Quantum methods

An arsenal of spectroscopic and microscopic methods is essential to the understanding and development of quantum materials.

When investigating the properties of quantum materials, there is no one technique to rule them all. Complementary methods sensitive to different degrees of freedom are becoming ever more necessary as researchers dig deeper into classic subjects like magnetism and more recent developments based on a topological classification of the electronic structure of materials. In the beginning of the modern development of these subjects, researchers utilized neutron scattering to directly evidence antiferromagnetism by guiding neutrons out of the reactor core and onto their samples, while low-energy photoemission served as an ideal probe of the metallic surface states of topological insulators. Today many open questions on the nature of quantum materials remain and, to dig still deeper, more methodological developments are needed.

Higher beam intensity, finer spatiotemporal resolution, polarization control, better energy resolution and tunability, coherence, in situ environments and more sensitive detectors are among the common demands that understanding of quantum materials places on the research community. Moreover, complementary techniques frequently must be combined to address the complexity of these materials. Meeting these demands often requires the collaboration of principal investigators of complementary technical expertise. In the case of utilizing X-rays or neutrons, large-scale facilities requiring the concerted effort of related research communities must be constructed and upgraded with a suite of endstations each dedicated to a particular technique.

In this issue of *Nature Materials* we showcase the progress being made by combining techniques to investigate the magnetic and electronic properties of two perovskite materials — the archetypal multiferroic ferrite BiFeO_3 and the colossal magnetoresistive manganite $\text{La}_{2/3}\text{Ca}_{1/3}\text{MnO}_3$. In addition, spectroscopic insight into the electronic structure of superconducting materials based on the nickelates (Nd/La) NiO_2 is reported.

Skyrmions are collective magnetic objects with topological protection that were discovered in ferromagnetic materials. However, antiferromagnetic skyrmions may have distinct technological advantages,

A modern spectrometer for resonant X-ray scattering at a synchrotron radiation facility. Credit: National Synchrotron Light Source-II

such as higher speed limits, over their ferromagnetic counterparts. As they have no net moment, it is difficult to couple their magnetization to external stimuli and manipulate them. To overcome this, one idea is to create antiferromagnetic skyrmions in a multiferroic material with strong magnetoelectric coupling, where control of the ferroelectric order could result in manipulation of the antiferromagnetic skyrmions. In a [Letter](#) Michel Viret and colleagues utilize a variety of microscopic and spectroscopic methods to reveal both chiral antiferromagnetic and electric textures in the high-temperature antiferromagnetic ferroelectric BiFeO_3 . First, they utilized their own lab-based piezo-force microscopy equipment to suggest that they had the desired ferroelectric domains in their films. They then took advantage of the intensity and energy and polarization tunability of synchrotron X-ray and neutron sources to show that they have chiral nanometre-scale antiferromagnetic and electric objects at the ferroelectric domain walls of their material. Further corroboration of these chiral objects was made by scanning nitrogen-vacancy magnetometry. The corresponding [News & Views](#) emphasizes the importance of combining several techniques to arrive at these conclusions.

In the work of Viret and colleagues, a particular state of a quantum material was demonstrated by combining real-space and reciprocal-space methods. In an [Article](#) in this issue, Dimitri Basov and colleagues investigate in more detail the light-induced control of a material by a multi-messenger combination of techniques. They use co-located atomic force microscopy,

cryogenic scanning near-field optical microscopy and magnetic force microscopy to visualize the topographic, electrical and magnetic properties in the same area with nanometre resolution. In particular they confirm that the light-induced metallic phase in $\text{La}_{2/3}\text{Ca}_{1/3}\text{MnO}_3$ is ferromagnetic and further show that this light-induced ferromagnetic phase is distinct from the ferromagnetic metallic phase that can be realized without light. In a related [News & Views](#) the combination of these techniques is highlighted, demonstrating that light can be used to realize quantum states not accessible by other stimuli.

Whereas these developments took advantage of two well-studied materials, in a [Letter](#) Wei-Sheng Lee and collaborators present X-ray absorption and resonant inelastic X-ray scattering performed at synchrotrons on the parent compounds of the recently discovered nickelate superconductors. This study provides a glimpse into the electronic structure of these materials, revealing that the $\text{Ni } 3d$ electrons — suspected to be responsible for the superconductivity — hybridize less with the O ions than their copper-based predecessors. Instead they hybridize with the $\text{Nd } 5d$ electrons, yielding a possible three-dimensional Kondo or Anderson-like metallic oxide parent compound, in contrast to the quasi-two-dimensional Mott insulating state from which high-temperature copper-based superconductivity typically arises.

These works, and others like them^{1–3}, highlight advanced spectroscopic and microscopic techniques that provide insight into quantum materials. There is still plenty to be done. For example, the lattice distortions implicated in [Basov et al.](#) could not yet be detected, while the low-energy spin excitations expected in [Lee et al.](#) were not resolved. Developments in quantum methods bring us closer to understanding the diversity of ground states in quantum materials and ultimately their control and integration into our daily lives. □

Published online: 24 March 2020
<https://doi.org/10.1038/s41563-020-0660-5>

References

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