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Field dependence of the ferromagnetic/superconducting proximity effect in a YBCO/STO/LCMO multilayer

Abstract

The interaction between superconductivity and magnetism in spatially confined heterostructures of thin film multilayers is investigated in the ferromagnetic manganite $\text{La}_{2/3}\text{Ca}_{1/3}\text{MnO}_3$ (LCMO) and the high-temperature superconductor $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (YBCO) mediated by an intermediate insulating SrTiO_3 (STO) layer. The STO layer is used to mediate and tune the range of interactions between the ferromagnet and superconductor. A magnetically depleted layer with zero-magnetisation within the LCMO layer is shown by polarised neutron reflectometry measurements. This zero-magnetisation layer is caused by the onset of superconductivity in YBCO despite being separated by an insulating layer with a thickness much larger than the superconducting coherence length. The magnetic field dependence of this interaction is also explored. We show that the magnetism of the depleted layer can be restored by applying a magnetic field that partially destroys the superconductivity in YBCO, restricting the electronic interaction between the materials.

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Field Dependence of the Ferromagnetic/Superconducting Proximity Effect in a YBCO/STO/LCMO Multilayer

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The interaction between superconductivity and magnetism in spatially confined heterostructures of thin film multilayers is investigated in the ferromagnetic manganite $\text{La}_{2/3}\text{Ca}_{1/3}\text{MnO}_3$ (LCMO) and the high-temperature superconductor $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (YBCO) mediated by an intermediate insulating SrTiO_3 (STO) layer. The STO layer is used to mediate and tune the range of interactions between the ferromagnet and superconductor. A magnetically depleted layer with zero-magnetisation within the LCMO layer is shown by polarised neutron reflectometry measurements. This zero-magnetisation layer is caused by the onset of superconductivity in YBCO despite being separated by an insulating layer with a thickness much larger than the superconducting coherence length. The magnetic field dependence of this interaction is also explored. We show that the magnetism of the depleted layer can be restored by applying a magnetic field that partially destroys the superconductivity in YBCO, restricting the electronic interaction between the materials.

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I. INTRODUCTION

The interaction between superconductivity and ferromagnetism as two mutually exclusive order parameters coexisting is an intense topic of research at present. This is attributed to a number of recent experimental findings such as orbital reconstruction at the interface of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (YBCO)/ $\text{La}_{2/3}\text{Ca}_{1/3}\text{MnO}_3$ (LCMO) hybrid structures [1], long range charge-density-wave proximity effects [2], as well as a magnetic proximity effect in YBCO/LCMO superlattices [3–6]. A thorough understanding of the interactions occurring at the interface between these two exotic materials has the potential to pave the way to a new era in electronics and devices [7].

A magnetically depleted (MD) layer was observed in YBCO/LCMO superlattices within the ferromagnetic material adjacent to the interface[3]. This MD layer had a reduced or completely suppressed magnetisation as observed by polarised neutron reflectometry (PNR) and resonant X-ray techniques. Self-consistent total energy calculations of this superlattice structure within density functional theory also confirmed that the coupling between Mn atoms becomes very weak and possibly anti-ferromagnetic near the interface [6]. Note, in contrast to the present work, these results were obtained for the interfaces between superconducting and ferromagnetic materials having no intermediate layers, which could potentially attenuate and/or control the interactions.

The range of influence of LCMO on YBCO was approximated by Fedoseev *et al.* by introducing an insulating SrTiO_3 (STO) layer between the ferromagnet and superconductor [8, 9]. It was found that the proximity effect of a 150 nm thick LCMO layer affecting the critical temperature of a 200 nm YBCO layer became negligible for STO thicknesses of > 5 nm.

Trilayer YBCO/STO/LCMO films, consisting of 30 nm LCMO and YBCO layers separated by varying thicknesses of STO, were investigated using PNR by Prajapat *et al.* [10, 11]. It was observed that even with the presence of a thin insulating STO layer (2.5 and 5 nm) between the superconducting and ferromagnetic material, a MD layer was still present in LCMO. This result was exclusively found below the superconducting transition temperature (T_c), where it was shown that the width of the MD layer was inversely proportional to the thickness of the STO interlayer. Although, the superconducting properties of the YBCO layers were relatively weak as indicated by a reduced T_c [10, 11], the tunnelling of Cooper pairs

through the STO layer was suggested to be responsible for the suppressed magnetisation in the LCMO layer near the interface.

