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Antiphase Magnetic Proximity Effect in Perovskite Superconductor / Ferromagnet Multilayers

25. 10. 2005

International Workshop on Reflectometry, Off-specular scattering and GISANS
ROG2005 24.–26. 10. 2005, PSI

cooperators:

samples:
G. Cristiani
HU. Habermeier

measurements:
T. Gutberlet
J. Hoppler
C. Niedermayer
E. Kenzinger
U. Rücker
M. Wolff
J. Chakhalian
S. Pekarek

analysis:
J. Hoppler
S. Pekarek

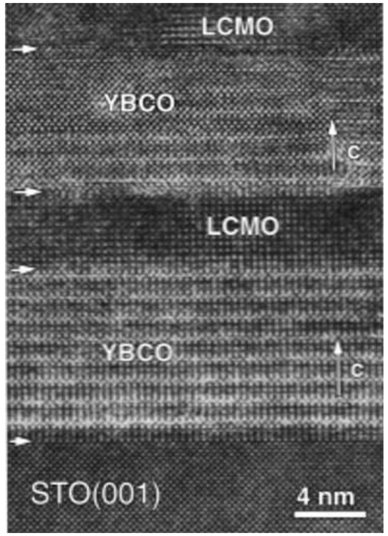
interpretation:
C. Bernhard
C. Niedermayer
E. Kenzinger
B. Keimer
J. Chakhalian

ETHZ
PSI
MPI-FKF
FZJ
RUB

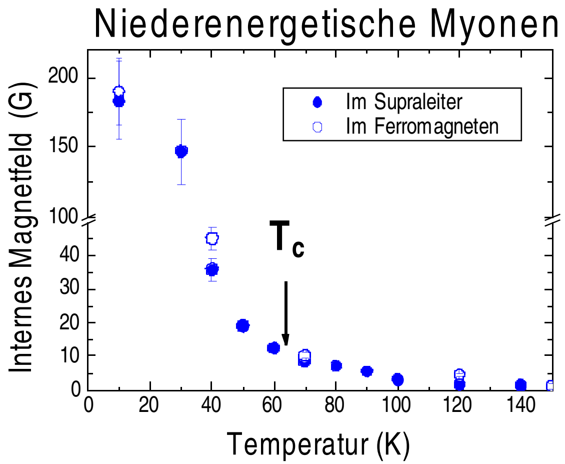
motivation / history:

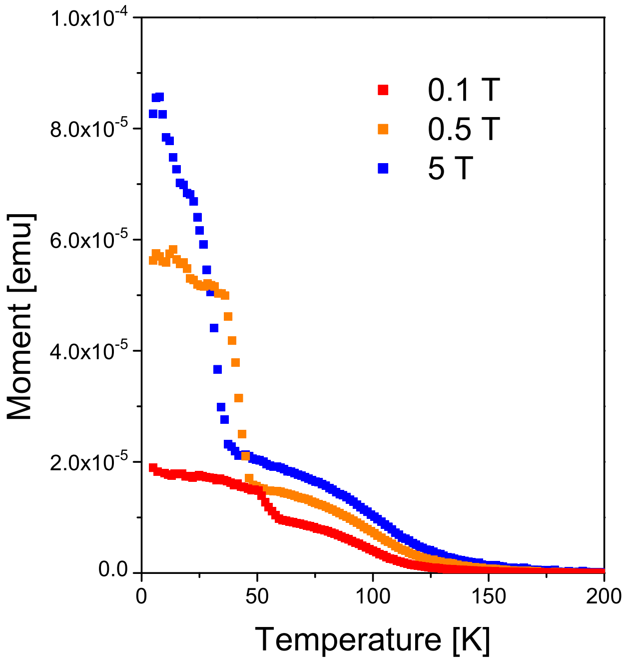
spring 2003:

C. Niedermayer presents nice μSR and magnetisation measurements at PSI



no explanation at that time.





Coexistence of FM and SC in RuSrCuGdO

$\longrightarrow$ competitive order parameters

artificial multilayers to investigate

– interaction of FM and SC at the interfaces and

– coupling through the layer

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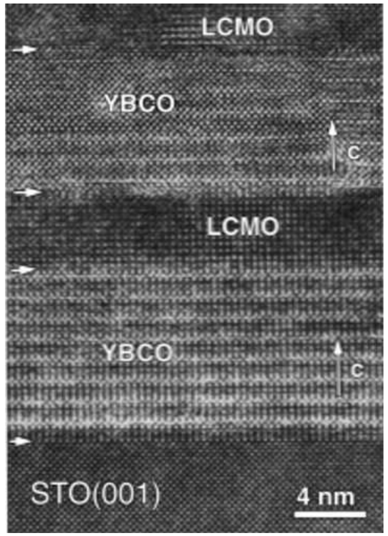

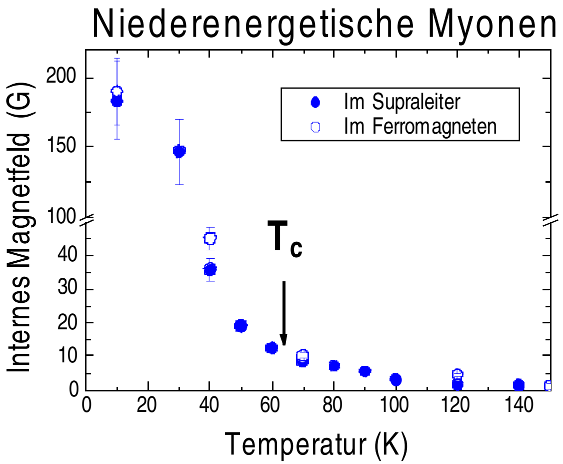

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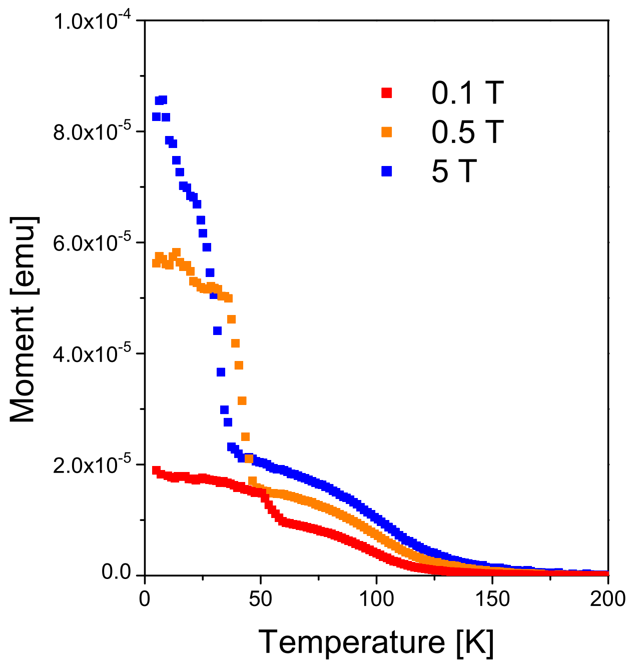


method of choice
(for a neutron scatterer):

neutrons!

in particular *polarised n-reflectometry*

tailored samples for reflectometry:

size: $10 \times 10\,\mathrm{mm}^2$ (instead of $5 \times 5\,\mathrm{mm}^2$)

period: 200 Å to 500 Å, 5 to 16 periods

thickness rations: 1 : 1 and 1 : 2 to cause extinction

non-rough interfaces (otherwise used to tune T_c)

materials:	FM	YBCO	$YBa_2Cu_3O_7$
	HTSC	LCMO	$La_{2/3}Ca_{1/3}MnO_3$
	substrate	STO	$SrTiO_3$

instruments:

Morpheus, SINQ

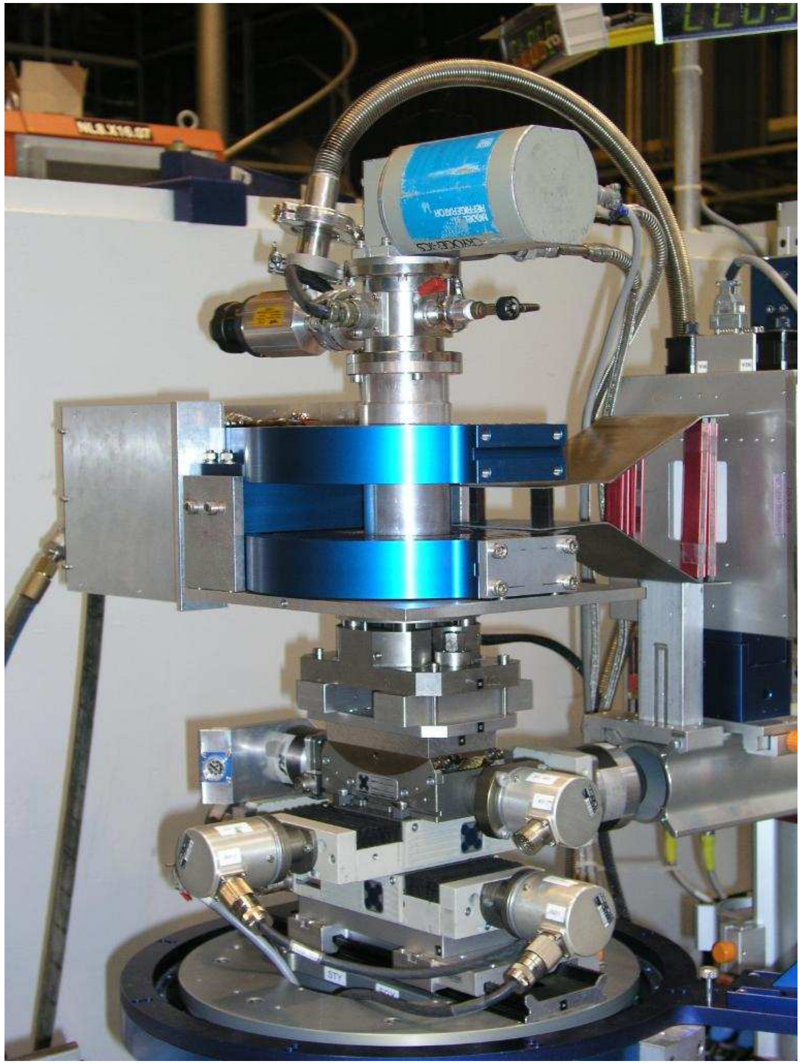
AMOR, SINQ

ADAM, ILL

HADAS, FZ Jülich

sample environment (at SINQ):

