Neutron Scattering Measurements of the Cuprate Superconductor $\mathrm{HgBa_2CuO_{4+\delta}}$

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Introduction

Superconductivity was first discovered in 1911 in elemental mercury. It is characterized by a sharp drop in resistance in a material below some critical temperature, T_c, as well as an expulsion of all magnetic fields from the material's interior. A comprehensive theory behind superconductivity was not put forward until 1957, when it was suggested that electrons pair together via phonons to form "Cooper pairs", allowing them to act as bosons and carry current with no resistance. However, in 1986, a new type of superconductor, one with relatively high T_c, was discovered. Eventually many of these types of materials were discovered. They were aptly named "high-temperature superconductors" (HTSCs). The isotope effect has shown that phonons are not the coupling mechanism for charge carriers in these materials. The search for the correct mechanism is one of the most pursued problems in condensed matter physics today.

The Cuprates and $\mathrm{HgBa_2CuO_{4+\delta}}$

One important class of HTSCs are the cuprates. They are characterized by their quasi-two-dimensional copper-oxygen planes. The cuprates all display a variety of phases, which can be summarized in a generic phase diagram (Figure 1) which has been empirically constructed over the years. These phases depend on the temperature and doping level of the material.

Of the cuprates, one of the best compounds to study is $HgBa_2CuO_{4+\delta}$ (Hg1201). The reason this compound is a model material is because of its relatively high optimal T_c (about 95 K), its simple crystal structure, and its low susceptibility to disorder effects [1].

