ABSTRACT

Strongly correlated electron systems, particularly low-dimensional quantum magnets, host a rich landscape of emergent phenomena driven by intense electron-electron interactions and reduced dimensionality. This thesis presents a unified theoretical investigation of multi-spin dynamics in spin-$1/2$ systems, leveraging Resonant Inelastic X-ray Scattering (RIXS) as a momentum-resolved probe of spin, charge, and orbital excitations. Employing the ultrashort core-hole lifetime (UCL) expansion of the Kramers-Heisenberg formalism, the work systematically decomposes RIXS cross-sections into spin-conserving and non-conserving channels, enabling the identification of both conventional and unconventional quasiparticles.

In two-dimensional cuprates, such as La_2CuO_4, experimental RIXS spectra reveal broad, weakly dispersive high-energy features that elude explanation within standard one- and two-magnon frameworks. Through linear spin wave theory (LSWT) and exact diagonalization, this thesis demonstrates that three-magnon excitations—arising from higher-order spin-flip processes in the non-conserving channel—account for these features, highlighting the essential role of multi-spin dynamics in 2D antiferromagnets.

Turning to one-dimensional systems, the thesis investigates trimerized spin-$1/2$ chains realized in $Na_2Cu_3Ge_4O_{12}$ ($J_1 > J_2$) and $Cu_3(P_2O_6OH)_2$ ($J_1 < J_2$). Using density matrix renormalization group (DMRG), exact diagonalization, and real-space renormalization group techniques, the study uncovers a hierarchy of excitations: gapless spinons, composite doublons and quartons, and multi-trimer modes, all directly observable via RIXS. The application of a magnetic field reveals a robust one-third magnetization plateau and a field-driven evolution of the excitation spectrum, culminating in the emergence of gapless spin-1 bosonic modes indicative of a field-tuned Bose-Einstein condensate.

Collectively, these results establish RIXS as a powerful tool for probing fractionalization and composite quasiparticles in strongly correlated quantum materials. The thesis bridges experimental observations and theoretical modeling, deepening our understanding of quantum magnetism and superconductivity in cuprates, and laying the groundwork for future studies of emergent phenomena in low-dimensional systems.