When spin supersolids become metallic

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The notion of a supersolid has fascinated physicists for more than half a century. Originally proposed in the context of solid helium, a supersolid combines two seemingly incompatible forms of order: the spatial rigidity of a crystal and the frictionless flow of a superfluid. Although its existence in helium remains debated, the concept has found fertile ground in other quantum many-body systems and materials. In the frustrated magnetic insulator material $Na_2BaCo(PO_4)_2$ (NBCP), this idea is realized as a spin supersolid,[1,2] where magnetic order coexists with long-range coherence of transverse spin components, providing a magnetic realization of the coexistence between crystalline and superfluid order.

It is further revealed that the spin supersolid exhibits a giant magnetocaloric effect, opening a new pathway for helium-3-free ultralow-temperature refrigeration.[1]

Over the past decade, theoretical and experimental studies have established spin supersolidity as an emergent phase in frustrated magnets, especially on triangular lattices. Before NBCP, few convincing realizations of a spin supersolid in materials had been reported, with most studied compounds sharing a common feature: they are electrical insulators which imposes a fundamental limitation on potential cooling applications, as in which the phonon thermal conductivity severely suppresses heat transport at low temperatures. Such low thermal conductivity restricts heat extraction and consequently compromises cooling performance. Currently, dilution refrigeration is the primary technology for achieving ultra-low temperatures; however, its reliance on ^3He — which is globally limited and highly demanded — poses constraints on the sustainable advancement of quantum sciences and technology. An alternative approach is adiabatic demagnetization refrigeration, for which the ideal magnetocaloric material would combine a large cooling capacity with metallic-like intrinsic thermal transport.

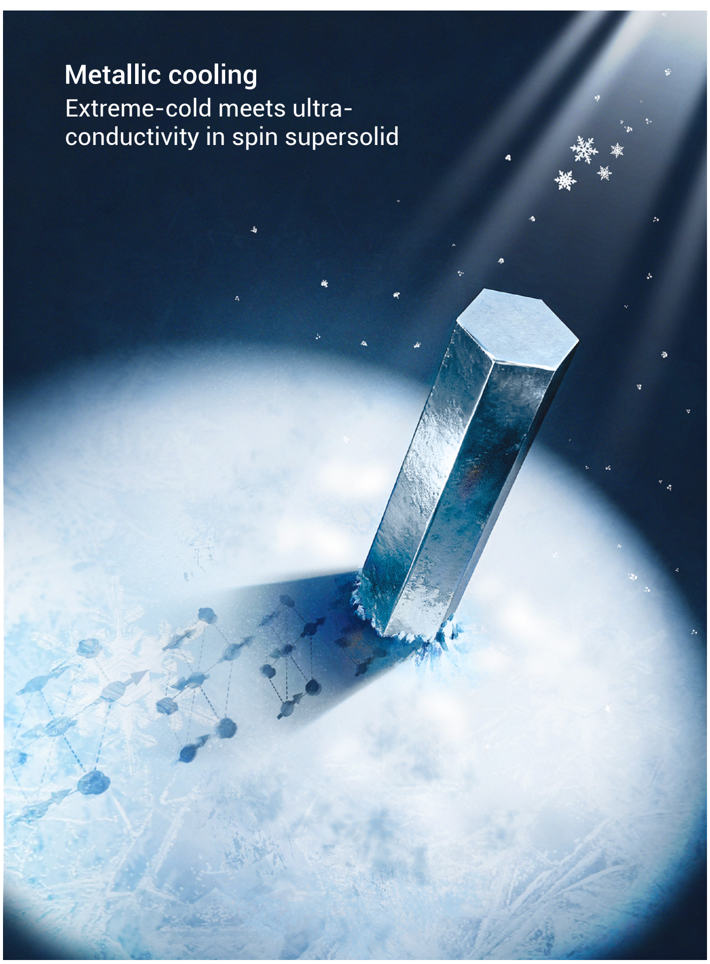

Figure 1. Schematic illustration of metallic cooling: the combination of extreme cold and ultraconductivity in spin supersolids.