sample holder
with absorber



closed cycle refrigerator

$8\,\mathrm{K} < T < 300\,\mathrm{K}$

Helmholtz coils

$H \leq 1000\,\mathrm{Oe}$

vol: $40 \times 40 \times 40\,\mathrm{mm}^3$

translation stages for alignment

ω-rotation stage

specular PNR & ω-scans

$\mathbf{H} = 100\,\mathrm{Oe}$

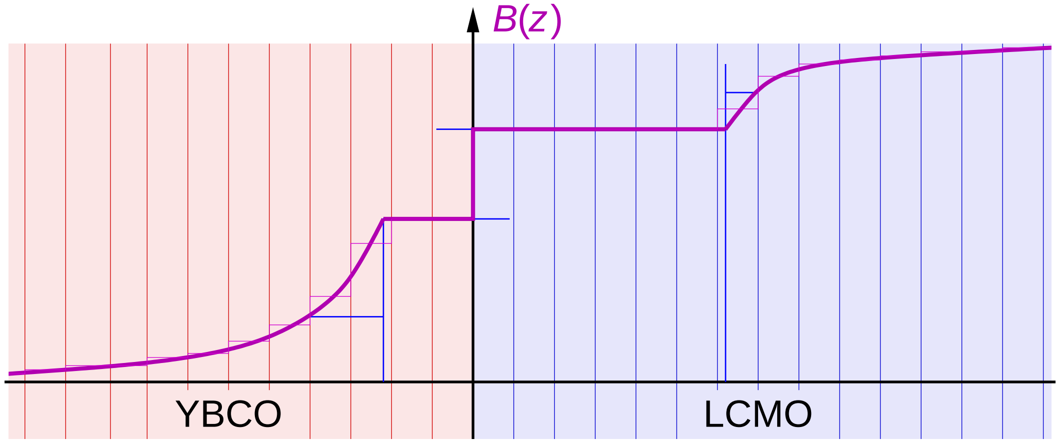
field cooled

$T = 10\ldots300\,\mathrm{K}$

simulations performed with EDXR by Petr Mikulík (no fitting)

bilayer structure has been broken down to some 100 sublayers to pay respect to $\mathbf{B}(z)$.

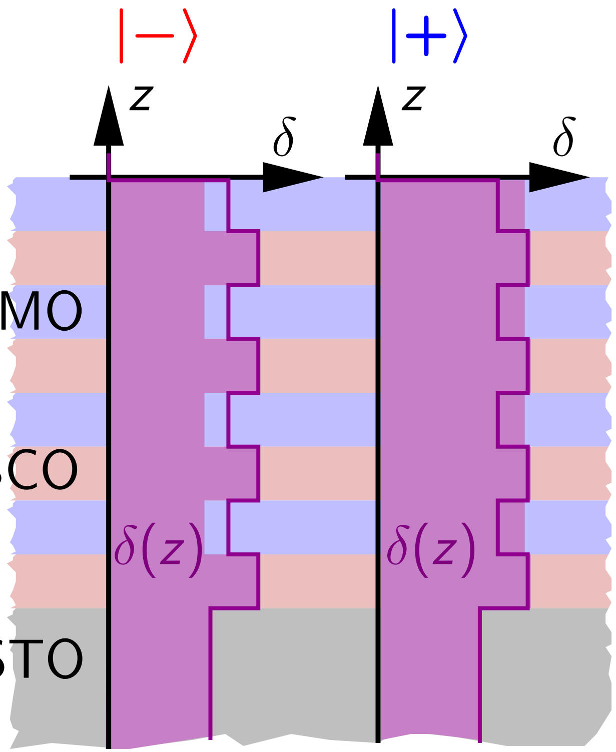
analytic expressions for $B(z)$:

