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CCQ NYU
LIGHT-MATTER SEMINAR

Title: Programming light-matter interactions in cavity QED

Abstract: Photon-mediated interactions between atoms coupled to light are a powerful tool for engineering highly entangled states. To achieve strong light-matter coupling, we trap ultracold atoms in an optical cavity designed to enable transverse optical access for high-resolution imaging and addressing of atomic sub-ensembles. Using this apparatus, we implement a nonlocal Heisenberg Hamiltonian, where the relative strength and sign of spin-exchange and Ising couplings are experimentally controlled parameters. This tunability enables, e.g., Loschmidt echo-type protocols that rely on reversing the sign of a global Ising Hamiltonian for use in quantum metrology. We furthermore directly demonstrate that spin-exchange interactions can protect the collective spin coherence against single-atom dephasing terms, showing that spin-exchange interactions can enhance the robustness of entanglement generation compared to pure Ising interactions. The optical access afforded by our cavity enables local addressing and imaging with micron-scale resolution, which in turn allows us to perform Hamiltonian tomography and to directly image the spin coherence. Imaging also enables spatially-resolved measurements of cavity-mediated spin-mixing in a spin-1 system, a new mechanism for generating correlated atom pairs. While our cavity most naturally mediates all-to-all couplings, we can also control the distance-dependence of the interactions and engineer the spatial structure of entanglement. Looking forward, I will discuss prospects for engineering coherent and programmable light-matter interactions in two-dimensional arrays of neutral atoms.