Shu et al., reported the discovery of a spin supersolid in the metallic rare-earth compound $EuCo_2Al_9$ (ECA).[3] Their work extends spin supersolidity into an entirely new setting — one in which localized magnetic moments coexist with itinerant conduction electrons. The magnetic degrees of freedom originate from the localized Eu^{2+} ions, whose $4f^7$ electronic configuration gives rise to a large spin moment S = 7/2. These moments are arranged on stacked triangular lattices, providing the geometric frustration necessary for stabilizing a rich sequence of field-induced magnetic phases. Neutron diffraction measurements reveal the simultaneous presence of longitudinal and transverse magnetic order, providing microscopic evidence for spin supersolidity. In contrast, the metallic conductivity arises from three-dimensional itinerant electrons primarily derived from the Co-Al conduction bands. The conduction electrons mediate long-range Ruderman-Kittel-Kasuya-Yosida (RKKY) interactions between the Eu moments. This coupling establishes an intimate interplay between frustrated magnetism and itinerant electronic degrees of freedom, ultimately enabling the emergence of metallic spin-supersolid phases. Owing to the large magnetic moment of Eu^{2+} (S = 7/2), the RKKY-dipolar model provides a remarkably successful description of the field-dependent magnetization. In particular, the calculated magnetization curves are in excellent agreement with experimental measurements over a broad range of finite magnetic fields. A notable discrepancy, however, emerges in the ultra-low-field regime ($H \lesssim 40$ mT). While the classical simulations consistently predict a finite residual magnetization, the experimental data exhibit a continuous evolution of the magnetization toward zero field with no obvious remanent moment.

Understanding this discrepancy requires going beyond the spin-only description and treating the mutual feedback between the gapless electronic degrees of freedom on the Fermi surface and the critical spin fluctuations. A prerequisite for such a theory is a proper identification of the low-energy bosonic modes underlying the spin-supersolid state. In this regard, the recent neutron-scattering measurements on the insulating spin-supersolid candidate NBCP revealed an intriguing feature:[4] a broad excitation continuum persists on top of the finite-momentum spin-density order at the K point. Such a continuum cannot be straightforwardly captured within conventional spin-wave descriptions, which is largely attributed to the fact that NBCP is close to the U(1) Dirac spin liquid in parameter space. However, the situation in ECA is even more complicated: Unlike NBCP, neutron scattering does not directly probe the relevant low-energy magnetic degrees of freedom with sufficient energy resolution. Consequently, the dynamical spin structure factor, which played a crucial role in identifying the excitation continuum in NBCP, remains largely inaccessible for ECA. As a result, the nature of the low-energy bosonic fluctuations in the metallic spin-supersolid state is presently unknown.

A promising theoretical route is therefore to start from an effective low-energy bosonic field theory motivated by the spin dynamics of the two-dimensional triangular-lattice supersolid counterpart realized in NBCP since the interlayer spin coupling is relatively weak. Subsequently, these bosonic modes are coupled to gapless fermionic excitations. Such a framework may provide a unified description of the interplay between critical spin fluctuations and itinerant electrons. The mutual feedback between numerical and field-theoretical results could yield experimentally testable predictions for the temperature and/or field-dependent magnetization and electronic transport in the low-field metallic spin-supersolid Y phase. This low-field phase is crucial for the performance of demagnetization cooling in achieving the lowest temperature. Perhaps the most exciting aspect of this fascinating discovery lies in the opportunities it creates rather than the questions it answers: Conduction electrons may modify emergent spin degree of freedom, alter critical dynamics and generate damping mechanisms absent in insulating systems. How do itinerant electrons influence the collective modes of a spin supersolid? Can critical supersolid fluctuations drive non-Fermi-liquid behaviour? What happens at the quantum phase transitions separating metallic supersolid phases from neighbouring magnetic states? Could transport, noise spectroscopy or spin-current measurements reveal signatures inaccessible to thermodynamic probes?

The work also carries a profound practical significance. The renewed interest in spin supersolids has been driven in part by their remarkable magnetocaloric properties. Near field-induced transitions, enhanced fluctuations generate large entropy changes that can be exploited for adiabatic demagnetization cooling. ECA cools to temperatures near 100 mK while maintaining exceptionally high thermal conductivity — a notable advantage over conventional insulating refrigerants. By combining strong magnetocaloric performance with metallic heat transport, ECA guides the design of metallic magnetic coolant and points toward a new era of cryogenic refrigerants.

The history of supersolidity has often been shaped by the migration of an idea from one physical platform to another — from helium to cold atoms, and from bosons to spins. ECA represents the next step in that evolution. By embedding a spin supersolid within a metal, it introduces a setting where magnetic order and itinerant electrons are inseparably intertwined. The result not only expands the family of supersolid materials, but also opens a pathway toward exploring how supersolidity manifests in the broader world of quantum matter.

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AUTHOR CONTRIBUTIONS

X.-T. Z wrote the original draft of the manuscript. H.L. revised the manuscript and prepared the figure. All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no conflicts of interest.