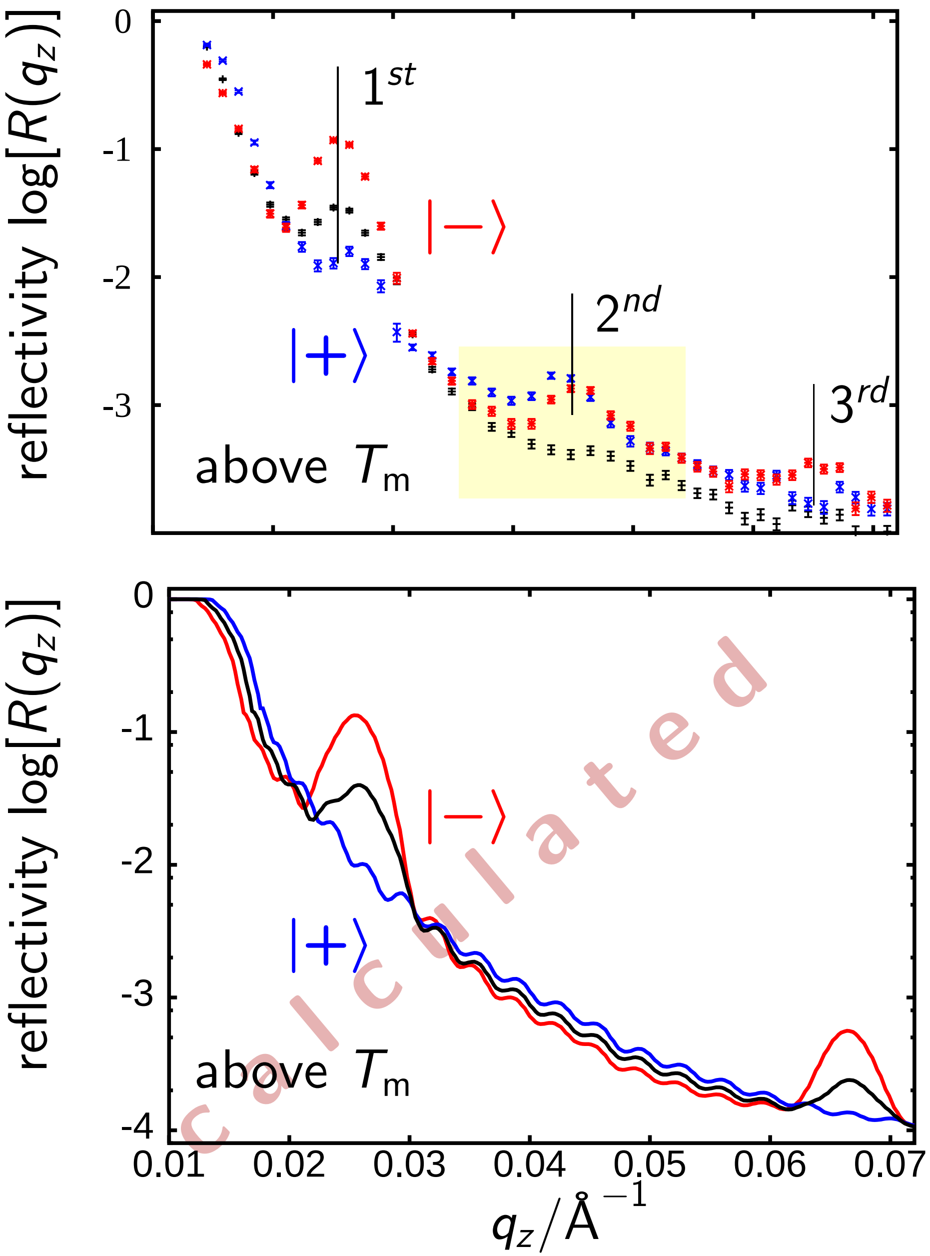


decrease of layer thickness towards the borders taken into account

reflectometry: specular, polarised

sample:
[YBCO(150 Å)/LCMO(140 Å)]$_5$





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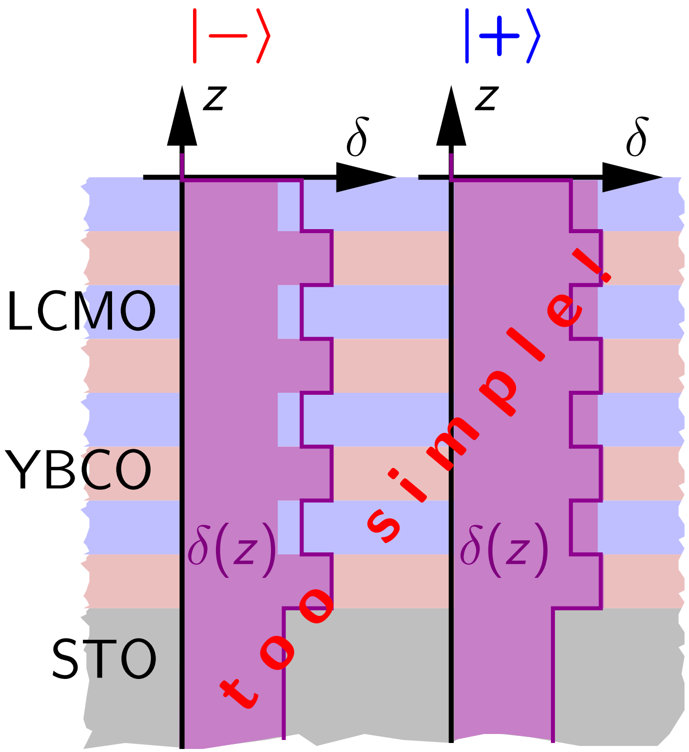
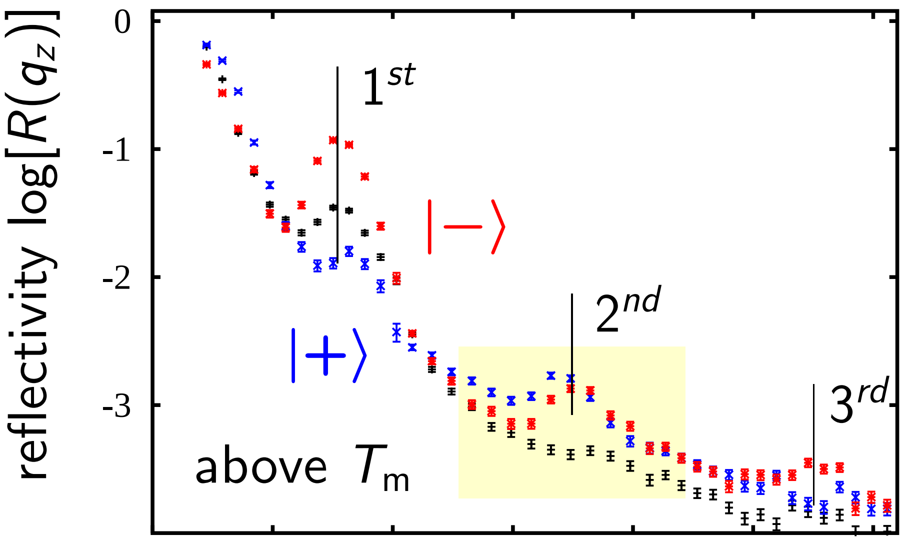
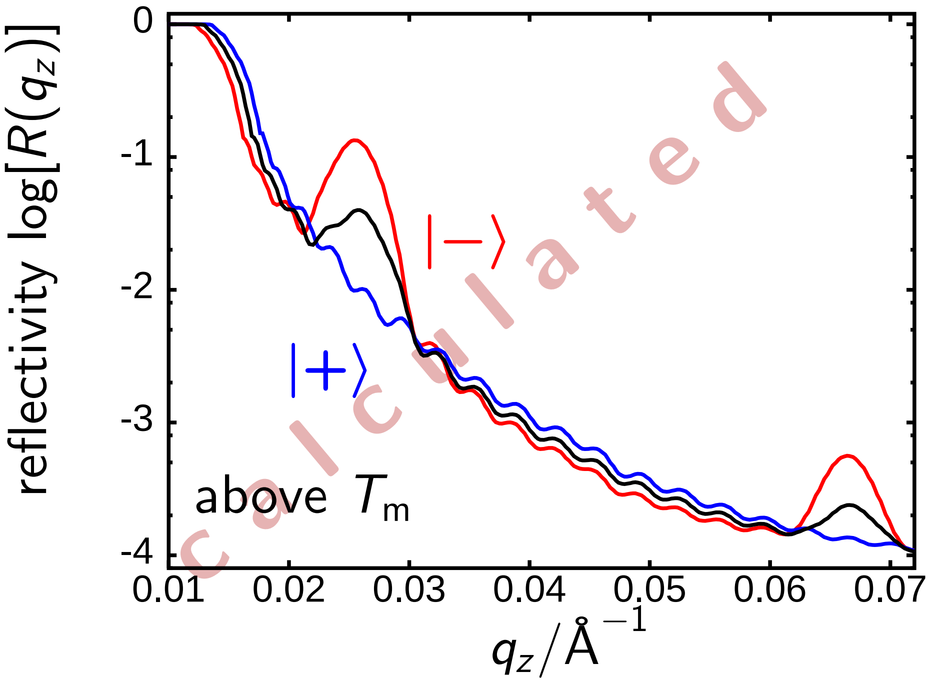






$$\delta_{mag}(z) \neq \delta_{nuc}(z) \times \begin{cases} 0 & \text{for YBCO} \\ const & \text{for LCMO} \end{cases}$$

modelling: magnetic profile at the interfaces

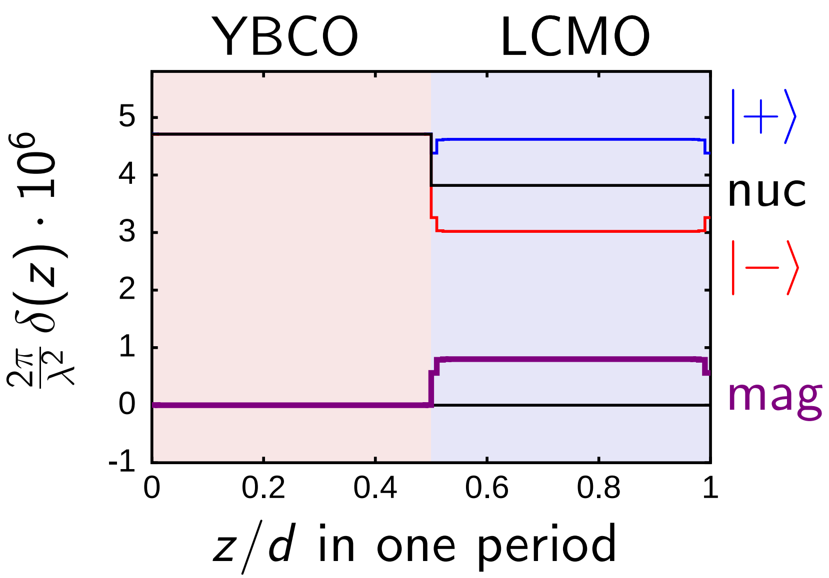
sharp contrast at the interface

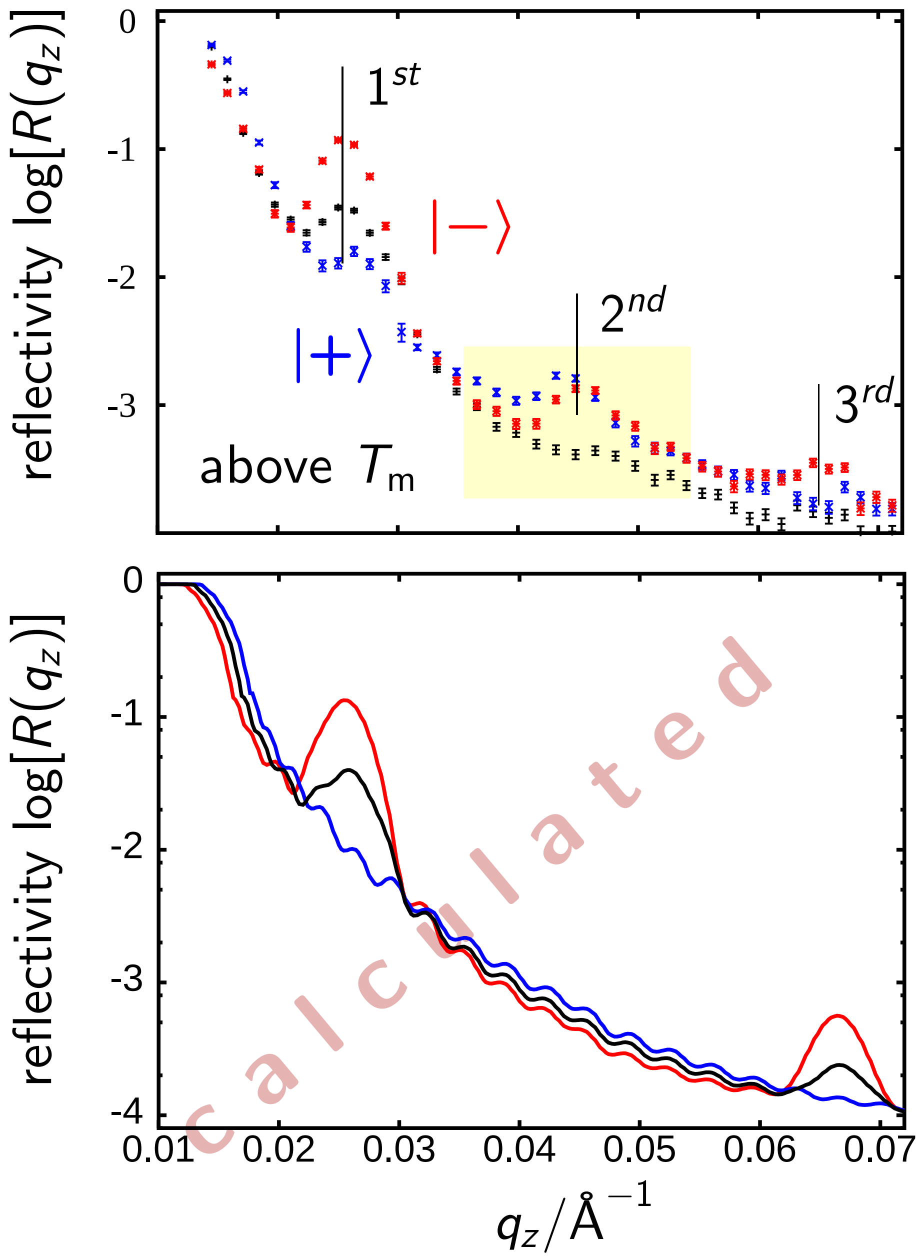
exponential decay into YBCO

AFM exponential decay into YBCO

penetration into YBCO

magnetically dead layer in LCMO





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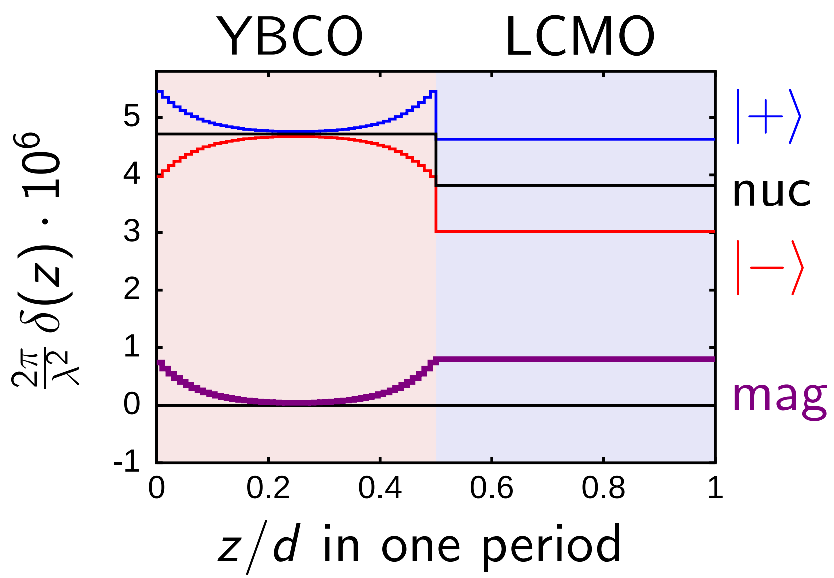

