Cavity QED with multiple atomic excited states

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Abstract: We consider cavity QED with single-photon Rabi frequency comparable to the hyperfine splitting of the atom's excited levels. We discuss experimental progress towards relevant measurements.

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With few exceptions, research to date in cavity QED has considered strong coupling for only two atomic levels. This description is appropriate when the other atomic transitions are forbidden or highly detuned from the transition frequency of interest. However, recent work [1] has achieved a single-photon Rabi frequency comparable to the excited-state hyperfine splittings of Cs. Future resonators may allow a coupling which is far greater [2]. In this new regime, multiple allowed atomic transitions must be considered.

We first seek an intuitive understanding by considering the Hamiltonian,

$$H = \hbar\omega_3\sigma_3^\dagger\sigma_3 + \hbar\omega_4\sigma_4^\dagger\sigma_4 + \hbar\omega_5\sigma_5^\dagger\sigma_5 + \hbar\omega_c a^\dagger a + \hbar g_3(a^\dagger\sigma_3 + \sigma_3^\dagger a) + \hbar g_4(a^\dagger\sigma_4 + \sigma_4^\dagger a) + \hbar g_5(a^\dagger\sigma_5 + \sigma_5^\dagger a)$$

where ω_n is the free space resonance frequency for the atomic excitation to the F'=n excited state, ω_c is the resonance frequency of the cavity, σ_n is the atomic lowering operator for the F'=n excited state, a is the annihilation operator for the cavity mode, and $g_n = g_0 C_n \psi(\vec{r})$ is half the single-photon Rabi frequency for exchange of quanta between the cavity and the atom's F'=n excited state. Here, C_n is a polarization dependent factor, and ψ is the cavity-mode function, with $\psi = 1$ at the anti-nodes of the field. Although this Hamiltonian neglects magnetic sublevels of the atom and the orthogonal polarizations of the cavity field, it contains important features expected from a full treatment. In Fig. 1, we plot the eigenvalues of H for states with one quantum of excitation as a function of cavity detuning for various atom-cavity couplings up to g_0=130 MHz, the maximal coupling possible with the cavity in our laboratory. For such large couplings, the eigenstates of the Hamiltonian no longer resemble the familiar dressed states of the Jaynes-Cummings ladder, which are superpositions with one quantum shared between the cavity mode and a single atomic excited state. The eigenstates now have the quantum distributed across multiple atomic excited states as well as the cavity field, with corresponding modifications of the basic phenomenology of cavity QED.

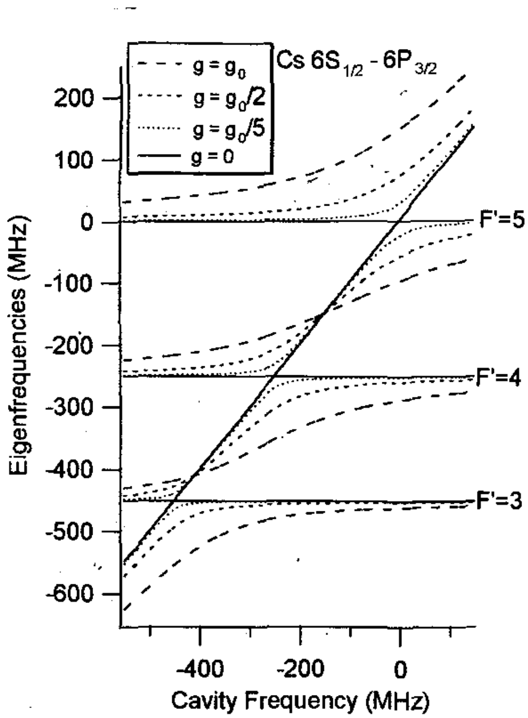

Fig. 1. Calculated eigenfrequencies for the Hamiltonian of the atom-cavity system for various coupling strengths. Here, we consider the $6S_{1/2}$, F=4 – $6P_{3/2}$, F'= 3, 4, 5 transitions in atomic Cesium with C_n given by the branching ratios of the respective excited states. All frequencies are measured relative to the F=4 to F'=5 transition frequency.

Experimental work in progress measures the structure of the transmission spectra of the coupled atom-cavity system in this new regime. A probe laser drives the cavity input, and heterodyne detection monitors the transmission as cold atoms fall through the cavity mode, for various detunings of the probe and cavity frequencies relative to the atomic transitions. By using circular input polarization, the familiar two-state atomic transition (F=4, m_F=4 – F'=5, m_F'=5) can be recovered, while by changing the ellipticity of the probe field, the relative couplings to various other excited states can be explored. Comparisons to a full theory based on the master equation for the damped, driven cavity coupled to an atom with hyperfine and magnetic sublevels and spontaneous emission will be discussed.

[1] C. J. Hood *et al.*, "The Atom-Cavity Microscope: Single Atoms Bound in Orbit by Single Photons," Science **287**, 1447-1453 (2000).

[2] Srinivasan et al., "Optical-fiber based measurement of an ultra-small volume high-Q photonic crystal microcavity," http://www.arxiv.org/abs/quant-ph/0309190