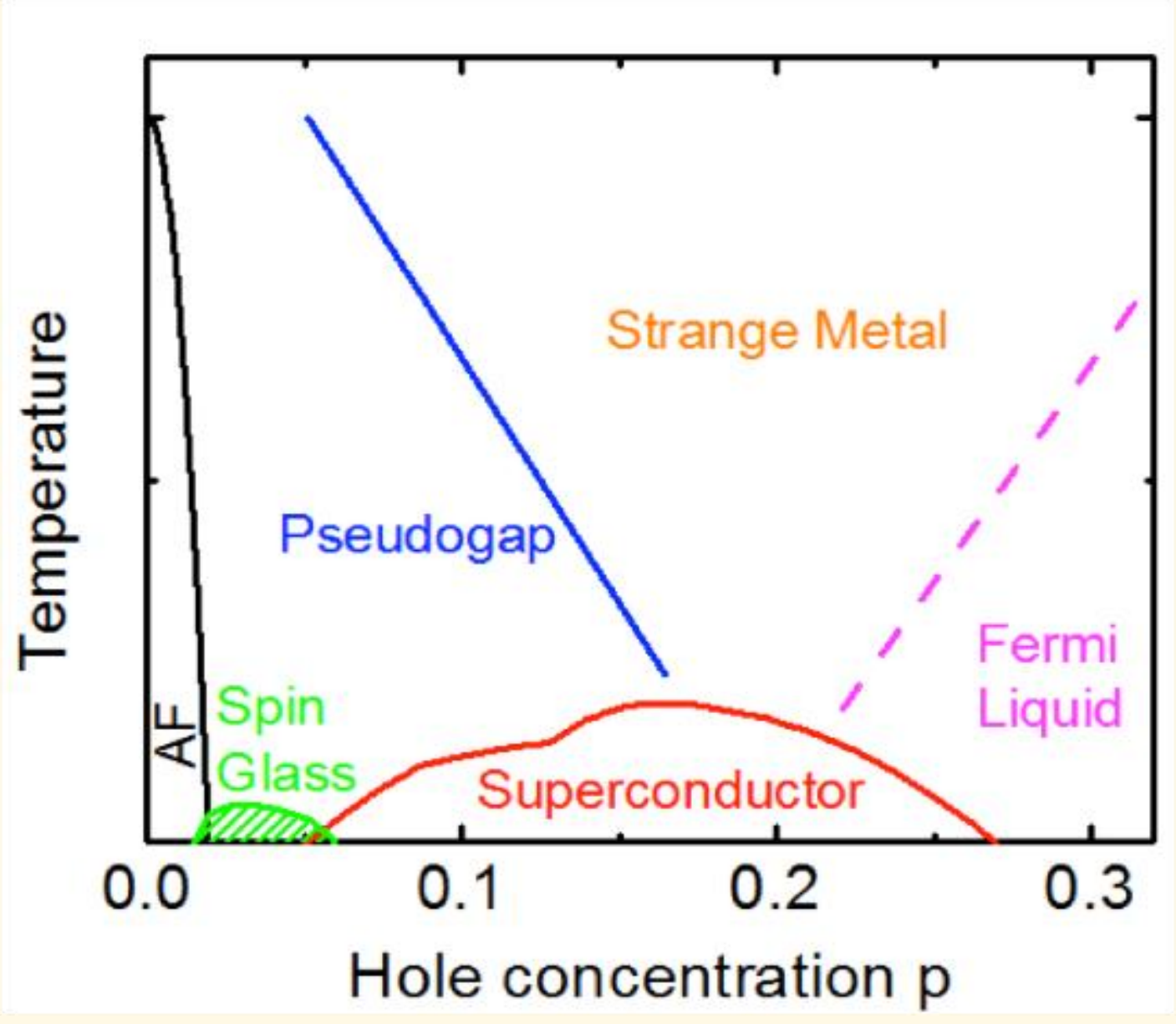


Figure 1: A generic hole-doped cuprate phase diagram. Note that the superconducting phase forms a "dome" shape.

Neutron Scattering

Neutron scattering has proven to be a powerful tool for probing magnetic properties of materials. Neutrons are useful for this for several reasons:

- They are uncharged, so they don't interact electromagnetically with charged particles such as electrons or nuclei
- They have a magnetic moment, which allows them to interact magnetically with the materials
- Thermal neutrons have kinetic energies on the order of magnetic excitations in cuprates

One method of inelastic neutron scattering is time-of-flight spectrometry, which uses principles of momentum and energy conservation to find the momentum and energy imparted to the sample by the neutron. This allows for the mapping of magnetic excitations of certain energies in 2D reciprocal space.

Antiferromagnetic Excitations In the Cuprates

Antiferromagnetic excitations are widely studied in the cuprates, since they are likely closely related to d-wave superconductivity [2]. In most other cuprates the dispersion relation between energy and wave vector for magnetic excitations follows an hourglass pattern. However, in Hg1201, The dispersion pattern is Y-shaped, with a gapped commensurate antiferromagnetic wavevector (q_{AF}), at [0.5,0.5] in the first Brillouin zone at low energies, which eventually becomes incommensurate at higher energies (see Figure 2). The commensurate peak is reflective of the onset of antiferromagnetic modes, while the onset of incommensurability is reflective of some breakdown of the modes.

