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Experiment Report Form

The double page inside this form is to be filled in by all users or groups of users who have had access to beam time for measurements at the ESRF.

Once completed, the report should be submitted electronically to the User Office using the **Electronic Report Submission Application:**

http://193.49.43.2:8080/smis/servlet/UserUtils?start

Reports supporting requests for additional beam time

Reports can now be submitted independently of new proposals – it is necessary simply to indicate the number of the report(s) supporting a new proposal on the proposal form.

The Review Committees reserve the right to reject new proposals from groups who have not reported on the use of beam time allocated previously.

Reports on experiments relating to long term projects

Proposers awarded beam time for a long term project are required to submit an interim report at the end of each year, irrespective of the number of shifts of beam time they have used.

Published papers

All users must give proper credit to ESRF staff members and proper mention to ESRF facilities which were essential for the results described in any ensuing publication. Further, they are obliged to send to the Joint ESRF/ ILL library the complete reference and the abstract of all papers appearing in print, and resulting from the use of the ESRF.

Should you wish to make more general comments on the experiment, please note them on the User Evaluation Form, and send both the Report and the Evaluation Form to the User Office.

Deadlines for submission of Experimental Reports

- 1st March for experiments carried out up until June of the previous year;
- 1st September for experiments carried out up until January of the same year.

Instructions for preparing your Report

- fill in a separate form for each project or series of measurements.
- type your report, in English.
- include the reference number of the proposal to which the report refers.
- make sure that the text, tables and figures fit into the space available.
- if your work is published or is in press, you may prefer to paste in the abstract, and add full reference details. If the abstract is in a language other than English, please include an English translation.

ESRF	**Experiment title:** **Magnetism and Superconductivity in HTSC/FM superlattices**	**Experiment number**: HE1761
Beamline:	**Date of experiment**: from: Nov. 3,2004 to: Nov. 8, 2004	**Date of report**: April 15, 2005
Shifts:	**Local contact(s)**: Júlio Criginski Cezar	*Received at ESRF:*

Names and affiliations of applicants (* indicates experimentalists):

- Jacques Chakhalian (Max Planck Institute for Solid State Research, Stuttgart. Germany) *
- Jorg Strempfer (Max Planck Institute for Solid State Research, Stuttgart. Germany) *
- Bernhard Keimer (Max Planck Institute for Solid State Research, Stuttgart. Germany)
- Christian Bernhard (Max Planck Institute for Solid State Research, Stuttgart. Germany)

Report:

Recently artificially fabricated perovskite superlattices consisting of transition metal oxides layers attracted considerable interest mainly due to possible technological applications in the field of spintronics and because those artificially tailored nanostructures present a unique playground for new physical phenomena associated with strongly correlated electrons. From this point of view, the superlattices made of a high temperature superconductor and half-metal ferromagnet (HTSC/FM) represent one of the most exciting examples of artificial nanostructures because of their mutually incompatible order parameters. On the theory side, studies of a FM/SC junction and associated with it phenomena is a very active field of current research. According to the theory a number of unusual phenomena have been predicted to exist at the interface or in the close proximity to it. Among them is the prediction of a novel magnetic many-body state which should occur at the FM/SC interface. This effect is called a magnetic proximity effect. This is unexpected since from the conventional theory the superconducting order parameter is merely suppressed by much stronger ferromagnetism of the magnetic layer. From the technology point of view, spin-tunnel junctions based on a 100% spin polarized ferromagnet $La2/3Ca1/3MnO_3$ (LCMO) coupled to the HTS superconductor (e.g. YBCO) is considered to be an important part of future spin-injection devices. However, in the experimentally realized structures their performance turned out to be far below original expectations . A likely explanation of such a large discrepancy lies in the physical properties of the `active' interfaces. This technologically important issue is still poorly understood largely because of the limited suitability of traditional techniques used to measure magnetism on nanoscale. X-ray magnetic circular dichroism (XMCD) spectroscopy is the modern and powerful technique uniquely suited for investigation of nano-magnetism at the "buried" interfaces. XMCD is capable of providing chemical element specific information on spin and orbital parts of a magnetic moment with a sub monolayer sensitivity. Also, this technique allows to measure element-specific hysteresis loops and identify an orientation of the magnetic moments. To investigate the interfacial magnetism in HTSC/FM superlattices we used a circularly polarized x-ray beam at the 4-ID08 at the European Synchrotron Radiation Facility (ESRF). In this report we demonstrate that by applying XMCD technique at the L2,3 absorption edges of Mn , we were able to study directly the ferromagnetism at the

