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Report:

The study of the superconducting gap (SG) and of the pseudogap (PG) in cuprate superconductors has been dominated by ARPES [1][2]. Although ARPES is very powerful, the limited range of samples that can be measured represents a motivation to find an alternative technique to study deeply these effects.
The sensitivity of RIXS to the SG opening has been recently demonstrated in ref. [3]. However, in order to extract the critical temperature Tc and to provide any conclusion on the possibility to characterize also the PG by means of RIXS, more careful experiments are required. We are looking to non vertical low energy electron-hole excitations in an energy region dominated by features of a different nature (phonons, charge fluctuations [4]). An accurate choice of the momentum transfer spot where to observe the maximum signal is necessary. Therefore, we complemented the experimental activity with calculations of the Lindhard susceptibility.
We measured temperature dependent RIXS spectra at Cu L_3 edge in a slightly underdoped ($p \approx 0.15$) and in a undoped $YBa_2Cu_3O_{7-\delta}$ (YBCO) samples. The undoped sample has not charge related features in the low energy scale, thus we measured it to monitor other T dependent components of the spectrum.
Over the whole experiment we kept fixed the scattering angle at 149.5° to reach the highest momentum transfer to the sample and the incoming photon polarization to be vertical. We worked at grazing incidence to maximize the intensity. Since the data analysis requires well counted spectra, we decided to stay in the combined low resolution configuration, reaching ≈40 meV which is sufficient for our purposes.
The experiment was divided in three steps. We started with the measurement in different **q** points of the underdoped sample at two temperatures (30 K and 250 K), below and above the putative Tc and T* estimated by transport measurements to be respectively ≈84 K and ≈200 K. The goal was to confirm the predictions from our calculations on the promising **q** points where to observe the maximum effect. We selected the optimal **q** to be (-0.20, 0.20) r.l.u..

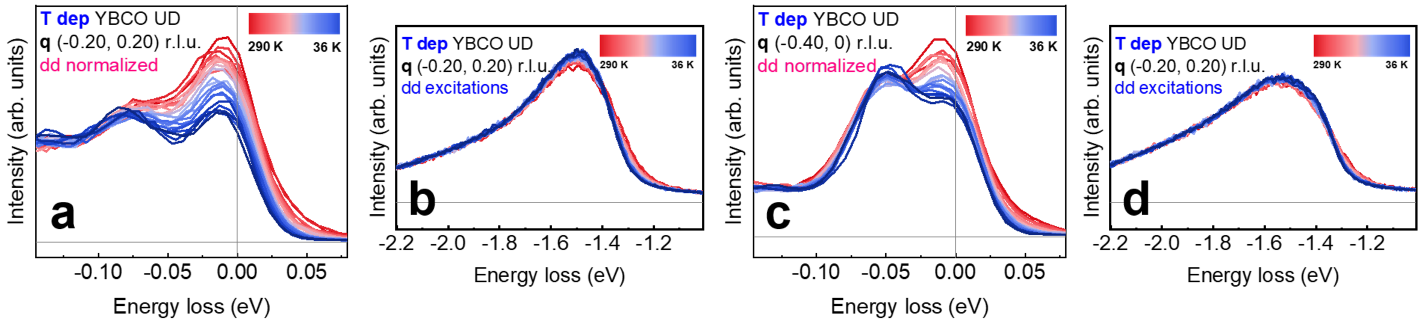

Figure 1 *Temperature dependent RIXS spectra of the favourable and unfavourable* ***q*** *points in the quasi elastic* ***(a, c)*** *and dd excitations* ***(b,d)*** *regions for YBCO slightly underdoped.*

The second step consisted in the T dependence for the underdoped sample. We measured at two different **q**: the optimal one and the (-0.40, 0) r.l.u.. The latter is a **q** point where the gap opening effects are negligible, both according to previous measurements [3] and to our calculations, and thus can be used as an additional reference. We started from the reference spectrum at 250 K which was counted for two hours to reduce the noise in the data analysis. We went down in T, counting each spectrum one hour and afterwards we added other temperatures of interest. The results are shown in *Figure 1*. A clear evolution in the low energy scale is present in both the **q** points (**a**, **c**). However, at (-0.20, 0.20) (**a**) two jumps around 90 K and 156 K are visible already from the spectra and seem not present in the unfavourable geometry (**c**). These two changes in intensity, that might be assigned to the SG and PG openings, occur on top of a more continuous evolution, which is present also in **c** and can be assigned to bosonic excitations [4]. Moreover, also the evolution of the dd excitations can be observed with this dataset (**b**, **d**). A continuous change in the shape of the peak is evident in both the geometries. A recent publication claims that also dds could be sensitive to the SG opening [5], representing an additional benchmark for the rising of superconductivity. A careful analysis of the dd intensity evolution is giving promising result in this direction.

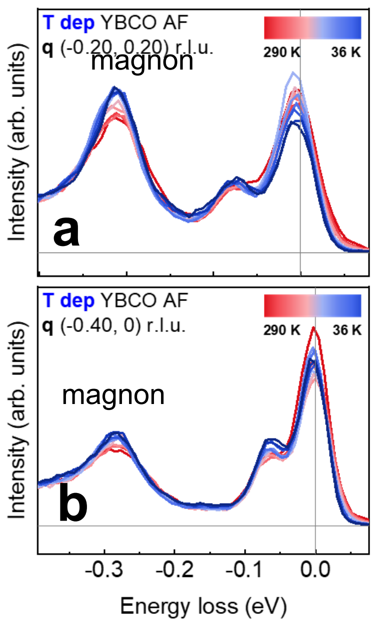

Figure 2 *Temperature dependent RIXS spectra for the undoped YBCO. We measured this sample for the same* ***q*** *as for the underdoped.*

The last step of the experiment was devoted to the undoped sample. We performed a less dense T dependence following the same procedure described above for both the **q** measured in the other sample. The results are shown in *Figure 2*. Although the evolution of the magnetic excitations is characterized by a monotonic sharpening of the magnon peak, the corresponding behaviour in the quasi-elastic region is far from obvious: an interpretation of these results requires a careful analysis.

In general, we are looking to small modulation of the spectral intensity and thus we are strongly sensitive to any source of instability. Although the experiment is extremely challenging from the technical point of view, the dataset looks extremely promising and the beamtime can be considered really successful. The final data analysis is being carried out with the greatest care with the aim of extracting the maximum of information. This very first experiment confirms that energy gaps of cuprates can be studied with RIXS and opens the way to further studies on samples with other dopings and of other families.

References:

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