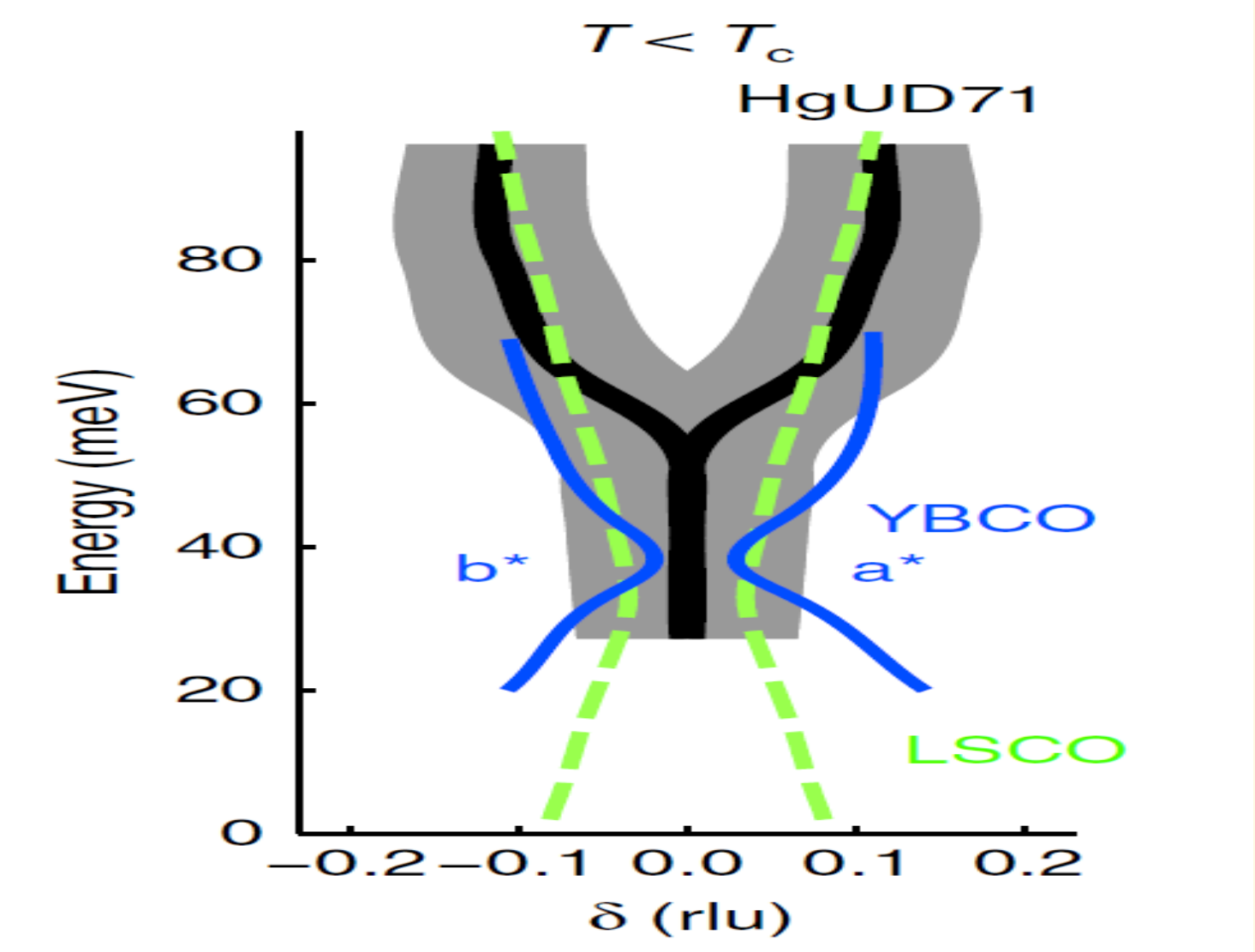


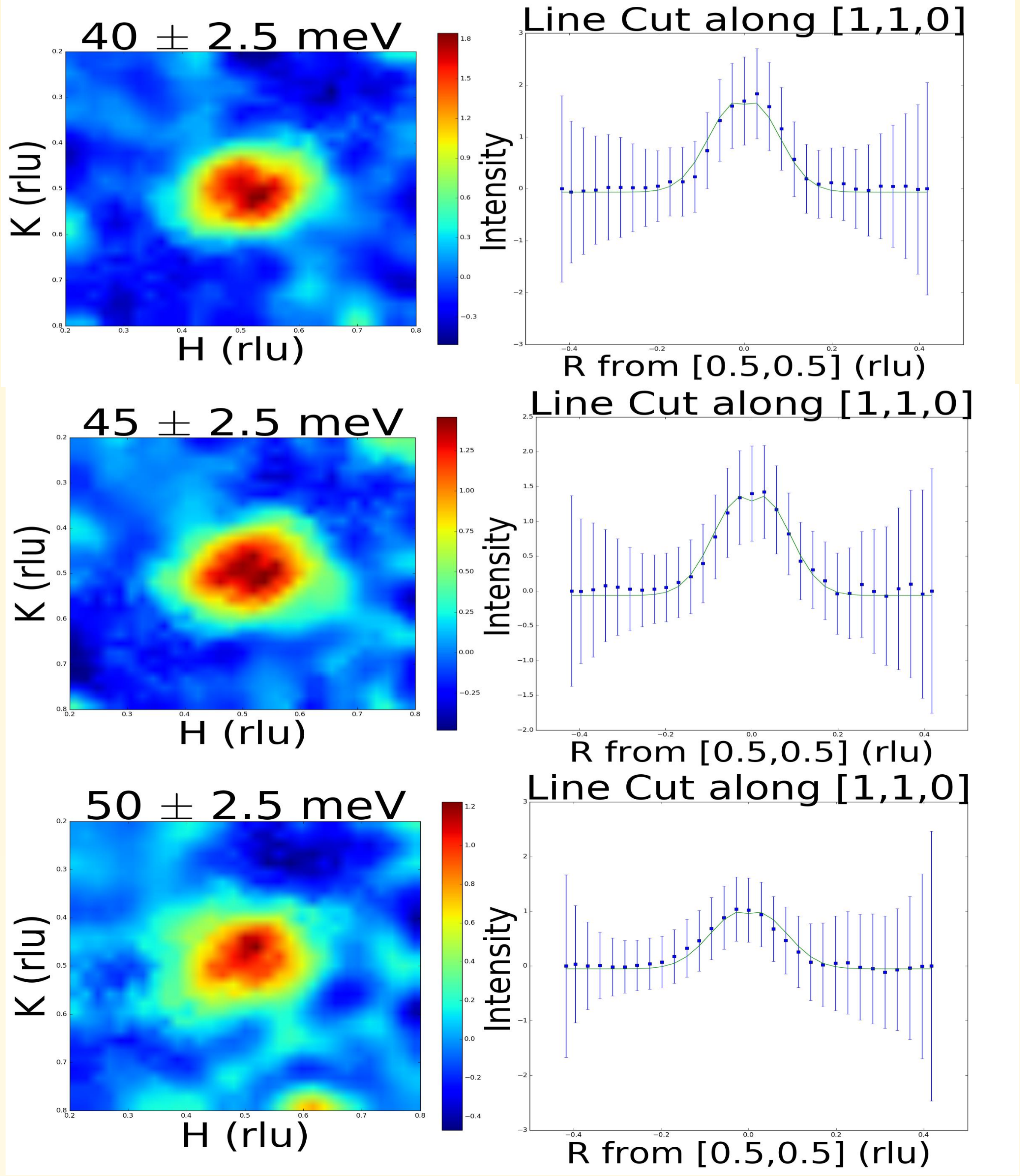
Figure 2: Dispersion relation for Hg1201 (UD71), YBCO, and LSCO, for $T < T_c$. Taken from [3].

Experiment Preparation

Single crystals of Hg1201 were grown using the self-flux encapsulation method. These crystals were annealed until they had a T_c of 55 K. Since individual crystals are not large enough to obtain an appreciable neutron signal, multiple crystals were mounted on an aluminum pad with their axes co-aligned to create a single sample for neutron scattering. Data was taken at the Spallation Neutron Source at Oak Ridge National Laboratory, using the Wide-Angular Range Chopper Spectrometer (ARCS), which uses time-of-flight techniques.

Results

Results for scattering data with incident energy of 70 meV at temperature 5 K are shown in Figure 3. Energy slices were taken in 2D reciprocal space with thickness of about 5 meV. The onset of the commensurate peak was at about 30 meV (not shown). At about 60 meV, it can be seen that the peak at [0.5,0.5] becomes incommensurate. However, these data are very noisy since the intensity of the signal is relatively low. This is due to the 60 meV slice is very close to the incident energy of the neutrons of 70 meV.



