Quantum Interface and Strong Coupling to Noble Gas Spins

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Macroscopic quantum systems typically suffer from rapid loss of coherence via coupling to the environment. An ensemble of noble-gas nuclear spins is a unique isolated system that could maintain its coherence for many hours at room temperature and above [1]. Notably, noble-gas nuclear spins can be employed as an exceptionally stable, low bandwidth, scalar magnetometer [2]. However, their isolation from the environment is a mixed blessing, impeding the coherent interfacing of noble-gas spins with other quantum systems.

We show that spin-exchange collisions between noble-gas and alkali-metal atoms provide for such a quantum interface. Furthermore, we outline the experimental requirements and present our recent progress towards realizing the coherent interface in the strong-coupling regime.

We formulate the many-body theory of the hybrid system and reveal a collective mechanism that can strongly couple the macroscopic quantum states of the two spin gases [3]. Despite their stochastic nature, these weak collisions enable entanglement and reversible exchange of non-classical states between the ensembles in an efficient, controllable, and deterministic manner. We present an experimental demonstration of strong coherent coupling between ^{3}He and K, with coupling-to-decay ratio of order 5. This is the first time this regime is reached, to the best of our knowledge. Additionally, we present a ^{3}He coherence time exceeding one hour and ^{129}Xe coherence time of ~ 20 sec. These results pave the way towards quantum memories and entanglement at room-temperature with minute-long lifetimes.

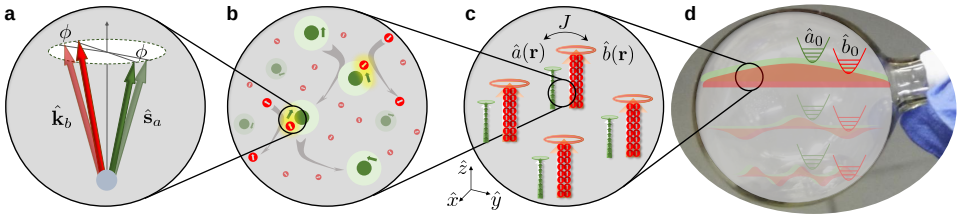

Figure 1. Quantum interface for noble-gas spins via spin-exchange collisions. **a**, Coherent interaction during a collision between alkali-metal electronic spins $\hat{\mathbf{s}}_a$ (green) and noble-gas nuclear spin $\hat{\mathbf{k}}_b$ (red) leads to acquiring a small random angle ϕ. **b**, A stochastic sequence of collisions. Spin exchange occurs when the wave-functions of the two spins overlap. **c**, For polarized ensembles, multiple collisions between different atoms accumulate into a coherent dynamics of spin excitations, described by local bosonic operators $\hat{a}(\mathbf{r})$ (alkali) and $\hat{b}(\mathbf{r})$ (noble gas) and a coupling rate J. **d**, Spatial motion of the gaseous atoms define nonlocal modes. The lowest-order modes $\hat{a}_0, \hat{b}_0$ govern the coherent evolution.

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