New Features in the Doped Cuprate Phase Diagram

*This report features the work of Wei-Sheng Lee and his co-workers published in Nature Physics **10**, 883 (2014).*

High-temperature superconductivity (HTSC) emerges on doping holes or electrons into antiferromagnetic (AFM) copper oxides. In undoped AFM cuprate, high-energy magnetic excitations, so-called magnons, are observed. In the under- and optimally hole-doped cuprates, superconductivity is accompanied by an *hourglass*-shaped dispersion of magnetic excitations around the scattering vector (0.5π, 0.5π).[1] Comparison of magnetic excitations and collective excitations in hole- and electron-doped superconductors is hence required to unravel the mechanism of HTSC. The energy resolution of measurement of Cu L_3-edge resonant inelastic X-ray scattering (RIXS) has improved from 1.6 eV to 130 meV in ten years[2] and can distinguish magnon excitation from an elastic feature. Cu L_3-edge RIXS research on magnetic excitations in hole-doped cuprates[3,4] is recently promoted keenly.

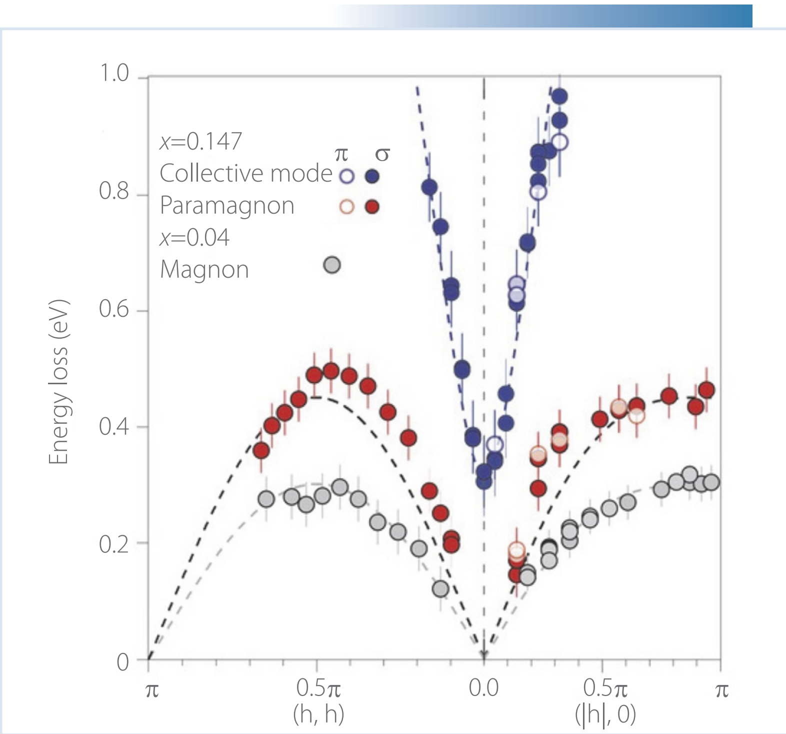

Fig. 1: Magnon, paramagnon and collective-mode dispersions along directions (0, 0)-(π, 0) and (0, 0)-(π, π) deduced from RIXS spectra of AFM NCCO (x = 0.04) and SC NCCO (x = 0.147). (Reproduced from Ref. 5)

On measuring Cu L_3-edge RIXS, Wei-Sheng Lee *et al*. investigated how magnetic excitations and collective modes evolve in the superconducting (SC) phase of electron-doped cuprates $Nd_{2-x}Ce_xCuO_4$ (NCCO) in comparison with hole-doped cuprates.[5] The data of the AFM phase (x = 0.04) and the SC phase (x = 0.147) were recorded at the ADRESS beamline at SLS, PSI and the data of the slightly overdoped SC phase (x = 0.166) were recorded at **BL05A1** at the TLS with the newly constructed AGM-AGS spectrometer.[6] All data were recorded with energy resolution approximately 130 meV.

Figure 1 presents the energy-momentum dispersions of magnetic excitations and collective excitations observed in RIXS spectra of AFM and electron-doped SC NCCO. Compared with the magnon excitation in the AFM (grey circle), two important features are observed in the electron-doped SC NCCO—a spin-wave-like dispersive magnetic excitation in the paramagnetic state, paramagnon (red circle) and additional unexpected collective modes (blue open and closed circles).

