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Antiphase Magnetic Proximity Effect in Perovskite Superconductor / Ferromagnet Multilayers

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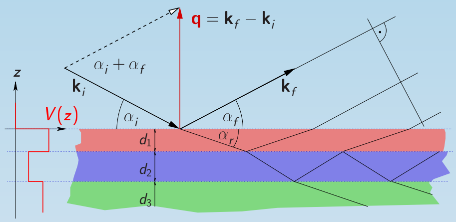
Neutron Reflectometry

Reflectometry in general allows to probe the depth profile of a potential V of some kind, averaged laterally. Basis are the changes of the index of refraction $n_i = \sqrt{1 - V_i/E_{\text{vacuum}}} \approx 1 - V_i/2E_{\text{vacuum}}$.

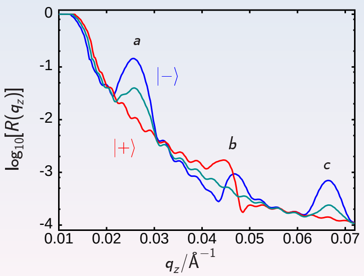
While optical light measures the optical density and X-rays the mean electron density, neutrons are sensitive to nuclear potentials (isotope selective) and to in-plane magnetic induction $\mathbf{B}_\parallel$ with $V^{\text{mag}}(z) = \mu_n \mathbf{B}_\parallel(z)$. The sign of the neutron magnetic moment μ_n is spin dependent. Thus spin polarised measurements allow for the separation of the nuclear profile V^{nuc} and V^{mag}



Sketch of the neutron wave propagation in a reflectometry experiment. $\mathbf{k}_{i,f}$ are wavevectors of the initial and final waves.

- total reflection for $\alpha_i < \alpha^c \propto \sqrt{V/E}$
- $\alpha_i > \alpha^c$: partial reflection at each interface: $r \propto \Delta V(z)$
  - ⇒ formation of descending and ascending wave fields
- interference of all partial beams leaving the surface $\mathbf{k}_f$
  - – phases encode the layer thicknesses d_i
  - – amplitudes encode the potential steps $\Delta V(z)$
- measurement of the reflectivity R as a function of q by varying α_i and α_f
- neglecting refraction ($\alpha_r = \alpha_i$) one gets $R(q_z) \propto q_z^4 \left|\mathcal{F}[V(z)]_{q_z}\right|^2$
  - ⇒ loss of the absolute phases
  - ⇒ analysis of $R(q)$ via modelling and simulations

Simulated $R(q_z)$ for a periodic bilayer structure without a magnetic contribution and for $|+\rangle$ and $|-\rangle$ neutrons, assuming every second layer to be magnetised.



J. Stahn, *et al.*: PRB **71**, 140509R (2005)

Motivation

The work on the perovskite oxide FM/SC superlattices is motivated by the appealing properties of the cuprate high T_c superconductors (HTSC) whose high SC critical temperatures make them potentially useful for technological applications. Further, since HTSC are believed to be susceptible to a variety of competing instabilities, there is a high potential for novel SC/FM quantum states in multilayer structures. This research is in its early stage, and relatively little is known about the nature of magnetism at the interface, the spatial distribution of the magnetisation throughout the layers, and the interplay of FM and SC order parameters in general.

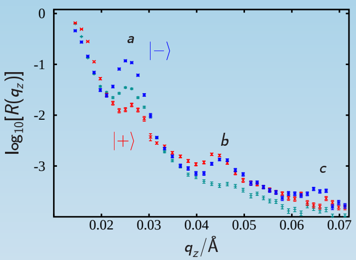
specular reflectometry

probing $V(z)$ $\alpha_f = \alpha_i$ ⇒ $q = q_z$

By an appropriate choice of the thickness ratio, extinction of some maxima in $R^{\text{nuc}}(q_z)$ can be reached. The corresponding q_z range (b) then is dominated by V^{mag}.

