Title: Developing resonant soft x-ray scattering technique in very high magnetic fields by using advanced pulse magnet design

Introductory part: (Abstract) The IMR team's extensive efforts have established the well-established use of X-ray techniques with a pulsed field magnet to explore complex phenomena in quantum materials. Here, we proposed moving one step further and developing a pulsed magnet with resonant soft X-ray scattering, enhancing our understanding of correlated electrons, particularly in high-temperature superconductors, under unprecedented magnetic fields.

Combining x-ray techniques with a magnetic field provides a groundbreaking set of advanced probes for quantum materials. This approach offers unique opportunities to unveil profound scientific phenomena, such as complex and exotic states in strongly correlated electron systems. When an applied magnetic field (H) reaches approximately 50 Tesla, its corresponding Zeeman energy (~70 K) approaches the perturbation of the phonon effect. This field strength aligns well with the energy scales of several phenomena observed in high-temperature superconductivity (HTSC) and other quantum materials. Despite this potential, conducting X-ray scattering experiments at fields greater than H = 20 Tesla presents significant technical challenges due to limitations in conventional superconducting DC magnets. Furthermore, x-ray spectroscopy under moderate magnetic fields to investigate correlated electron phenomena in quantum materials remains a highly desired but unachieved goal.

Proposed Development: I proposed developing a pulsed magnet to achieve state-of-the-art X-ray instrumentation at SLAC with both macroscopic and microscopic sensitivities for investigating quantum materials. A team at the Institute for Materials Research (IMR) at Tohoku University, led by Professor Nojiri, is uniquely positioned to implement this development. The critical innovation involves integrating a 30 Tesla, ultimately 50 Tesla, pulse magnet with a resonant soft x-ray scattering (RSXS) setup. This development will enable the exploration of correlated electrons and corresponding bonding phenomena in high-Tc superconductors, such as intertwined self-organization forms, for example, charge-density wave (CDW) or its stripe-order, under unprecedented magnetic field strengths.

Project Plan: I outlined a one-month project for this magnet development at IMR/Tohoku. During my visit, we, together with the Nojiri team, focused on designing and engineering a prototype of the pulsed magnet for RSXS (see Figure 1). Since the soft x-ray has a short wavelength, it was critical to define the scattering geometry properly. In this sense, we adopted the concept of the split-pair type magnet. Also, the magnet will be rotated with the sample through a different rotation stage to maintain proper open angles.

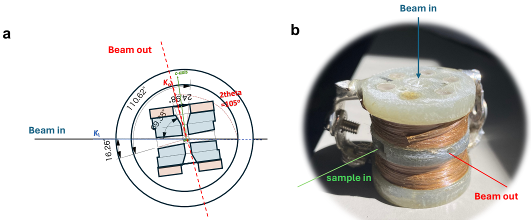

Fig. 1: a. Designed split-pair magnet for RXSX. **b.**, The initial prototype magnet was made by the Nojiri team._

Upon returning to the home institute at SLAC, I started to design other setups for integrating the magnet into the x-ray setup (Figure 2). Meanwhile, prof. Nojiri and I used the developed RSXS instrumentation for HTSC case studies. As a demonstration, we will initially explore the self-organization forms of paired 3d-electrons in copper-oxide compounds (Y-based cuprate) using RSXS under 30 Tesla. The expected test run will be by the end of 2024.

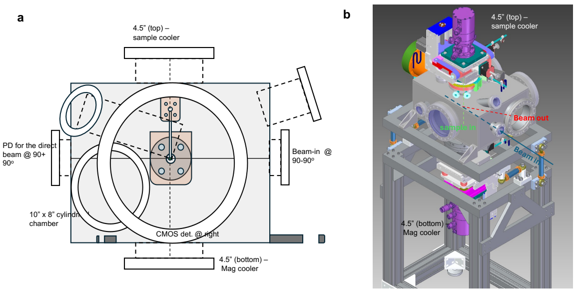

Fig. 2: a. Schematic drawing for integrating the magnet inside a scattering chamber. **b.**, The designed RSXS setup.

Significance and Impact: The discovery and utilization of functional materials are vital to our technology-rich society. Materials with strongly correlated electronic systems have the potential to offer new functionalities and pathways to applications. For instance, research on quantum materials paves the way for functional quantum computers, resistance-free electricity, and many other potentially transformative applications. Unique system-level behavior and related functional properties generally emerge from the intercoupling behavior among constituents such as spin, orbital, charge, and lattice. Our team ultimately discovered a remarkable 3D arrangement of a material's electrons closely linked to the phenomenon of high-temperature superconductivity [1-3].

While investigating the role of CDW in HTSC in the past [1-10], I encountered a limitation related to the sample environment. This is because not only is the magnetic field strength low, but also the spectroscopic information is lacking. Despite our previous efforts [1-3, 9, 10], most of the high magnetic field scattering experiments have been performed at a hard x-ray range, particularly the non-resonant x-ray scattering regimes. Through this proposed development, indeed, we believe that we could overcome the limitation. In particular, the resonant process will shed new light on microscopic information on the field-induced phenomena in high-Tc cuprates, such as the 3D CDW order [1-3].

Conclusion: Given my experience, including the Nojiri team's expertise, I believe the proposed development and its successful demonstration can reveal new quantum phases of matter, potentially altering our understanding of the essential physics regarding the mother state in HTSC. Furthermore, the success of this project could reshape our understanding of quantum materials and pave the way for transformative technological applications.

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