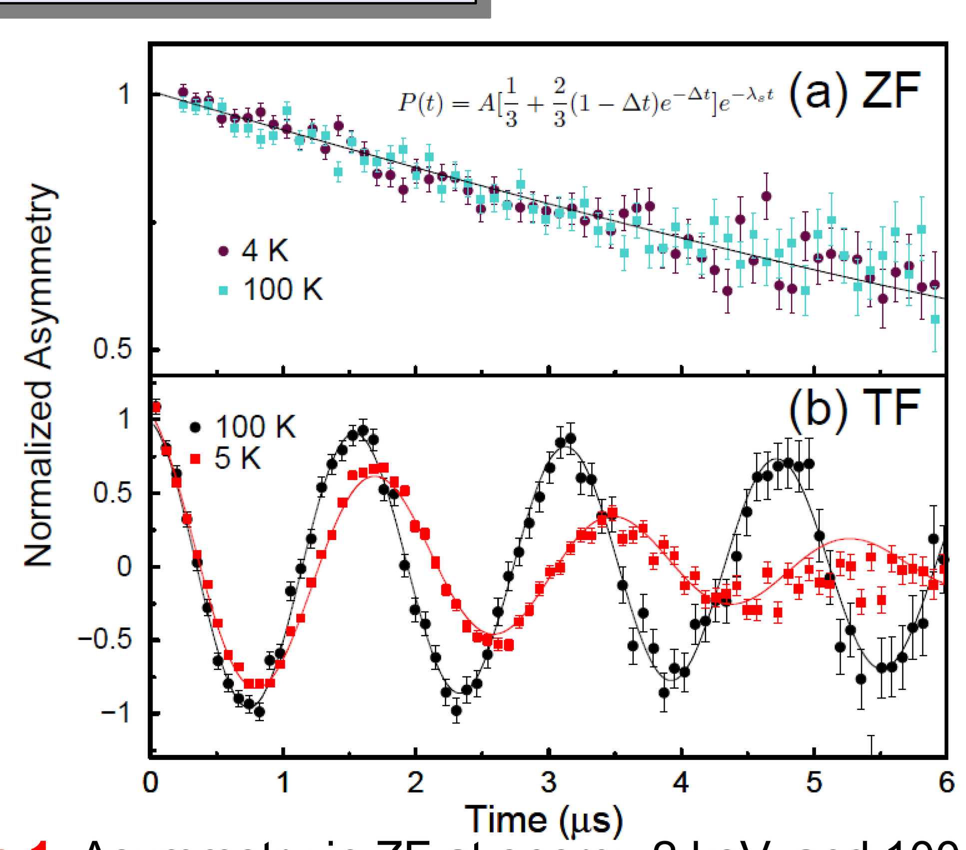


Figure 1: Asymmetry in ZF at energy 2 keV, and 100 and 4 K. (b) Asymmetry in weak TF of 4.64 mT with 14 keV muons At 100 and 5 K. Solid lines are fits.