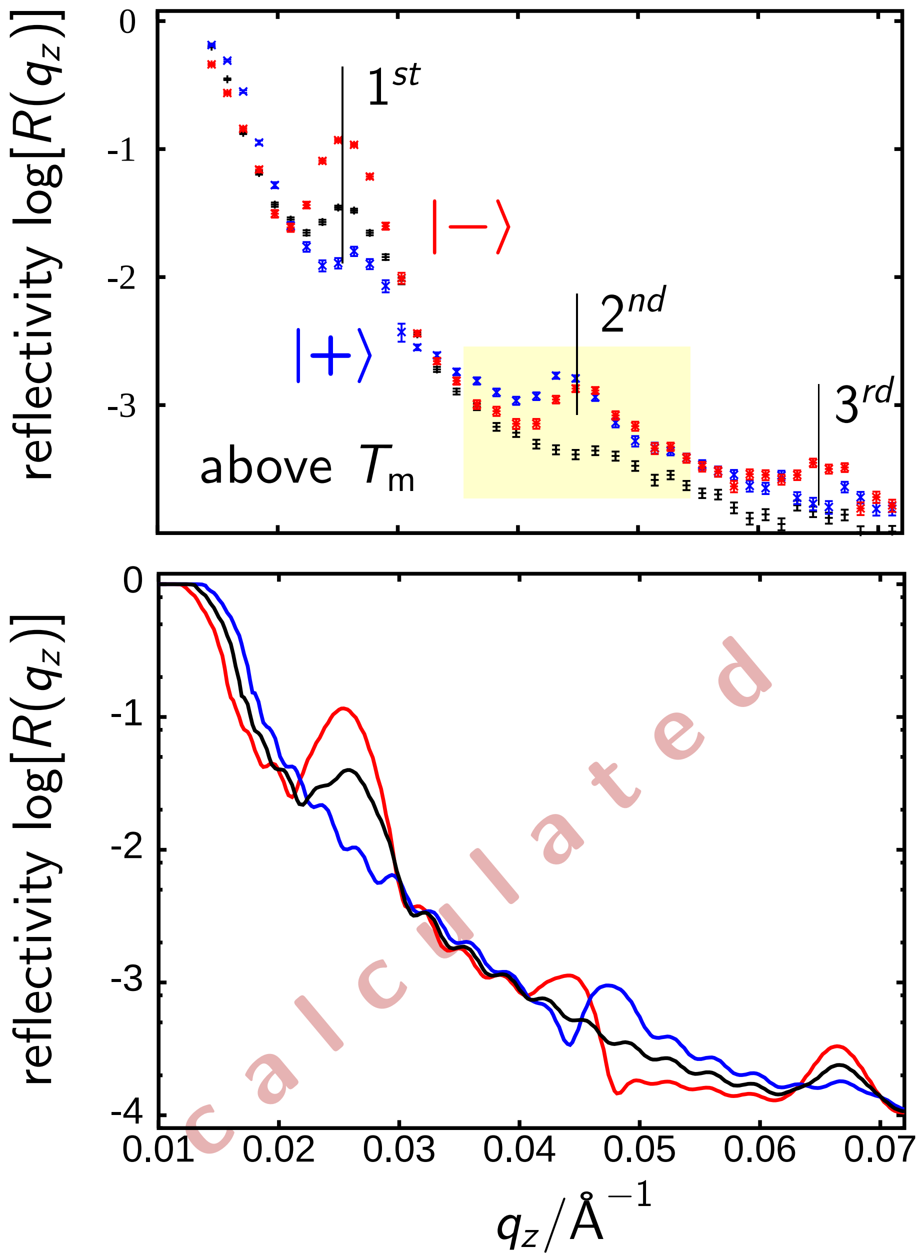

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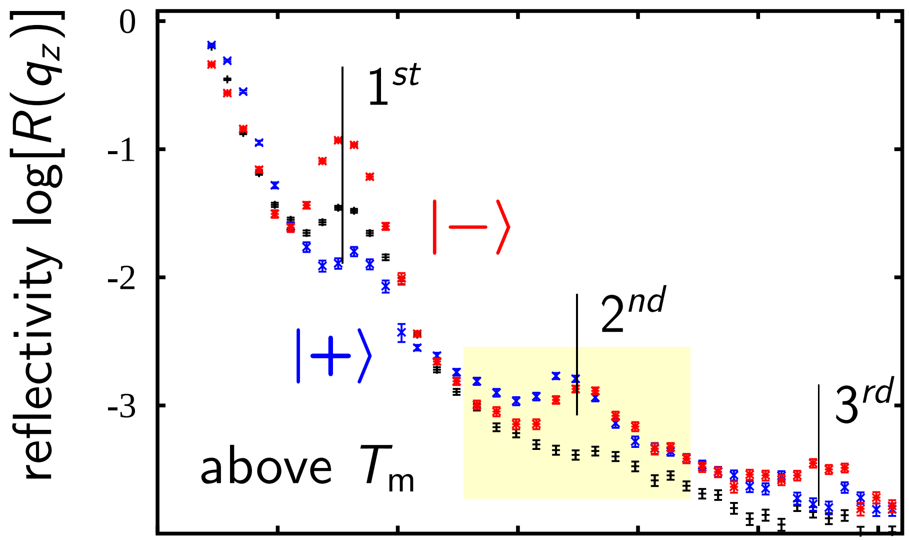

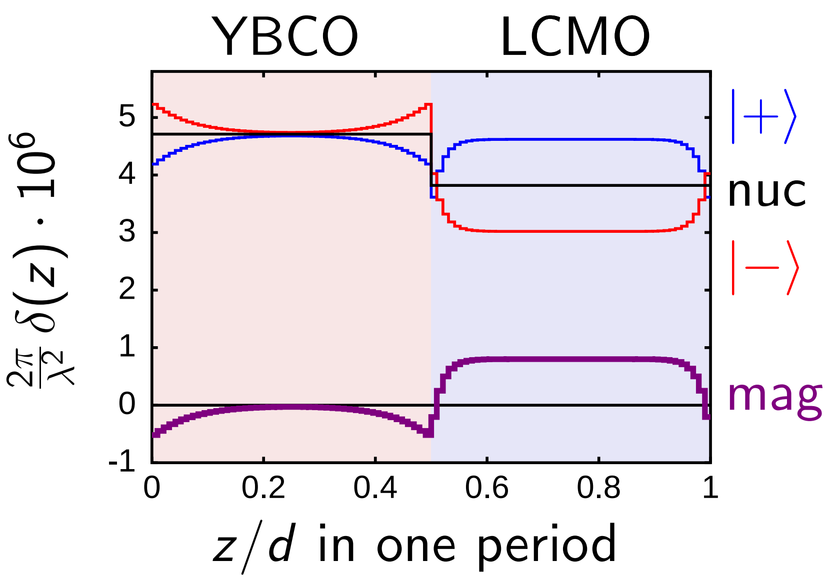

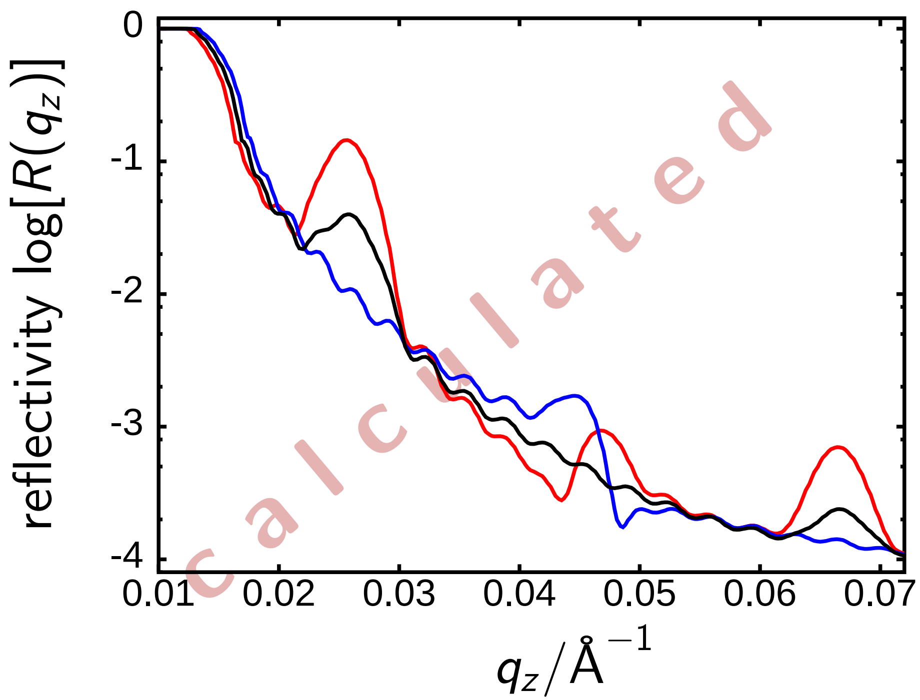

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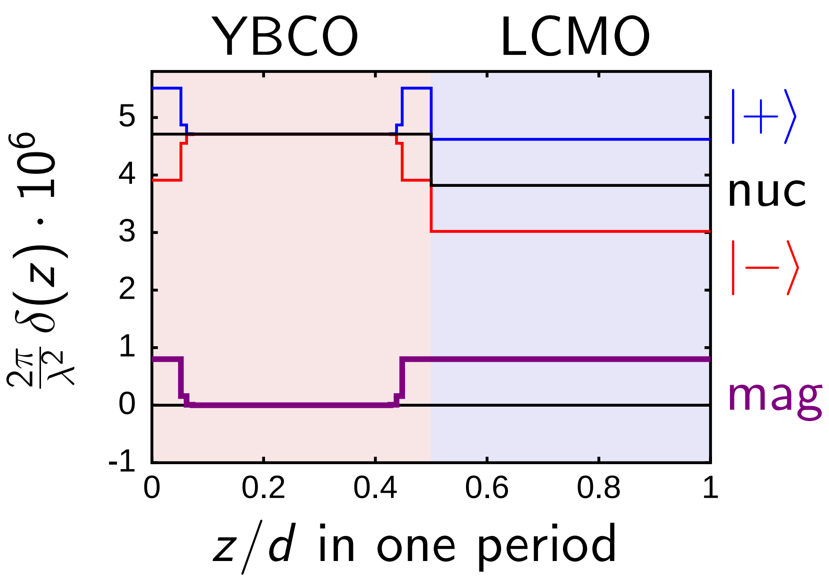