In this work, we investigate the magnetic field dependence of the magnetically depleted layer in YBCO (30 nm)/STO (1.5 nm)/LCMO (30 nm) trilayers. We show that the application of a magnetic field results in an increase of the magnetisation in LCMO at the interface with STO, as seen by PNR investigations from the reversal of magnetisation suppression in the depleted layer. This reversal may indicate another tool, along with the intermediate insulating layer, for the manipulation and control of the confined magnetic properties in superconducting/ferromagnetic heterostructures, for their potential use in future spintronic applications.

II. RESULTS

A. X-Ray Diffraction

In this work, we investigate the YBCO/STO/LCMO trilayers of 30 nm/1.5 nm/30 nm thick grown by pulsed laser deposition (PLD) on an Yttria-Stabilised Zirconia (YSZ) substrate as described in our previous work [15, 16].

X-Ray Diffraction (XRD) is used to indicate the quality of the epitaxial growth of the sample. Figure 1 shows that all diffraction peaks measured in the $\omega - 2\theta$ geometry are c -axis oriented demonstrating epitaxial growth of the sample in the correct crystallographic direction. The observation of YBCO peaks up to (00 10) shows the high quality growth of the superconducting material in the trilayer.

The YBCO(001) diffraction peak shown in the inset to Figure 1 (not visible in the main figure) was fitted with the one-dimensional interference function $[\sin(NQc)/\sin(Qc)]^2$. This equation describes the finite thickness interference fringes surrounding a diffraction peak, and the thickness of a single-crystal layer can be extracted from it. In this equation, c is the c -axis lattice parameter, Q is the momentum transfer proportional to the experimental reflection angle, and N is the number of unit cells in the z -direction. The fitting procedure has determined $N = 28$ and $c = 11.74 \text{ \AA}$. N determines the thickness of the YBCO layer which agrees with the thickness found by both XRR and PNR measurements, and the measured c -axis parameter for YBCO is elongated by $0.06 \text{ \AA}$ from its bulk value [12, 13]

FIG. 1. X-ray Diffraction measurements in $\omega - 2\theta$ geometry. Inset shows the YBCO (001) peak fitted with the 1D interference function.

indicating an in-plane compressive strain on YBCO from the YSZ substrate.

In order to further quantify the quality of the film's uniaxial growth, rocking curve measurements were performed on YBCO and LCMO diffraction peaks (results not shown). The full width at half maximum (FWHM) extracted from a Gaussian fit of the rocking curve around the YBCO (005) and LCMO (004) reflections are $\Delta\omega = 0.397^\circ$ and $\Delta\omega = 0.371^\circ$ respectively, with an instrumental resolution of 0.031° . These values verify the low mosaicity of the YBCO and LCMO layers in the multilayer.

FIG. 2. X-ray reflectometry of trilayer. The inset shows the corresponding electron SLD profile. The first two layers on the left-hand side of the SLD profile inset are the substrate YSZ and a layer of initial imperfect YBCO growth.

B. X-ray Reflectometry

Figure 2 displays the X-ray reflectometry data (circle symbols) and fit (line) for the YBCO/STO/LCMO trilayer. The scattering length density (SLD) profile constructed from fitting the X-ray reflectometry data is shown in the inset of Figure 2. The SLD profile shows an approximate thickness of the layers, agreeing with the ~ 32 nm thickness of YBCO and LCMO determined by the interference function and by the pulsed laser deposition parameters. The roughness in the sample is less than 2 nm on the surface and less than 1 nm throughout the material layers.

The dip in SLD between the substrate and YBCO is a layer of initial non-perfect epitaxial

FIG. 3. (a) In-plane magnetisation hysteresis curves of the trilayer at different temperatures. (b) Low-field region of the hysteresis curves of the trilayer shown in a). (c) In-plane magnetisation curve of LCMO thin film, and (d) Resistivity, indicating a sharp superconducting transition at $T_c = 88.5$ K.

growth of YBCO on YSZ before proper growth starts. This non-perfect layer is usually present in PLD grown films on any substrate (e.g., see transmission electron microscopy images near the substrate in Refs. [14, 15]). This feature was also found in the PNR SLD profile, but it did not affect the measurements in any other way. The X-ray diffraction in Figure 1 also shows that this initial layer does not produce any additional diffraction peaks, confirming that there is no other crystallographic phases present.

C. Magnetometry and Transport Measurements

Magnetic hysteresis measurements have been carried out at 100 K, 60 K, and 5 K. Each measurement is obtained by field-cooling the sample in the magnetic field of $B_a = 0.03$ T applied in-plane to the trilayer sample, then starting the field sweep from that magnetic field. The magnetisation loops are shown in Figure 3a) with Figure 3b) displaying the low-field part of the curves.