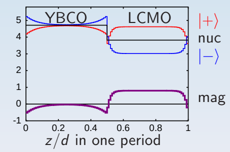
$R(q_z)$ measured at RT and at 15 K with $|+\rangle$ and $|-\rangle$ neutrons.

- change of 1st (a) and 3rd (c) Bragg peak intensities
  ⇒ increased/decreased contrast for $|-\rangle/|+\rangle$ neutrons
- appearance of 2nd Bragg peak (b)
  ⇒ B has an other z-dependence than V^{nuc}

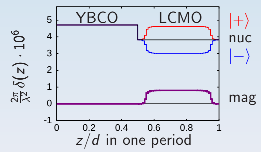


Comparison with simulated spectra leads to two possible magnetisation profiles:

(1) A FM surface layer within the SC, antiparallel to the one in the FM layer.

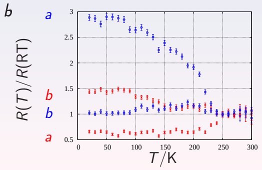


(2) A significant magnetically *dead* region in the FM layer.



T dependence of $R(q_z)$ at positions a and b

- $T < 240$ K onset of ferromagnetism, $V^{\text{mag}} \neq 0$
- $T < 140$ K splitting of 2nd Bragg peak intensities
- $T < 80$ K onset of superconductivity



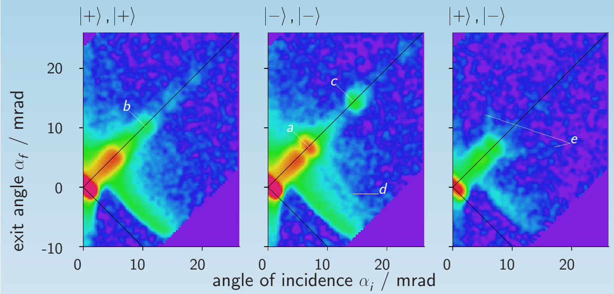
Conclusion

We obtained detailed, microscopic information about the in-plain magnetisation profile. Characteristic differences between the nuclear and the magnetic scattering profiles allowed us to identify two possible scenarios of (1) an antiphase magnetic proximity coupling where FM moment is induced in YBCO that is oriented antiparallel to the one in LCMO (10 Å), and (2) a ferrimagnetically dead layer (paramagnetic or anti ferromagnetic) of about 15 Å within the LCMO region.
Also, we observed an anomalous enhancement of the off-specular reflection in the SC state which suggests a strong mutual interaction between the SC and the FM order parameters.

off-specular reflectometry

probing lateral inhomogeneities of V $\alpha_f \neq \alpha_i$ ⇒ $q = q_z + q_x$

$R(\alpha_i, \alpha_f)$ for polarised neutrons with spin analysis taken at $T = 130$ K (out of a set with 10 K $< T <$ 300 K). The measurements have been performed on HADAS@FZ-Jülich with the help of E. Kentzinger and U. Rücker.



- No off-specular sheets (d) at RT or 200 K
  ⇒ no structural roughness detectable
- Increase of the Bragg sheet at 1st Bragg peak (d) below 160 K
  ⇒ magnetic roughness, correlated vertically
- Appearance of Yoneda-like sheets in the spin-flip channel (e)
  ⇒ formation of a lateral magnetic pattern, magnetic moments not parallel to the neutron spins

Interpretation: magnetic domains of similar size ($\approx 20\mu$m) are formed in the LCMO layers at $T \approx 140$ K. These are correlated through YBCO over the whole stack. The domains shrink below T_c down to 5μm at 10 K.

Samples

The samples consist of up to 16 bilayers of $YBa_2Cu_3O_7$ and $La_{2/3}Ca_{1/3}MnO_3$ with equal thicknesses. The bilayer period varies from 100 to 25-Å. They have been deposited by PLD on a $SrTiO_3$ substrate.