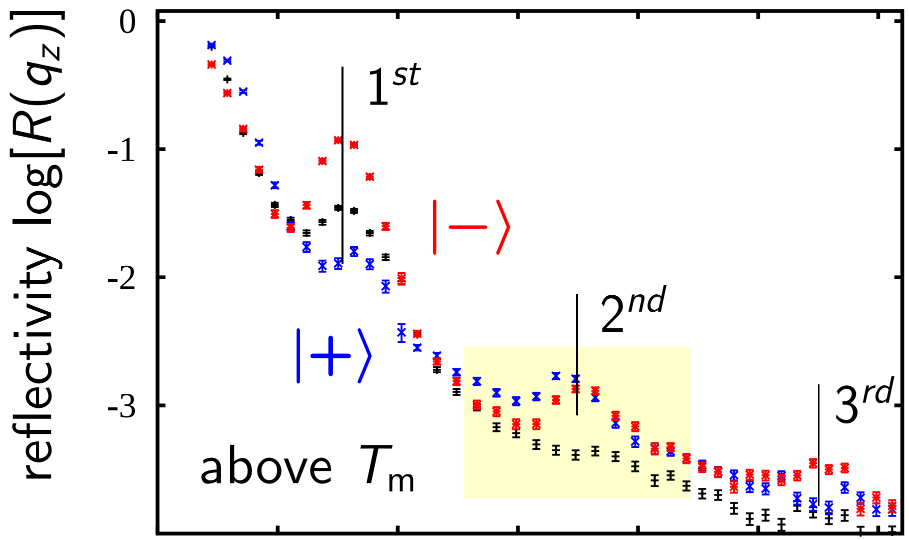

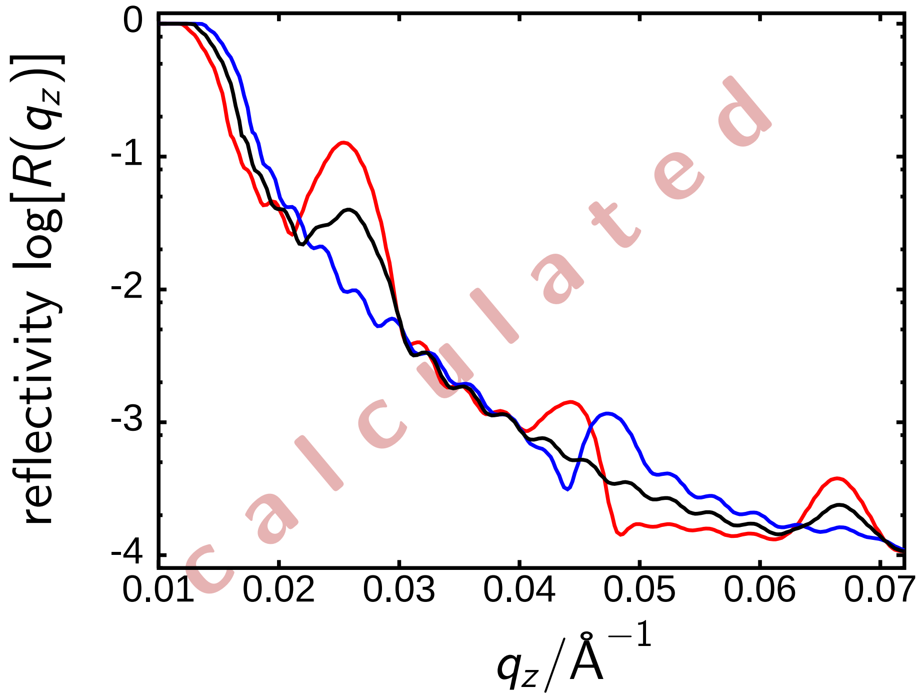

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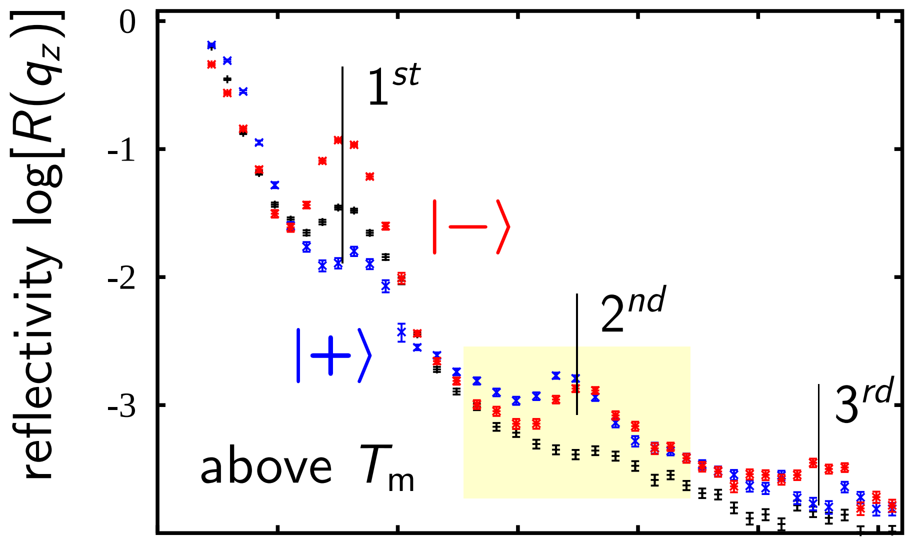
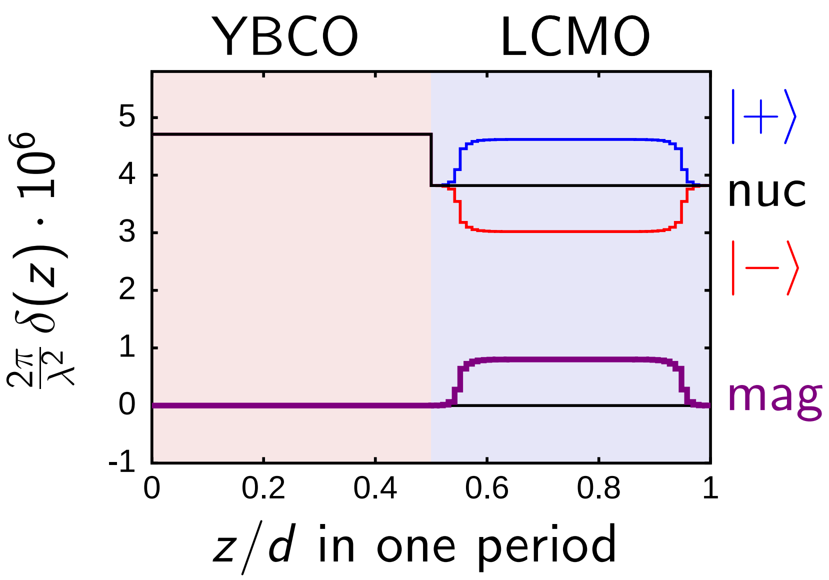
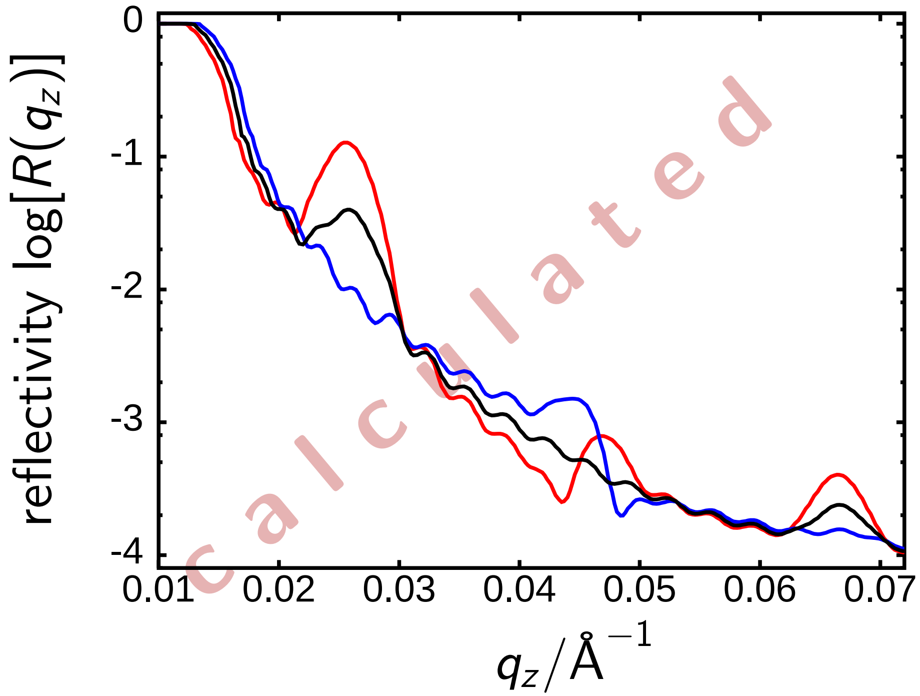