Transport measurements shown in Figure 3d) display a superconducting critical temperature $T_c = 88.5$ K with a sharp transition. This value of T_c is remarkably close to the optimal value of 91 K for YBCO thin films [14, 16], especially considering that (i) the thickness of the YBCO film in this work is only 30 nm (YBCO film thicknesses below ~ 50 nm are known to exhibit lower T_c due to reduced crystallinity at the interface with a substrate upon the initial epitaxial growth [17]); and that (ii) it is in close proximity to the ferromagnetic material, which might affect the YBCO film via residual stray fields. However, we would like to emphasise that there is an STO interlayer between the YBCO and LCMO layers [8, 9], presumably preventing close range interactions, which would suppress superconductivity and T_c due to the *inverse* proximity effect [18, 19]. On the other hand, we do not expect any measurable change in the “global” resistivity of the YBCO layer as the result of the loss of Cooper pairs to the neighboring STO and LCMO layers due to the proximity effect. For this, a localised technique such as scanning tunnelling spectroscopy [18, 19] should be employed.

This T_c value of 88.5 K is significantly higher than what was found in similar hybrid systems in the literature [5, 10, 11]. This is further evidence of the high-quality crystallinity in our YBCO thin film layer.

At $T = 100$ K, which is above T_c , the hysteresis loops shows purely ferromagnetic behaviour (Fig. 3a,b) similar to that measured for the pure LCMO film (Fig. 3c). As the temperature is reduced below T_c to 60 K and 5 K, the loops become increasingly distorted by addition of the irreversible component of superconducting magnetisation over the broad field range due to pinning properties in the YBCO layer. A similar superposition of ferromagnetic and superconducting magnetisation response was previously observed in different hybrid structures [20, 21].

The virgin part of the magnetisation loop at 5 K initially exhibits a typical behaviour for

the initial magnetic flux penetration in a type II superconductor above the first critical field (Fig. 3a,b). Notably, the magnetisation remains positive for the entire virgin curve due to the superposition of the saturated magnetisation of ferromagnetic LCMO and the magnetic flux frozen in YBCO after the field-cooling procedure.

Thus, it is evident that the trilayer at $T = 5$ K and 60 K displays strong contributions from both ferromagnetism in LCMO as well as superconductivity in YBCO.

D. Polarised Neutron Reflectometry

Polarised neutron reflectometry (PNR) was measured for the sample in two different magnetic fields (0.03 T and 1 T) for three different temperatures: 100 K (Fig. 4), and 60 K and 5 K (Fig. 5a-c). Each measurement was obtained by field-cooling the sample in $B_a = 0.03$ T applied in-plane to the trilayer down to the desired temperature, then changing the magnetic field to the value needed.

Each fitted reflectivity model corresponds to an associated SLD profile. From the reflectivities of the R^{++} and R^{--} spin channels, the normalised spin asymmetry (NSA) can be found. This is defined as

$$NSA = \frac{R^{++} - R^{--}}{R^{++} + R^{--}}. \quad (1)$$

It is sensitive exclusively to the magnetic features of the sample, which will be used to help determine the magnetic profile throughout the sample.

The PNR measurement at 100 K (above T_c for YBCO) in 0.03 T (Fig. 4a) has been fitted using Simulreflec simulation software [22]. The corresponding SLD profile in Figure 4c) displays a magnetic SLD (MSLD) profile (red) within the LCMO layer that persists up to the LCMO/STO interface. As these data are measured above T_c for YBCO, they serve as the undisturbed benchmark for the LCMO magnetisation depth profile.

This magnetic SLD has also been given a second y -axis in Fig. 4c) corresponding to the number of Bohr magnetons per Mn atom.