Paramagnon dispersion in electron-doped SC extends much further than magnon dispersion of the AFM. The energy at the AFM zone boundary of a paramagnon is approximately 450 meV, an increase 50% above that of a magnon (~ 300 meV). This behavior differs from that in

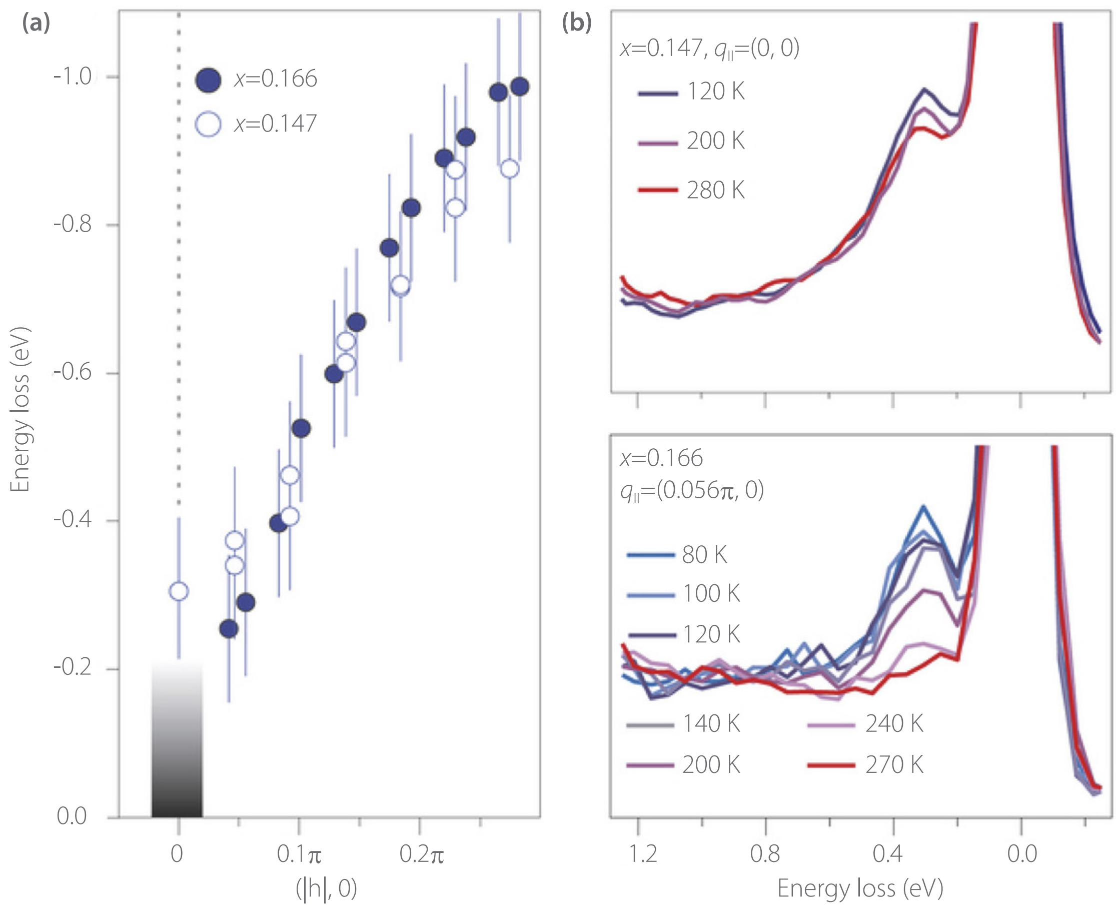

Fig. 2: (a) Energy-momentum dispersion of collective modes in SC compounds, $x = 0.147$ (open circle) and $x = 0.166$ (closed circle). The shaded area indicates the region that was unresolved because of finite resolution of instruments. (b) Temperature-dependent RIXS spectra recorded at a momentum position near the Γ point for SC compounds, $x = 0.147$ and $x = 0.166$. (Reproduced from Ref. 5)

hole-doped cuprates, in which magnetic excitation softens slightly with doping.[3,4]

The additional collective modes are absent in the heavily underdoped AFM NCCO ($x = 0.04$) and in any hole-doped superconductor. Wei-Sheng Lee *et al*. considered the origin of these unexpected collective modes from their dependence on doping and temperature in Figs. 2(a) and 2(b), and suggested that they are associated with a symmetry-broken state. The energy level at Γ point (0, 0) decreases with doping from $x = 0.147$ to 0.166 in Fig. 2(a), which is consistent with the mass of a collective mode altering near a quantum critical point (QCP) associated with a symmetry-broken state. The collective mode near the Γ point becomes weak as temperature increases; the mode at $x = 0.166$ vanishes at 240 K but that at $x = 0.147$ persists to 280 K in Fig. 2(b). This condition indicates that there exists transition temperature T_Γ and that it increases with underdoping. A doping-dependent T_Γ might be associated with the emergence of a doping-induced symmetry-broken state, which vanishes or becomes fluctuating at high temperatures. The existence of a symmetry-broken state implies the existence of a QCP beyond the AFM-SC phase boundary, as discussed for hole-doped cuprates.[7]