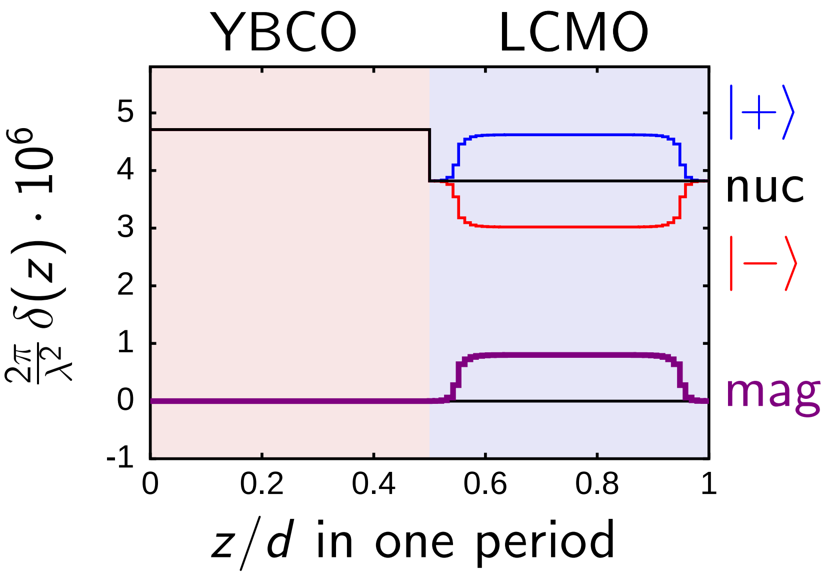


résumé:

PNR at RT and below T_m and T_c exclude *all* models besides

AFM-region within LCMO

charge-injection from YBCO leads to a doping of LCMO and thus to an AFM ground state

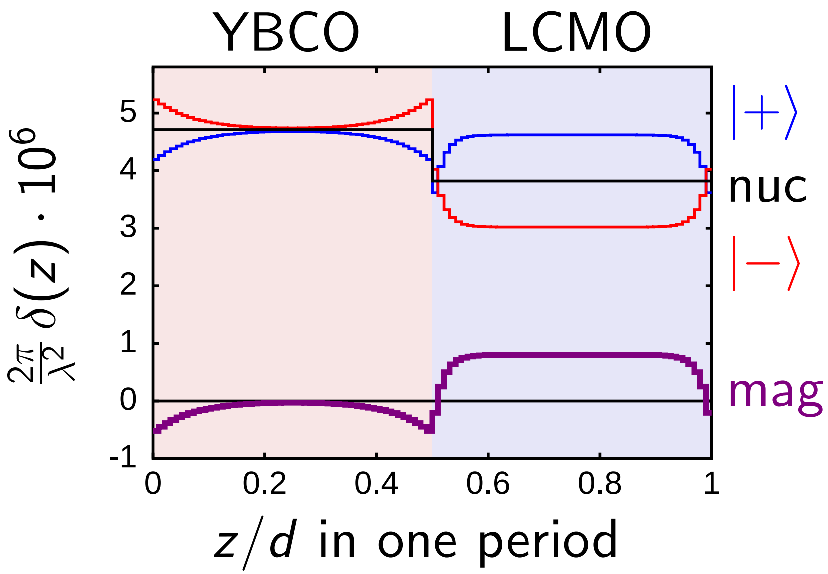


antiphase magnetic proximity effect

FA coupling of Mn and Cu moments through oxygen

or

Cooper pairs penetrate into LCMO and are *polarised* ⇒ antiparallel magnetisation in YBCO



magnetometry:

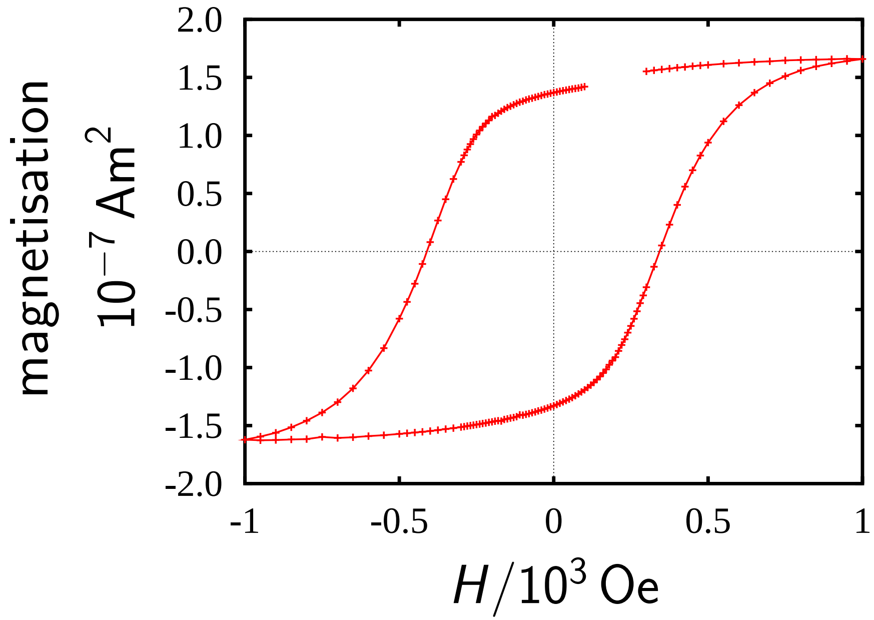
SQUID measurements by F. Treubel, Konstanz

$T = 5\,\mathrm{K}$

cooled in $H = 100\,\mathrm{Oe}$

coercitive field $H_{co} \approx \pm 400\,\mathrm{Oe}$

exchange bias field $H_{eb} \approx -60\,\mathrm{Oe}$



$\Downarrow$

presence of an AFM coupling
at the FM-interface

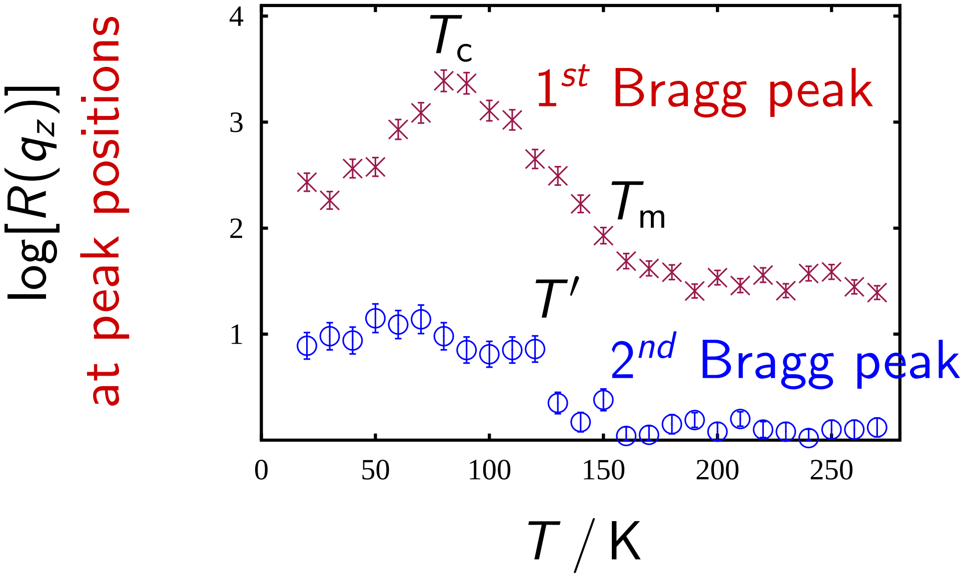
but:

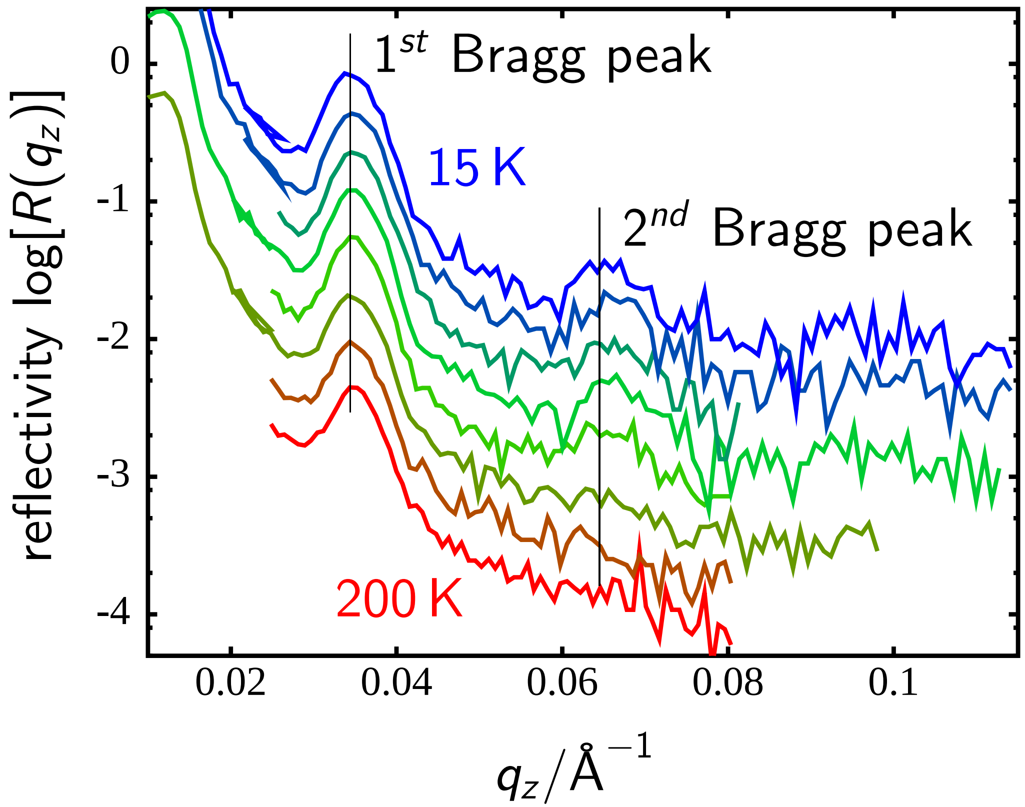
– *magnetically dead layer* might be an AFM