HTSC/FM interface. To experimentally verify the presence of the novel magnetism, we fabricated a number of superlattices of varying thickness. Here we report results on the representative superlattice composed of the 100 Å thick YBCO and 100 Å thick LCMO layers grown on a 0.5 mm thick, atomically flat single crystal STO (001) substrate by the pulsed laser deposition (PLD) techniques. The bulk magnetic and transport properties of the superlattices were determined from the measurement in a superconducting quantum interference device (SQUID) and physical properties measurement system (PPMS). These measurements yield the onset of ferromagnetism at Tm=170 K and the transition into the superconducting state at Tsc=75 K. To investigate dynamics associated with the magnetic moments we performed XMCD measurements in a broad range of temperatures from 290 K down to 15 K at the Mn L2,3 edges. Figure 1 shows the results of temperature scans compared to the bulk magnetization data. As seen, at the elevated temperature of about 180 K the dichroism on Mn is practically zero which is consistent with the paramagnet-ferromagnet transition as confirmed by the SQUID. It is well known that a reduced atomic coordination at the interface and surface may lead to a dramatic modification of the long-range order. Therefore, the temperature dependence of the Mn XMCD signal and its magnitude can provide some additional insight on the origin of the observed magnetic moments. As seen from Fig. 1 the dichroism and the transition temperature Tm are both reduced compared to those of the bulk. Since the film is completely relaxed as evidenced from XRD, the observed reduction of the magnetic moment cannot be explained by the presence of remnant tensile (compressive) stress from the STO substrate whose effect is to modify the bandwidth via distortion of MnO_6 octrahedra. Instead a profound modification of the ferromagnetism at the interface is most likely caused by the interaction with SC appearing at the interface below Tsc and divergence of the spin-spin correlations associated with a reduced film thickness. The XMCD *T*-dependence is also very different from the magnetization measured in a SQUID where it varies similar to that of the bulk. Specifically, it reaches a full saturation below 70 K but shows practically a linear decrease upon heating. This is greatly different from a continuous 3D phase of the *XY*-universality class for a 3D Heisenberg ferromagnet. The observed deviation is more in accord with the theoretical predictions for interfacial magnetism which is very different from either a free surface and bulk magnetization . This temperature dependence is another strong evidence for the interfacial nature of magnetism under the study.

Conventionally, the presence of hysteresis in magnetization is a strong evidence for ferromagnetism. With this goal in mind we measured hysteresis loops by scanning the magnetic field at the sample position with the fixed helicity of light at the Mn L_3 edge. Figure 2 shows a typical set of hysteresis loops acquired above and below the superconducting transition. As a function of temperature, the Mn hysteresis loops shows continuing reduction of coercitivity. The overall shape of the Mn loops indicates that the easy direction of magnetization is in-plane which is expected for thin LCMO layers. However, what is unexpected is the sudden change in the shape of the Mn hysteresis loops when the temperatures passes through the superconducting transition. If above Tsc the hysteresis loops show a step which indicates that the top layer is softer and it switches first followed by the rest of the Mn layers. As the temperature drops below Tsc the step suddenly disappear and the overall hysteresis shape is S-like. This indicates one of two possibilities: a) the coupling between Mn layers across SC YBCO layers increases dramatically and therefore the overall magnetic volume is increases as well. b) Or if the magnetic roughness increases (which is confirmed by the off-specular neutron reflectivity on the same sample which show that the size of magnetic domains becomes very small and the diffuse scattering gets rather large) then we can assume that we deal with strong pinning of SC magnetic flux by the FM domains which of course doesn't allow to move the domain walls freely anymore compared to the case of T>Tsc. This we deal with FM controlled superconductivity. Any of those scenarios can account for this rather unusual observation. The work to further investigate these unusual findings is in progress.

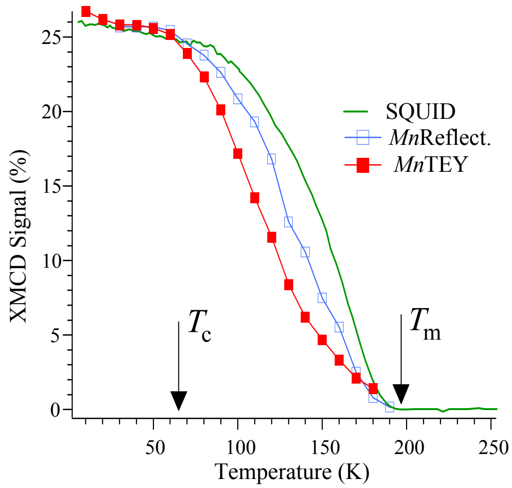

Fig 1. Comparison between tmperature depence of the bulk magnetisation v.s. XMCD taken at L3 Mn edge. For XMCD the data are presented for both TEY (filled boxes) and reflectivity modes(empty boxes).

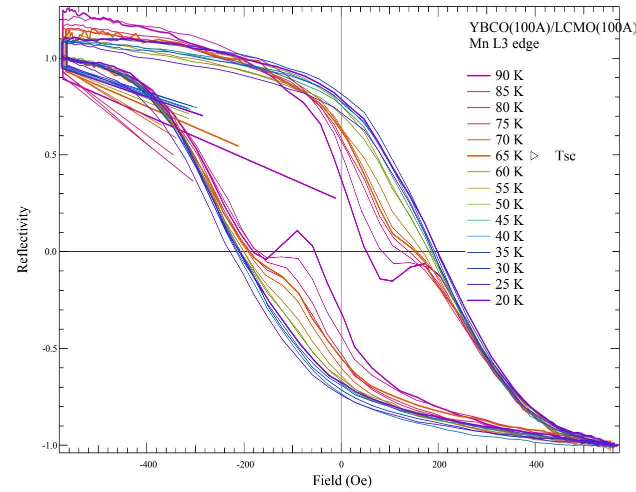

Fig. 2. *Evolution of Mn hysteresis loops with temperature taken at the L3 Mn edge. A double step at the temperatures above Tsc is associated with the softer top Mn layer.*