Wei-Sheng Lee *et al*. drew complete pictures regarding the doping evolution of collective modes in doped cuprates and a phase diagram by complementing existing knowledge with their results in Figs. 3(a)

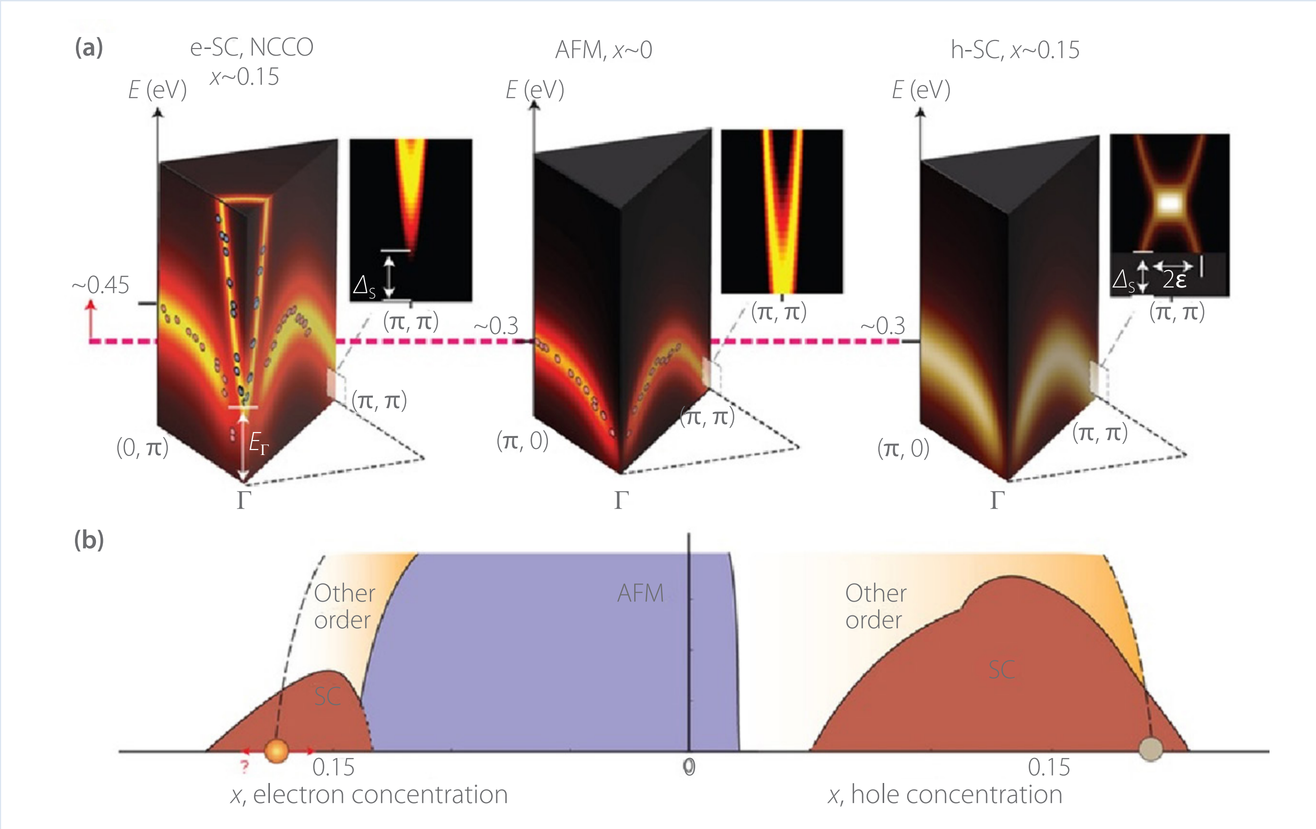

Fig. 3: (a) Sketches of collective excitation spectra in energy-momentum space for electron-doped (e-SC, NCCO), lightly doped AFM and hole-doped (h-SC) superconducting cuprates. (b) A sketch of the cuprate phase diagram. The dots represent QCPs associated with symmetry-broken states (labelled as "other order") on both sides of the phase diagram. (Reproduced from Ref. 5)

and 3(b). Their research revealed that the persistence of magnetic excitations and the existence of a distinct quantum phase are universal in both hole- and electron-doped cuprates, although slight differences exist in their features. (Reported by Jun Okamoto)

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