– **B** in YBCO might be an AFM with net magnetic moment

T dependence of $R(q_z)$

sample: $[\mathrm{YBCO}(100\,\text{Å})/\mathrm{LCMO}(100\,\text{Å})]_7$





$T_\mathrm{m} \Rightarrow$ intensity increase of 1$^\mathrm{st}$ peak

! onset of FM: changed contrast

$T' \Rightarrow$ formation of 2$^\mathrm{nd}$ peaks

! $B(z)$ is no longer congruent with $\delta(z)$

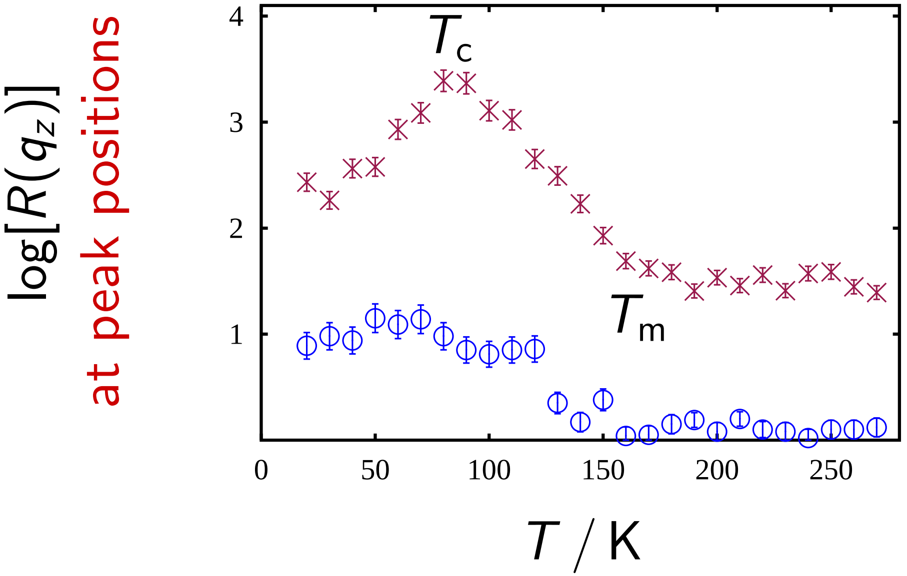
$T_\mathrm{c} \Rightarrow$ decrease of 1$^\mathrm{st}$ peak

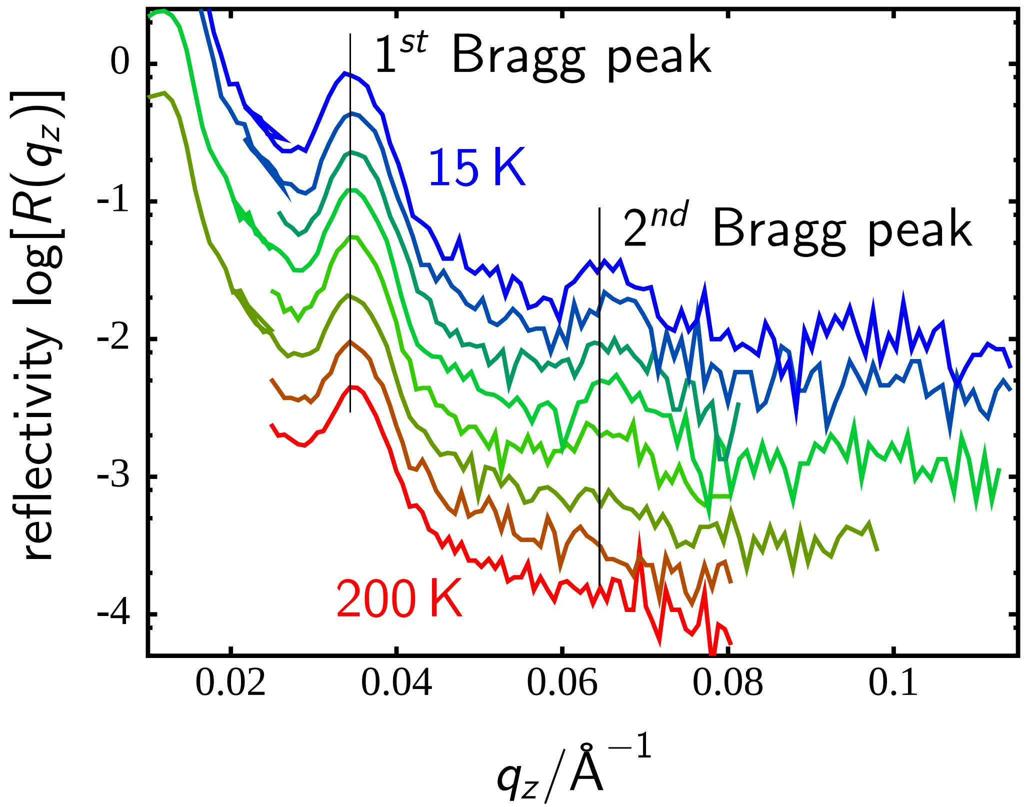
? formation of lateral magnetic inhomogeneities

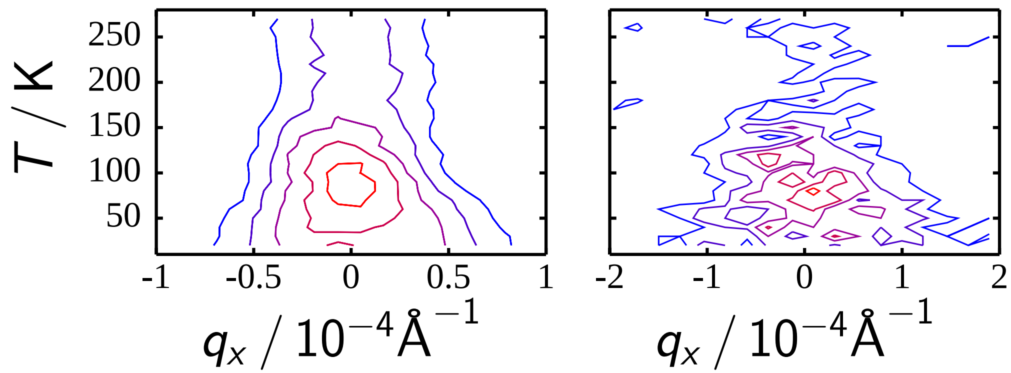
? reduction of B

off-specular measurements: periodic ml, non-polarised, various T

sample: [YBCO(100 Å)/LCMO(100 Å)]$_7$







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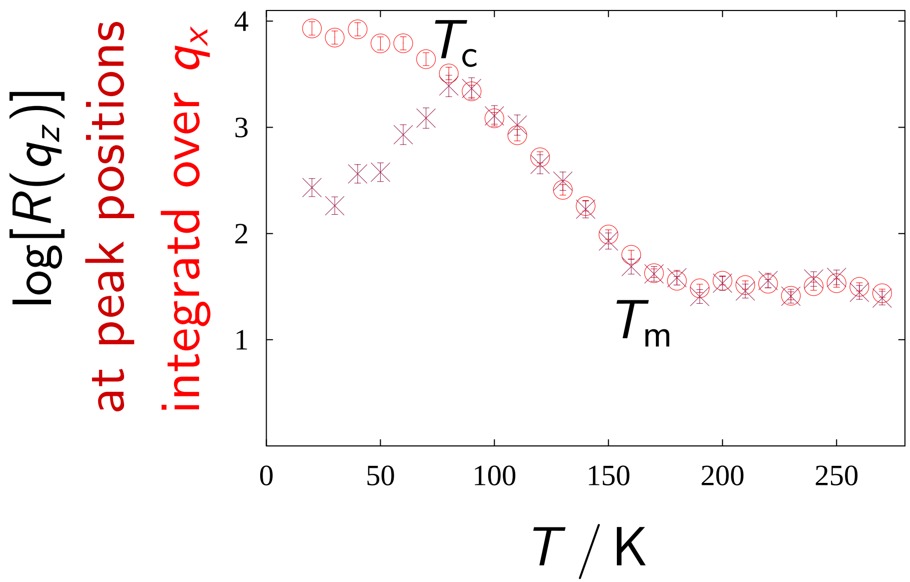
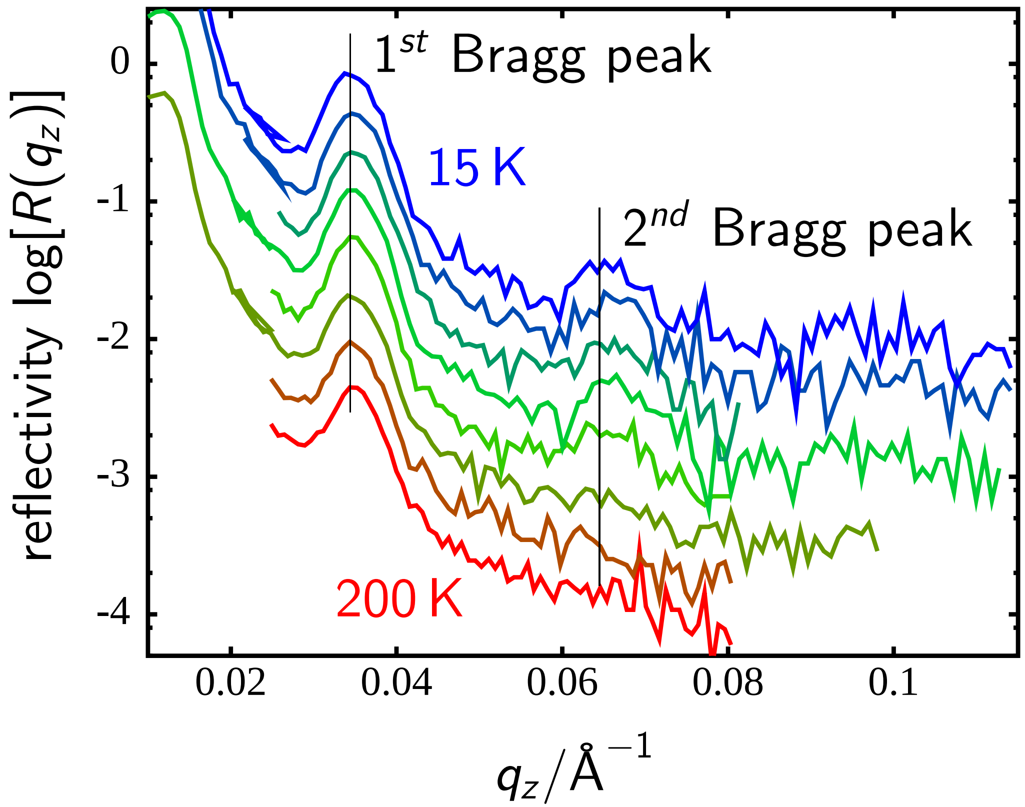
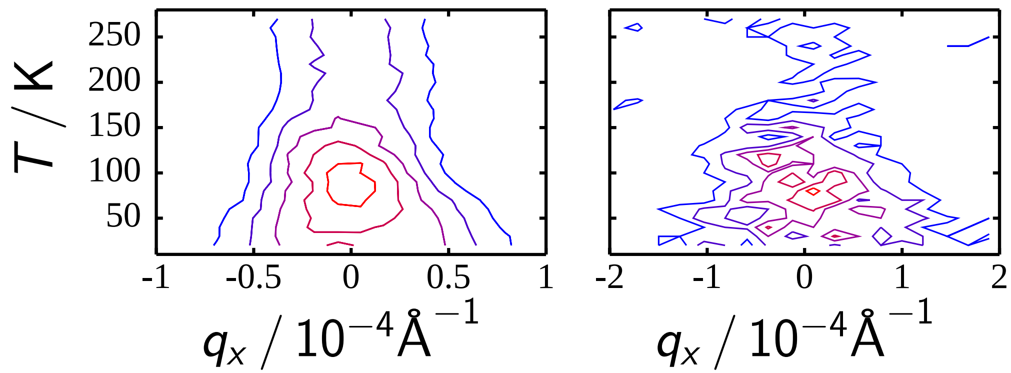




