Probing quantum thermalization and quantum magnetism with lattice-trapped dipolar atoms

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Cold atoms placed in optical lattices have become a prominent platform for quantum simulations and the investigation of quantum many-body physics. There is in particular a very strong interest into long-range interacting systems that can allow studying quantum magnetism in completely new regimes. In our setup we use strongly magnetic spin-3 chromium atoms, and study out-of-equilibrium spin dynamics after a quench.

The most interesting regime – the itinerant regime – is when spin-dynamics and transport occur over similar timescales. Using advanced dynamical decoupling techniques to overcome past experimental limitations, we have performed the 1st study of the itinerant regime for bosonic particles with long-range interactions [1], throughout a phase transition where transport properties abruptly vary from superfluid to insulating (the superfluid to Mott transition, see Fig 1). In the superfluid regime, we find that a dynamical instability destabilizes ferromagnetism when the transition is approached. In the insulating regime, super-exchange interactions are modified by a subtle interplay between intersite and on-site dipolar interactions.

Deep in the Mott insulating regime, we have investigated the process of quantum thermalization through measurement of the growth of spin quantum correlations. We use a new technique to obtain bipartition separation within a 3D lattice (Fig 2), which offers an alternative to quantum gas microscope for investigating local quantum correlations. We demonstrate the growth of spin anti-correlations between two separated spin ensembles, and as the same time we measure positive spin correlations within the two spin ensembles. This peculiar correlation landscape, analyzed through theoretical and numerical models, provides evidence for quantum thermalization at negative temperature, a feature which is for the first time demonstrated experimentally regarding internal degrees of freedom [2].

References

[1] T. Lauprêtre, A. M. Rey, L. Vernac, and B. Laburthe-Tolra, arXiv:2501.11402 (2025)

[2] Y. A. Alaoui, S. R. Muleady, E. Chaparro, Y. Trifa, A. M Rey, T. Roscilde, B. Laburthe-Tolra, and L. Vernac, Phys. Rev. Lett. 133, 203401 (2024)

Figures

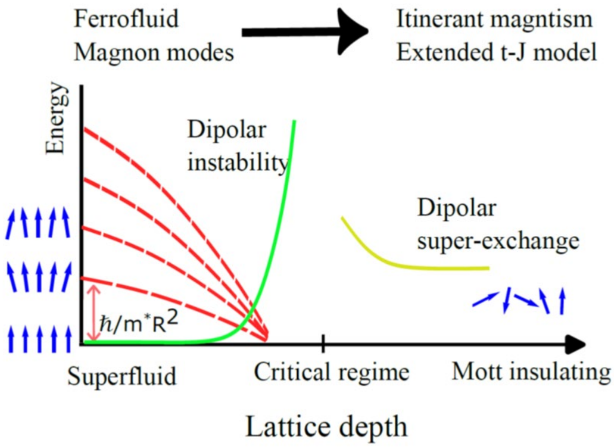

Figure 1: Dipolar Quantum Magnetism through a Quantum Phase Transition [1]

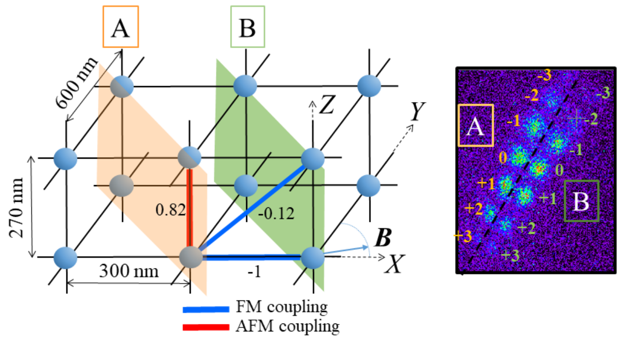

Figure 2: Bipartition scheme in a 3D lattice-trapped spin system. After bipartition, each atom can be measured in seven different spin states, and belongs to one of the two sub-ensembles (A or B).