Cavity-protected Multifrequency Polaritons in a Cold Atomic System

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Frequency-homogeneous CQED

Collective Coupling
\[ \Omega = \sqrt{\sum_i g_i^2} \]

Upper Polariton
\[ N - 1 \text{ Dark States not coupled with light} \]

Lower Polariton
\[ \Omega \]

Frequency-excitation
\[ \left\langle \text{Polariton} \right\rangle = \pm \left\langle \text{Atomic excitation} \right\rangle \]

No "real" Dark States:
All eigenstates have a photonic weight \( PW_i \)
\[ = |\langle \psi_i | 1_{cav} ; 0_1, \ldots, 0_N \rangle|^2 \]

J. Dubail et al. arXiv 2105.08444 (2021)

Frequency-inhomogeneous CQED

Can we measure photonic weight distribution?

Frequency width \( \Delta \omega \)

Collective coupling \( \Omega \)

Interplay
Tunable inhomogeneous frequency in a cold atom CQED system

Fiber Fabry-Perot Cavity
Single atom
Cooperativity: $C \approx 60$

145 $\mu$m

10 to 800 $^{87}$Rb atoms:
Tunable collective coupling

$$\Omega = \sqrt{\sum_i g_i^2}$$

$^{87}$Rb levels
4D
1529 nm
5P$_{3/2}$

1560 nm

1560 nm

Trap trapping potential

$\approx 50 U_0$

$\Delta \omega$

frequency

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$\Delta \omega$

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1560 nm

Trapped atoms:
- $U_0 = 310 \mu$K
- $U_0 = 1400 \mu$K

Relative atom losses

Free atoms

Trapped atoms:
- $U_0 = 310 \mu$K
- $U_0 = 1400 \mu$K

Trap intensity
→ Tunable
distribution widths:
$\Delta \omega = 100s$ MHz → 1 GHz
Photonic weight distribution in a CQED spectral measurement

The coherence is preserved if the photonic excitation is carried by only two eigenstates: $S = 1 - (PW_{\text{max}1} + PW_{\text{max}2})$.

$S \to 0$: High coherence

Experimentally: cannot distinguish peaks because of photon shot-noise $\Rightarrow$ Fraction $F$ of photon counts far from peak:

$$F = 1 - \frac{\text{counts in}}{\text{counts total}}$$

$F \to 0$: High coherence
Cavity protection

Protection by the Cavity: \( \Omega \gg \Delta \omega \)

Coherent interaction despite large inhomogeneities if: \( \Omega \gg \Delta \omega \)

See also previous in solid state CQED:
S. Putz et al., Nat. Phys., 10(10) (2014)
Frequency modulated polaritons

Control of atomic qubit frequency

\[ \omega_a [I_{\text{trap}}(t)] = \omega_{a,0} + \beta \omega_m \cos(\omega_m t) \]

Spectral Shaping of Polaritons

D. M. Lukin et al., Quan. Inf. 6, 1 (2020)
I. Craiciu et al., Optica 8, 114 (2021)

Cavity-protected polaritons with multiple frequencies!