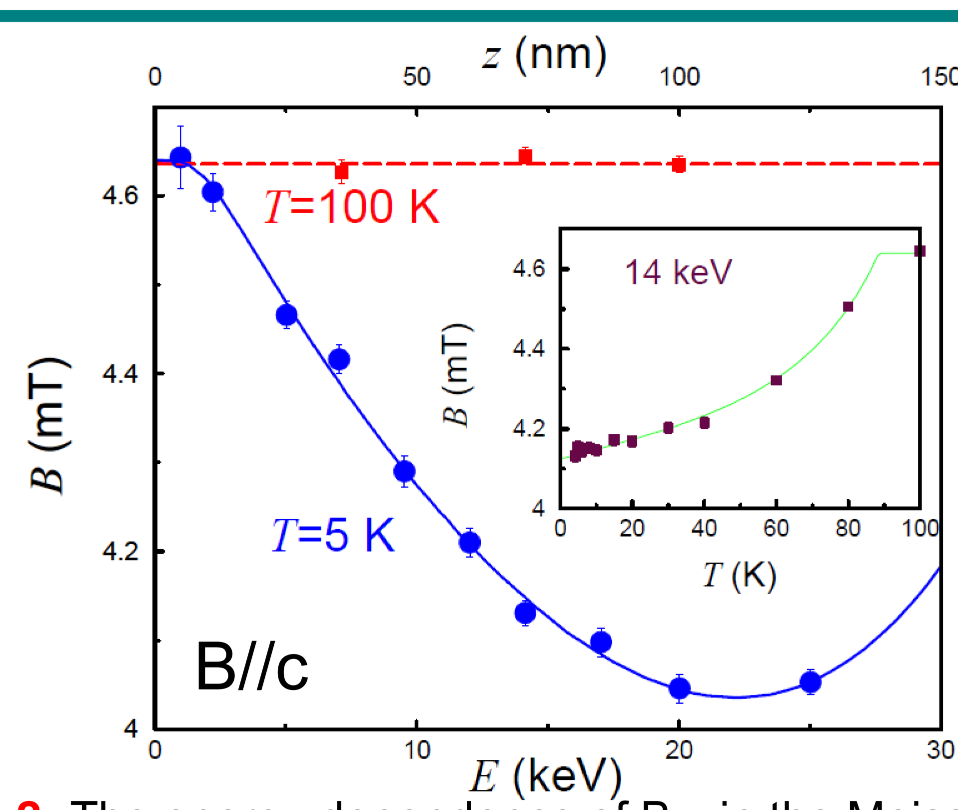


Figure 2: The energy dependence of B_{loc} in the Meissner state at 5 K. The applied field of 4.64 mT as measured in the normal state at 100 K (dashed line). The average depth corresponding to the muons energy as simulated by TRIM.SP is displayed on the top axis. Inset: variation of the average magnetic field versus temperature with 14 keV muons.

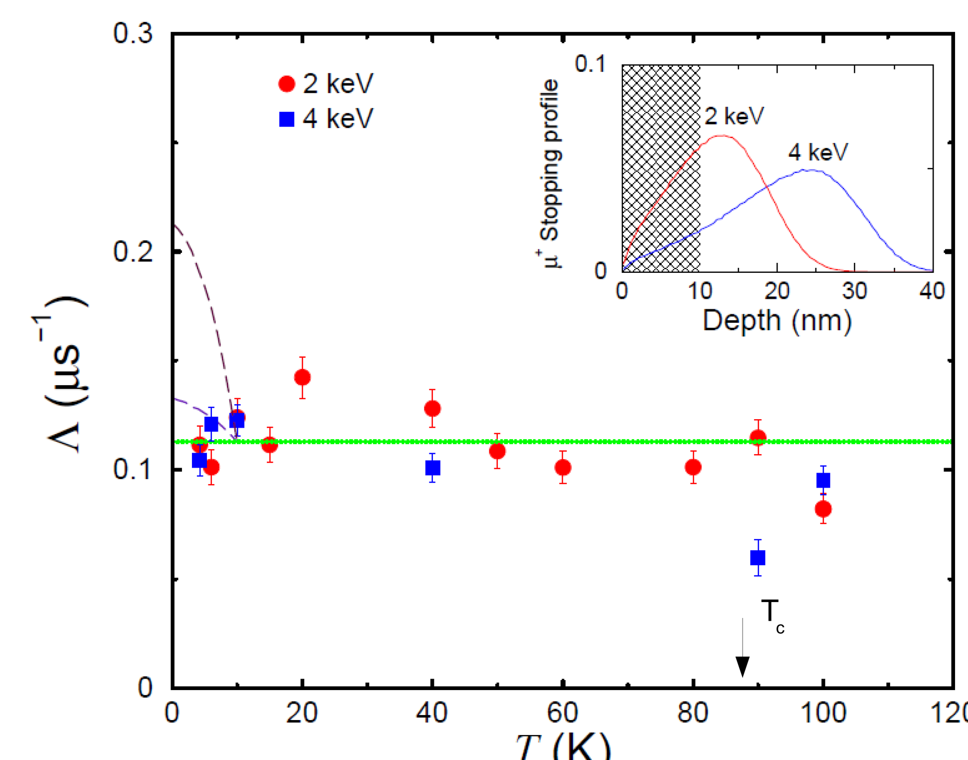


Figure 3: The depolarization rate versus T at 2 and 4 keV implanted in YBCO. Dashed lines show the expected signal for B_{BTRS} of amplitude 0.1 mT and 0.02 mT. Inset shows the stopping profile of the implanted muons [5], where the average depth for 2 and 4 keV muons is 12(5) and 21(8) nm, respectively. Dashed area is where BTRS may arise.

Conclusion

From results from zero field depolarization at mean implantation depths of 10 and 25 nm, in temperatures from 150 K to 2.9 K and magnetic field profiles in the Meissner state, we find no evidence of spontaneous magnetic fields by means of low-energy µSR in (110)-oriented YBCO films. . We establish an upper limit of 0.02 mT of TRSB fields. This is smaller than the value estimated from theory or from tunneling experiments [3,4].

References

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More details can be found in H. Saadaoui et al., Phys. Rev. B **88**, 180501(R) (2013)