Benchmarking Cavity QED using Single Atom Spins on a Surface

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Quantum electrodynamics in a cavity (cavity-QED) allows an enhanced and controllable coupling between a single photon and a single atom, providing an ideal platform to study quantum coherence and entanglement, the fundamental ingredients of quantum technologies. Recently, scanning tunneling microscopy (STM) combined with electron spin resonance (ESR) [1] has pushed the cavity-QED to the fundamental size limit as demonstrated by driving and probing dressed states of a single Ti spin (S = 1/2) on an ultrathin MgO surface [2]. This is due to the sub-nanometer tip-sample vacuum gap in STM, easily allowing an electric field as high as ~ 1 GV/m, which enables an efficient coupling of single spins on a surface with a moderate radio-frequency bias voltage of tens of mV [3]. Lanthanides are promising elements for STM cavity-QED of a long quantum coherence due to the strongly localized 4f shells and rich characteristics of their electron angular momenta.

In this work, we studied electron spin quantum transitions in a single Er atom on MgO surface by utilizing a nearby Ti atom as a quantum sensor [4]. Pulsed ESR on the Er-Ti pair showed two novel features, distinct from a Ti-Ti pair [2,5]: (i) a Rabi coupling of the Er spin, an order of magnitude more efficient than a single Ti spin. (ii) a single-photon transition of $\Delta m = \pm 2$, flipping both spins together. Using a 3-dimensional control of external magnetic field, tuning the eigenstates of the Er-Ti pair allowed us to access two more unconventional transitions stemming from higher-order atom-photon interactions: (i) a two-photon transition of $\Delta m = \pm 2$. (ii) the second-order dressed states of the spin pair.

A model study using a generalized exchange tensor approach addressed that such rich cavity-QED features are accessible due to the large anisotropy and asymmetry in the pair interaction, stemming from the large asymmetry of the Er's orbital momentum and resultant spin-orbit coupling energy when combined with the broken inversion symmetry at the vacuum-solid interface.

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[3] Yang et al. Science 366, 509-512 (2019)
[4] Reale et al. Nat. Communications 15, 5289 (2024)
[5] Yang et al. Phys. Rev. Lett. 119, 227206 (2017); Phark et al. ACS Nano 17, 14144 (2023)