The nuclear SLD of LCMO (black bold line) in Fig. 4c) is reduced as it approaches the air interface. In this region, the magnetisation (red) is also reduced compared to the middle of the layer, which is consistent with previous neutron studies on doped manganites [23]. The LCMO layer also has an increased nuclear SLD towards the LCMO/STO interface, accompanied with a reduced magnetisation in comparison to the middle of the layer. It

FIG. 4. (a) Polarised neutron reflectometry data (symbols) and fitted model (lines) at $T = 100\text{ K}$ and $B_a = 0.03\text{ T}$, (b) Corresponding NSA data (symbols) and fit (line), and (c) constructed SLD profile based on fitted model in (a). The right y -axis in (c) translates the MSLD to Bohr magnetons per Mn atom.

has previously been found that LCMO deposited on STO causes tensile strain, which in turn proliferates oxygen vacancies in LCMO near the interface. These oxygen vacancies significantly reduce the magnetisation [24]. The reduced nuclear SLD near the LCMO-air interface is indicative of relaxation in the crystal lattice. The increased nuclear SLD in LCMO towards the LCMO/STO interface is understood to be as a result of YBCO epitaxial growth. YBCO films develop by the island growth model (Stranski-Krastanov mode), and as such their surfaces are not atomically flat [13, 25]. Deposition of STO and LCMO on top of a YBCO structure such as this propagates the waviness throughout the multilayer in a similar fashion as observed for superlattices in ours and others' previous work [15, 26]. The resultant laterally averaged SLD is the weighted addition of mainly LCMO and YBCO, which has a net increase in structural SLD compared to bulk LCMO.

It is worthwhile to once again emphasise that in the absence of the superconducting state in the YBCO layer, the magnetic (red) SLD profile of LCMO extends all the way up to the STO layer at $B_a = 0.03$ T and $T = 100$ K, which is well above $T_c = 88.5$ K for our YBCO layer.

Figure 5 shows the low-field (0.03 T) and high-field (1 T) PNR measurements for 5 K and 60 K for the trilayer sample. The inset of each measurement is the associated MSLD for the data (red).

At $T < T_c$, there exists a ~ 1.5 nm thick layer in the LCMO adjacent to the LCMO/STO interface that has approximately zero net magnetic moment in the applied field of 0.03 T. This layer is shown in the MSLD profile inset in Figures 5a) and 5c). This suppression of the net magnetisation near the LCMO/STO interface is obviously triggered by the presence of superconductivity in the YBCO layer. Indeed, at $T > T_c$, the non-zero magnetisation extends up to STO/LCMO interface (Fig. 4c).

Under the application of the strong magnetic field of 1 T, the layer of depleted magnetisation is restored (Figs. 5b and d). This is assumed to result from the partial destruction of the superconducting state by the high magnetic field, restricting the amount of Cooper pairs that are able to tunnel through (or be transported via) the STO layer to the LCMO layer. These pairs, once in the LCMO layer, would fall apart thereby reducing the number of the unpaired spin-polarised electrons around the Mn^{3+} in the LCMO layer, which are responsible for the double-exchange mechanism giving rise to ferromagnetism in the LCMO layer [27, 28]. The partial destruction of superconductivity is obvious from the reduced

FIG. 5. Polarised neutron reflectivity at (a) 5 K in 0.03 T, (b) 5 K in 1 T, (c) 60 K in 0.03 T, and (d) 60 K in 1 T. The inset in each figure is the associated magnetic SLD for the PNR data. In all insets, the red area indicates the ‘Best Fit’ of the MSLD determined by the fitting process. The horizontal black lines (from 32 nm to 42 nm) in a) and c) (measured at 0.03 T) show a magnetic “Uniform M” model in which a constant LCMO magnetisation extends all the way to the STO interface. The black lines in b) and d) (measured at 1 T) show a magnetically depleted “MD Layer” close to the STO interface. The black lines in all insets serve as alternate models for comparison to determine the presence of a magnetically depleted layer, and the vertical black stripes indicate that these models only vary from the “Best Fit” close to the interface. Each MSLD has been converted to Bohr magnetons per Mn atom on the right y-axis. The χ parameter for each model is a statistical goodness-of-fit parameter for the normalised spin asymmetry. The interfaces between the LCMO, STO and YBCO layers are indicated by vertical dashed lines.

height of the magnetisation loops at $B_a = 1$ T compared to the low-field region at ~ 0.03 T in Fig. 3a), which is measured in the identical geometry employed for the PNR measurements (Fig. 5). Indeed, more vortices appear inside the superconductor with increasing field. This implies an ever increasing non-superconducting volume due to the increasing number of non-superconducting vortex cores, hence an overall lower number of Cooper pairs.

Here, we should note that strong applied field of 1 T likely may also assist in enhancement of spin polarisation in the LCMO layer to its complete saturation as can be seen in Fig. 3a). However, if the superconducting Cooper pairs play a significant role in suppressing the ability of spin polarisation within the double-exchange mechanism [27, 28] as proposed above, it is likely that the effect of the magnetisation saturation in the LCMO layer at the high field would play a secondary role.

