Cavity Mediated Collective Spin Exchange Interactions in a Strontium Superradiant Laser

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Laser cooled and quantum degenerate atoms are widely being pursued as quantum simulators that may explain the behavior of strongly correlated material systems, and as the basis of today’s most precise sensors. A key challenge towards these goals is to understand and control coherent interactions between the atoms. Recently, we realized long-range exchange interactions mediated by an optical cavity [arXiv:1711.03673 (2017)], which manifest as tunable spin-spin interactions on the pseudo spin-1/2 system composed of the millihertz linewidth clock transition in strontium. We have experimentally observed so-called one axis twisting dynamics, the emergence of a many-body energy gap, and signatures of gap protection of the optical coherence against certain sources of decoherence. These effects manifest in the output of a pulsed, superradiant laser operating on the millihertz linewidth transition. Our observations will aid in the future design of versatile quantum simulators that take advantage of the unique control and probing capabilities of cavity QED and the rich internal structure of long-lived Sr atoms. They also open a route for the next generation of atomic clocks that utilize quantum correlations for enhanced metrology.

A crucial requirement for the development of atomic quantum simulators is the ability to create controllable coherent interactions between the atoms. Implementations of these interactions include direct atomic collisions, direct electric and magnetic dipole interactions, phonon-mediated couplings in trapped ions, and photon-mediated coupling in a driven optical cavity. In this talk, I discuss a recent a new type of interaction recently added to this list: spin-exchange interactions between ultra-long-lived optical dipoles mediated by photons in an undriven optical cavity. The effective spins are encoded in the ground and excited state of the millihertz linewidth strontium clock transition (see Fig. 1a). These optical transitions currently forms the basis of the most precise atomic clocks, and is a promising candidate for the development of superradiant optical lasers with coherence times beyond 100 seconds.

The exchange interactions manifest in our system as a collective XX-Heisenberg spin model, an iconic model that describes the behavior of a broad class of phenomena ranging from superconductivity to quantum magnetism. We observe evidence of two of the main characteristic features of the collective XX-Heisenberg model dynamics (see Fig. 1c): an orientation-dependent global spin precession of the collective Bloch vector, referred to as one-axis twisting (OAT), and the emergence of a many-body energy gap between states of different symmetry. One-axis twisting can generate useful spin squeezing, Schrodinger cat states, quantum phase magnification, and enables new measures of entanglement. The energy gap can protect collective dynamics against single-particle sources of dephasing that limit the atomic coherence times needed for high precision measurements and for preserving interesting quantum correlations.

Figure 1. (a) An ensemble of ⁸⁷Sr atoms interacts with a detuned mode of a high-finesse optical cavity that couples to the millihertz linewidth (150 s lifetime) ¹⁹⁸⁸ transition. (b) The cavity mode mediates interactions between the atoms, which lead to both dissipative dynamics in the form of superradiant emission of light through the cavity mirrors and to unitary spin-exchange dynamics that are governed by a Hamiltonian of the form \( H_{\text{eff}} = \hbar \chi [\hat{J}^+ \hat{J}^-] \) where \( \hat{J}^\pm \) are the collective-spin raising and lowering operators respectively. Exchange interactions cause one atom to emit a photon which is then absorbed by another atom, driving anti-correlated spin flips. (c) The spin-exchange interaction can be rewritten as \( H_{\text{eff}} \approx \hbar \chi [\hat{J}^2 - \hat{J}_z^2] \), where \( \hat{J}_z \) is the collective spin operator associated with atomic inversion and \( \hat{J}^2 = \hat{J}_x^2 + \hat{J}_y^2 + \hat{J}_z^2 \) is the total spin operator. The \( \chi \hat{J}_z^2 \) term in \( H_{\text{eff}} \) leads to an inversion dependent frequency shift known as one-axis twisting (OAT), while the \( \chi \hat{J}_z^2 \) creates a many-body energy gap that suppresses detrimental changes in the total spin caused by single particle dephasing.