Hot topic presentation

Observation of three and four-body interactions between momentum states in a high-finesse cavity

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Spin Hamiltonians in quantum simulation and quantum sensing have traditionally relied on pairwise (two-body) interactions between system constituents. Here, we present an experimental realization of an effective three-body (n = 3) Hamiltonian in a system of laser-cooled rubidium atoms in a high-finesse optical cavity[1]. The pseudo-spin-1/2 states are encoded in two atomic momentum states, and the interaction is achieved through two dressing tones that drive photon exchange via the cavity. This enables a virtual six-photon process while suppressing lower-order interactions through destructive interference. By tuning the desired process into resonance and detuning the unwanted processes, pure n-body interactions can be generated with the lower-order processes canceled via symmetry. The n-body interaction can be understood as n different atoms flipping their momentum states in concert from $p_0 - \hbar k$ to $p_0 + \hbar k$. The n-body interactions are experimentally observed both via a spectroscopic signal and through mean-field dynamics measured over the Bloch sphere. The resulting interactions exhibit an all-to-all connectivity, making them suitable for rapid entanglement generation and the exploration of exotic quantum phases. The flexibility of our platform also allows for extension to multi-level systems and higher-order interactions, such as a four-body (n = 4) interaction mediated by a virtual eight-photon process.

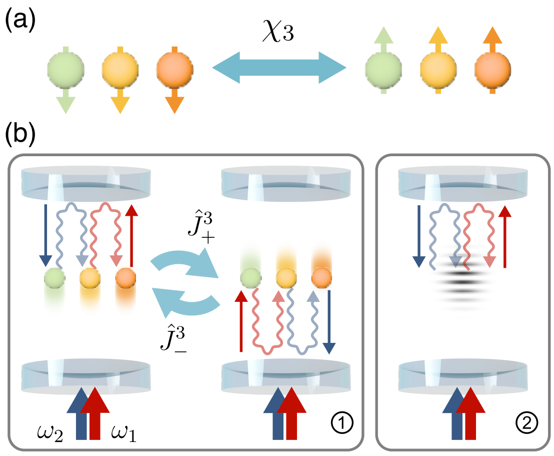

Figure 1: **(a)** A 3-body interaction with strength χ_3 causes a trio of spins to flip their spin states simultaneously. **(b)** Here, the pseudo-spin consists of two atomic momentum states $|p_0 \pm \hbar k\rangle$ along the cavity axis, separated by $2\hbar k$. The atoms are driven by two dressing lasers (red and blue), and an all-to-all three-body interaction arises from photon exchange via the cavity. A density grating is formed when atoms are in superpositions of momentum states, enabling multiple light back-reflections that mediate the interaction.

[1] Chengyi Luo et al., *Science* **384**, 551-556 (2024).