Physics Colloquium

Quantum many-body entanglement and simulation: Insights, challenges and opportunities

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Entanglement has become central to physicists' understanding of many-particle quantum mechanics in the twenty-first century. Its structure in quantum ground states has provided a window toward understanding and characterizing quantum phases both with and without an energy gap. Its structure in eigenstates of finite energy density has provided deep insights into the nature of thermalization in isolated quantum systems. And while it is entanglement that prevents, in general, the efficient simulation of quantum mechanics on a classical computer, one of the most important classes of simulation methods -- namely, tensor-network methods -- works well precisely in situations with limited entanglement. Of course, the longstanding goal of general simulation will require continued experimental progress in engineering highly controlled quantum devices, which are themselves able to harness the computational power stemming from their own entanglement. Such devices include both analog quantum simulators (in which a desired Hamiltonian is carefully engineered in a finely tuned system) as well as digital (i.e., gate-based) quantum computers. Remarkably, insights from entanglement are again central in developing efficient state preparation procedures and algorithms for these new classes of devices. Furthermore, many of the highly controlled systems used for such quantum simulation are built using atomic/molecular/optical platforms which harbor long-range interactions that decay as a power law. Systems with such interactions are outside the realm of traditional solid state physics, and they exhibit interesting new physical phenomena and entanglement properties.

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