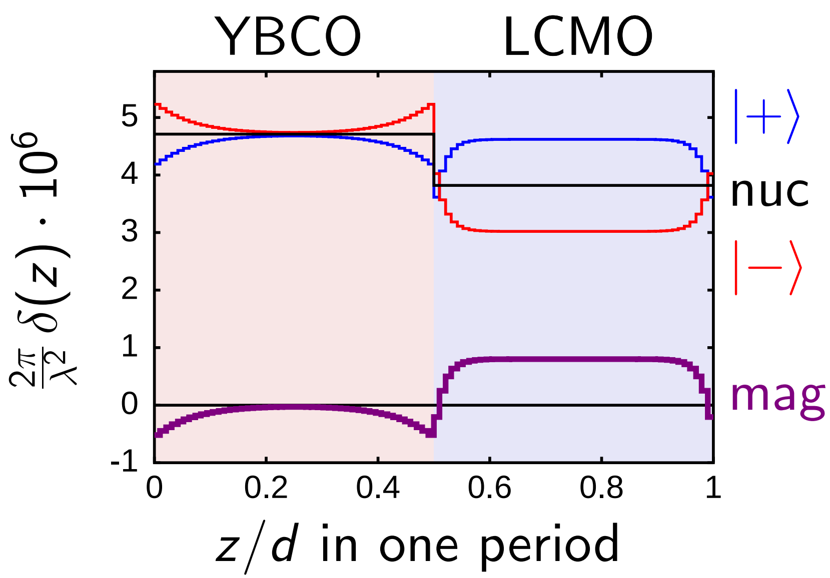


magnetic domains are formed at T_c and they shrink from $10\,\mu$m to $5\,\mu$m when cooling

interpretation of off-specular scans:

⇒ SC directly influences the lateral correlation of $\mathbf{B}_{||}$
⇒ model of direct contact of SC and FM is favoured!
⇒ *antiphase magnetic proximity effect*

A magnetic moment on Cu antiparallel to Mn has been measured by XMCD (J. Chakhalian, B. Keimer)



F. S. BERGERET, A. F. VOLKOV AND K. B. EFETOV

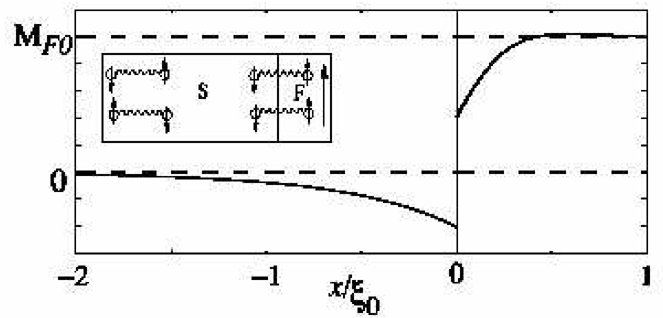


FIG. 1. Spatial dependence of the magnetization in the whole system. Here $\gamma_F/\gamma_S=0.5$, $\bar{\gamma}_F=\gamma_F/\xi_0=0.1$ ($\xi_0=\sqrt{D_S/2T_c}$), $J/T_c=15$, and $d_F/\xi_0=1$. Inset: Schematic view of the inverse proximity effect in a S/F system (for discussion see text).

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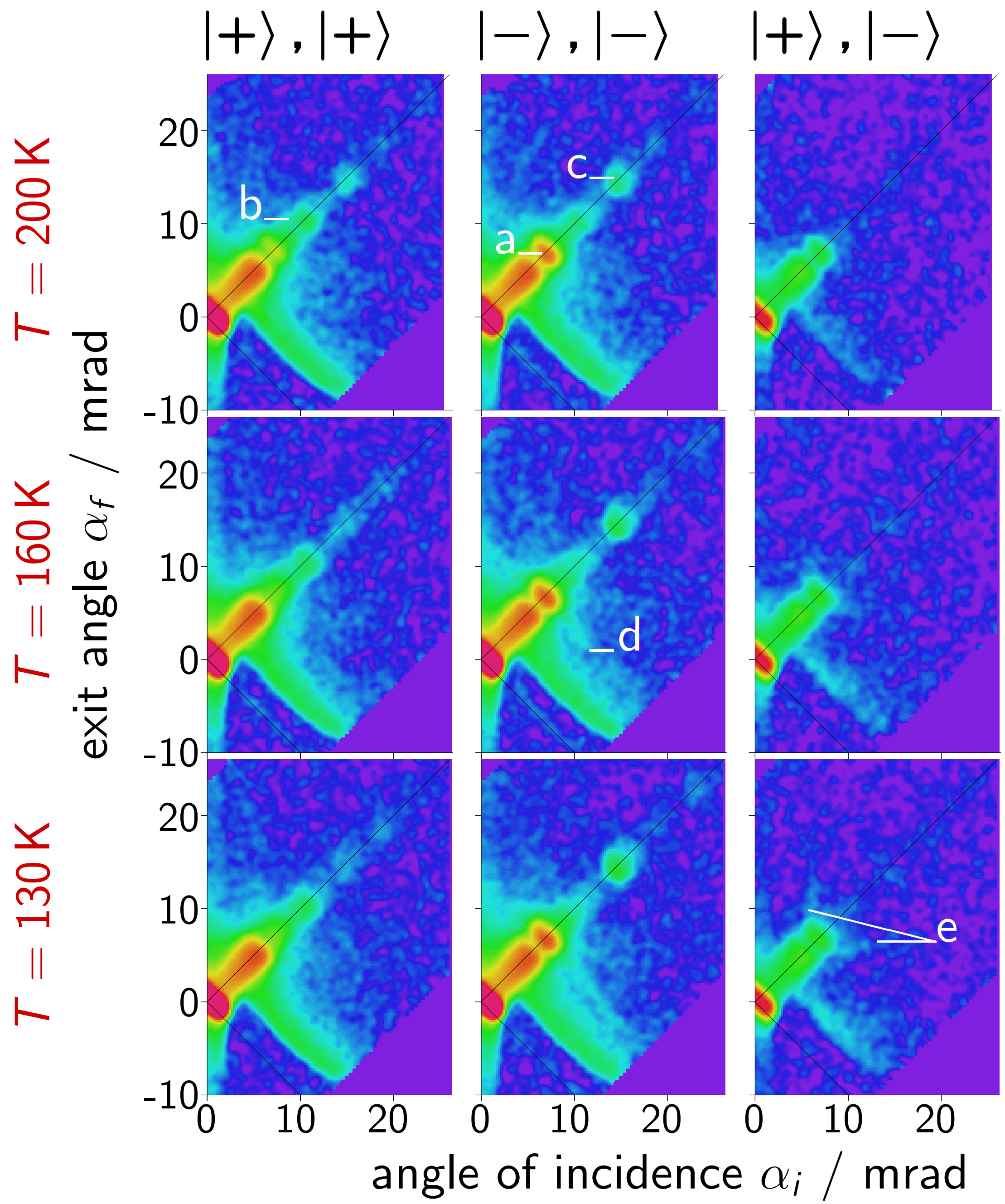
real off-specular measurements



No off-specular sheets 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 sheets in the spin-flip channel (e)
⇒ magnetic moments not parallel to the neutron spins

Interpretation (of all measurements):
Magnetic domains of similar size ($\approx$ 5 to 10μm) are formed in the LCMO layers. These are correlated through YBCO over the whole stack.

conclusion:

- all LCMO layers are magnetised parallel

- interface effect of $\mathbf{B}(z)$ of the order of 10 Å is measured at $T_c < T' \approx 140\,\mathrm{K} < T_m$

– *magnetic dead layer* or *antiphase proximity effect*

- simultaneous appearance of Bragg-sheets

– vertical correlation of magnetic domains

- increase of off-specular scattering below T_c

– shrinking of magnetic domains / characteristic lengthscale

- correlation of domain size with T_c and XMCD measurements favours the *antiphase proximity effect*