For comparison, the MSLD profiles in the insets of Figure 5 have also been fitted with an alternative magnetic profile. For the low field measurements (Figure 5a, c), this profile is named ‘Uniform M’ that assumes a constant magnetisation up to the LCMO/STO interface. For high-field measurements (Figure 5b, d), this profile is named ‘MD Layer’ that assumes a magnetically dead layer in LCMO adjacent to the LCMO/STO interface. The vertical black stripes in the MSLD insets indicate that these alternate models only vary from the “Best Fit” close to the STO interface.

To reinforce the claim of the MD layer being present exclusively in low magnetic fields below the superconducting T_c , residual sum of squares were taken between the magnetic SLD models in the insets of Figure 5 (‘Best fit’ and ‘Uniform M/MD layer’) and the datapoints. This gives a statistical comparison between the quality of each fit, using the equation

$$\chi = \sum_i [\text{NSA}(q_i) - f(q_i)]^2, \quad (2)$$

where $\text{NSA}(q_i)$ and $f(q_i)$ are the data points and fitted model at momentum transfer q_i respectively. The smaller the χ , the better the fit. Thus, from the χ values corresponding to each MSLD model in the insets of Figure 5, it is conclusive that a magnetically depleted layer is present below T_c in low magnetic fields. It is because for the Best fit $\chi = 1.093$, which is smaller than $\chi = 1.622$ for the Uniform Fit (Figure 5a and c), and after subsequently applying a high magnetic field this depleted layer is restored: the Best Fit with $\chi = 0.222$ is smaller than $\chi = 0.420$ for the MD Layer Fit (Figs. 5b and d).

FIG. 6. Magnetisation profile at 60 K near the LCMO/STO interface in low (0.03 T) and high (1 T) field. At low field the length of the proximity effect ξ_{GPE} is significantly larger than the superconducting coherence length ξ_c .

III. SUMMARY

In this work, the magnetic field dependence of the MD layer in a YBCO (30 nm)/STO (1.5 nm)/LCMO (30 nm) was investigated. The thickness of the MD layer within LCMO is identified to be $\sim 1.5 \text{ nm}$, which is approximately an order of magnitude larger than the superconducting c -axis coherence length ($\xi_c = 0.2 - 0.3 \text{ nm}$) for YBCO [29]. The total thickness of the STO interlayer and MD layer indicates that the length (ξ_{GPE}) of the ferromagnetic/superconducting proximity effect across the LCMO/STO/YBCO interfaces measurably extends over $\xi_{\text{GPE}} \sim 10$ to $15\xi_c$. When compared to the model corresponding to the dataset collected in 1 T, this depleted layer is restored (see Figure 6). The large length of this proximity effect is reminiscent of a Giant Proximity Effect (GPE) that has been observed in Superconductor/Normal metal/Superconductor (SNS) trilayer sandwiches with sizeable supercurrent flowing through barriers of up to $\sim 100\xi_c$ (20 nm) thick [30].

A similar Josephson tunnelling through a 20 nm barrier for Superconductor/Ferromagnetic Insulator/Superconductor (S-FI-S) junctions was also found by applying a voltage across the superconducting electrodes [31]. The proximity effect facilitates Josephson tunnelling. Hence, in our system of a Superconductor/Insulator/Ferromagnetic Half-Metal (S-I-FHM) with a thin insulating layer, the magnetically depleted layer could be the result of GPE with the Cooper pair tunnelling through (or transported across) the insulator due to supercurrents arising in YBCO in response to the applied magnetic field. Once a Cooper pair has reached the LCMO layer, one (or both) electron(s) from the Cooper pairs becomes bound with an initially unpaired electron in the Mn *d*-orbital of LCMO, which is the origin of the double-exchange mechanism responsible for its ferromagnetism [27, 28], thereby suppressing it.

In conclusion, the experimental results obtained by XRR, XRD, VSM and PNR are conclusive that there is simultaneous ferromagnetic and superconducting ordering within the trilayer. The magnetically depleted layer has been found within LCMO layer adjacent to STO/LCMO interface in low magnetic fields, which is attributed to the proximity effect between superconducting and magnetic materials. The MD layer in LCMO is clearly shown to be triggered by the influence of superconductivity in YBCO across the STO interlayer. The overall proximity effect extends over the length of up to $\xi_{\text{GPE}} \sim 15\xi_c$. Notably, the results presented here provide convincing evidence through comparison between normalised spin asymmetry (NSA) data at low and high magnetic fields that the magnetically depleted layer can be restored under the application of a high magnetic field, which partially suppresses the superconductivity in YBCO. This may support the hypothesis that the MD layer is dependent on the density of superconducting Cooper pairs tunnelling (or being transported) from the YBCO through the STO into the LCMO over length scales significantly larger than the coherence length ξ_c . The fact that the MD layer can be reliably restored and controlled, indicates potential for future spintronic devices.