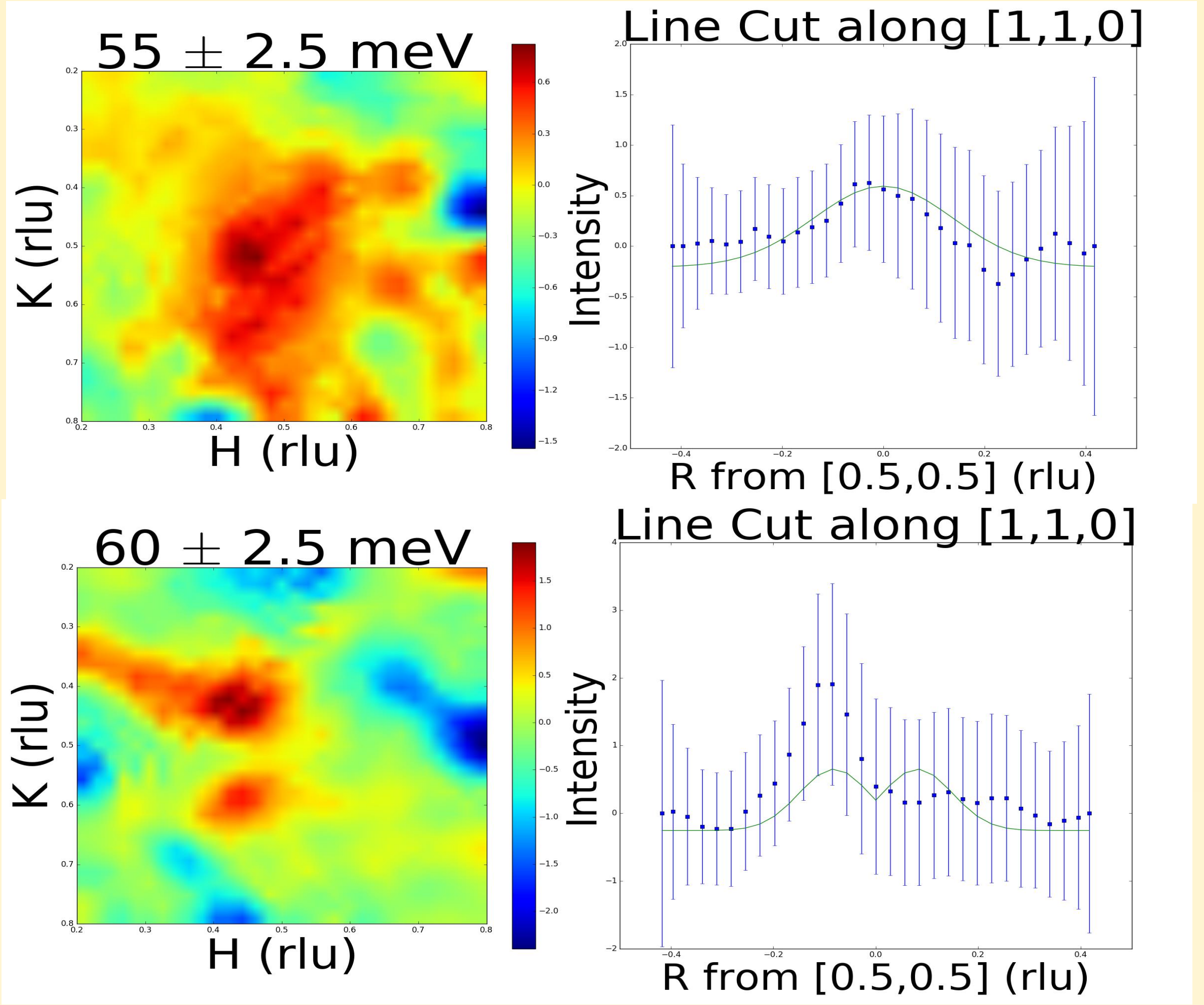


Figure 3: Color mappings of (subtracted) count intensity in reciprocal space with specific energy slices. All data were collected at 5 K. The large source of error comes from the signal being fairly weak. The data appear to become incommensurate around 60 meV.

Conclusion

Neutron scattering data for a Hg1201 sample with a T_c of 55 K were collected at 5 K, using a time-of-flight spectrometer. An observed commensurate peak with onset around 30 meV appeared to become incommensurate around 60 meV. Due to large amounts of noise at higher energies, additional data must be taken with higher incident energy to obtain a better signal, and to verify the incommensurability.

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References

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