IV. METHODS

A. Sample Growth

The YBCO(30 nm)/STO(1.5 nm)/LCMO(30 nm) trilayers were grown with pulsed laser deposition (PLD) on a Yttria-Stabilised Zirconia (YSZ) substrate as described in our previous work [15, 16]. The PLD system uses a 248 nm KrF laser with a fluence of $1\text{--}2\text{ J cm}^{-2}$. The pressure of the deposition chamber is maintained at 300 mTorr, and the samples are kept at 780°C . The frequency of the laser is set to 4 Hz during deposition.

YSZ substrates have been chosen to substitute STO, in order to eliminate effects from the structural phase transition of STO which occurs below 105 K, changing the crystal structure from cubic perovskite to tetragonal [32, 33]. Although STO is well known to facilitate the best superconducting properties of YBCO thin films [16] due to the compatibility of their crystal lattice parameters, the structural distortion at 105 K creates crystallographic facets in the surface of the STO substrate, promoting off-specular scattering, which significantly restricts the quality of specular PNR methods. Similarly, Uribe-Laverde *et al.* used $\text{La}_{0.3}\text{Sr}_{0.7}\text{Al}_{0.65}\text{Ta}_{0.35}\text{O}_3$ as a substrate to substitute STO [4].

B. Measurement Techniques

X-ray reflectometry (XRR) is utilised to determine the quality of the surfaces in the sample, the thickness of the material layers, and the roughness between material layers. This is done using the PANalytical Xpert PRO X-ray reflectometer using $\omega - 2\theta$ geometry. XRR data are fitted using Motofit [34]. X-ray diffraction (XRD) is performed on the same machine in diffraction mode to determine the quality of the epitaxial growth of the crystal structure of the materials used.

The SLD for X-rays and neutrons in a given material is a measure of the incident particle's ability to be scattered from the material. In a multilayered material, X-ray and neutron reflectometry allow to reconstruct the depth-dependence of the SLDs and over what distance the SLD transitions from one layer to the other which is a measure of the interfacial roughness [35].

PNR was performed at Australian Nuclear Science and Technology Organisation (ANSTO) in Sydney using PLATYPUS, the time-of-flight polarised neutron reflectometer [36, 37].

PNR is a non-destructive technique that allows the chemical and magnetic profiles to be determined in a sample with sub-nanometre depth resolution. The SLD profile corresponding to a given polarised neutron reflectivity pattern is comprised of a nuclear and magnetic component, $\rho_{\pm} = \rho_n + \rho_m = \rho_n \pm C \sum_i N_i \mu_i$ where ρ_n and ρ_m is the nuclear and magnetic SLD, $C = 2.645 \text{ fm } \mu_B^{-1}$, N_i is the number density of the i th atom, μ_i is the magnetic moment of the i th atom in Bohr magnetons. The magnetic SLD is added or subtracted from the nuclear SLD depending on whether the spin of the incident neutron is parallel or anti-parallel to the magnetisation of the sample [38].

A Quantum Design Physical Properties Measurement System (PPMS) is used to measure the sample's magnetic and transport current properties using the Vibrating Sample Magnetometer (VSM) and resistivity measurement options, respectively. Magnetisation has been measured with the magnetic field applied in-plane to the trilayer, which is parallel to the surface of the sample. We should note that a certain degree of misalignment (of ~ 5 degrees) between the surface and the applied magnetic field should be expected for all the type of measurements.

Due to the irreversible magnetic nature of the YBCO type II superconductor, the magnetic history of measured samples has been reproduced for all measurements. During PNR (and PPMS) measurements, the sample is field-cooled to the desired temperature in the magnetic field of 0.03 T applied in-plane of the films in order to fully saturate magnetisation of LCMO before cooling it through the superconducting transition temperature T_c . Then, the magnetic field is tuned (or swept) to the desired strength.

The resistivity measurements have been carried out employing the standard 4-probe technique with Au/Pd contact pads of about 100 nm thick deposited as a series of four stripes on the top of the LCMO layer. The T_c of the 30 nm thick YBCO layer was determined as the onset of the superconducting transition measured at 100 μA in zero magnetic field.

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