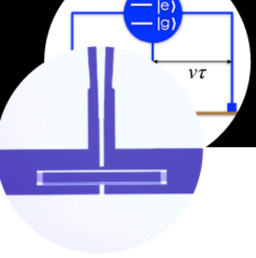


Non-Markovian quantum optics with giant artificial atom

MPL, Germany
Lingzhen Guo
Florian Marquardt

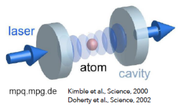
"Non-exponential decay of a giant artificial atom", Nature Physics 15, 1123 (2019)
G. Andersson, B. Suri, Lingzhen Guo, T. Aref, P. Delsing

"Oscillating bound states for a giant atom", arXiv:1911.13028 (2019)[accepted by Phy. Rev. Reseaerch]
Lingzhen Guo, A. F. Kockum, F. Marquardt, G. Johansson

From Small Atom to Giant Atom

Cavity QED

Atom + Lights



Atom size: $r \approx 10^{-10} m$

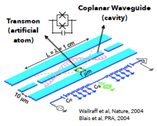
Wavelength: $\lambda \approx 10^{-7} - 10^{-6} m$

$\frac{\text{Atom}}{\text{Wave}} \approx 10^{-4} - 10^{-3}$

Atom is small, a point-like model.

Circuit QED

Transmon + Microwaves



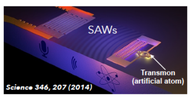
Atom size: $r \approx 10^{-5} - 10^{-3} m$

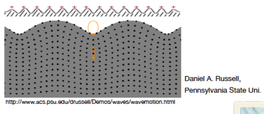
Wavelength: $\lambda \approx 10^{-3} - 10^{-1} m$

$\frac{\text{Atom}}{\text{Wave}} \approx 10^{-4} - 1$

Circuit QAD (Circuit Quantum AcoustoDynamics)

Transmon + Surface Acoustic Wave (SAWs)





Low sound speed: $v \approx 3000\ m/s$

Atom size: $r \approx 10^{-5} - 10^{-3} m$

Wavelength: $\lambda \approx 10^{-6} - 10^{-5} m$

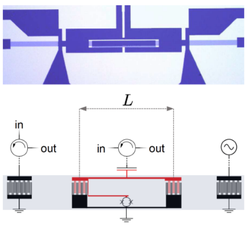
$\frac{\text{Atom}}{\text{Wave}} \approx 1 - 1000$

Giant !

Atom is giant, the point-like model is not valid!

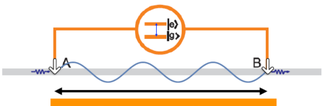
Non-exponential decay of a giant artificial atom

Experimental Setup



G. Andersson, B. Suri, **LG**, T. Aref, P. Delsing, Nature Physics **15**, 1123 (2019)

Theoretical Model

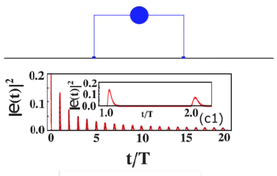


T = L/v : traveling time

Here, the time delay between the two legs, that is, the non-Markovian dynamics is crucial!

Theoretical Prediction

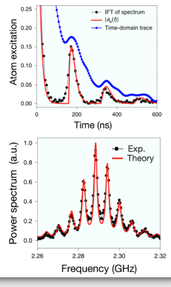
$\gamma T = 37.5,\ \Omega T = 2000\pi$



$$E_{T/P} \approx \frac{\hbar\Omega}{2\sqrt{\pi}} \left(\frac{t}{T}\right)^{-1/2}$$

L. Guo, *et al.*, PRA 95, 053821 (2017)

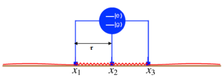
Experimental Results

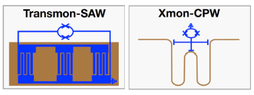


L. Guo, et al., Nat. Phy. 15, 1123 (2019)

Spontaneous emission for a multi-leg giant atom

Multi-leg Giant Atom





Dynamics of Atom's probability amplitude:

$$\frac{d}{dt}\beta(t) = -i\Omega\beta(t) - \frac{1}{2}N\gamma\beta(t) - \gamma\sum_{l=1}^{N-1}(N-l)\beta(t-l\tau)\Theta(t-l\tau)$$

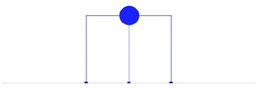
Collective relaxation (Markovian) | Correlated relaxation (Non-Markovian)

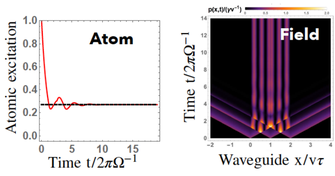
Field in the waveguide:

$$\varphi(x,t) = -i\sqrt{\frac{\gamma}{2v}}\sum_{m=1}^{N}\beta\left(t-\frac{|x-x_m|}{v}\right)\Theta\left(t-\frac{|x-x_m|}{v}\right)$$

LG, et al., arXiv:1911.13028 (2019) [Accepted by Physical Review Research]

$\gamma T/2\pi = 0.073,\ \Omega T/2\pi = 1.27$





Dark mode condition:

$$\Omega\tau = \frac{2n\pi}{N} - \frac{1}{2}N\gamma\tau\cot\left(\frac{n\pi}{N}\right), \quad n \in \mathbb{Z}.$$

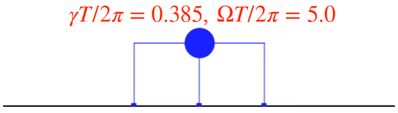
L. Guo et al, arXiv:1911.13028 (2019) [Accepted by PRR]

$$\beta(t) \to A(n)e^{-i\frac{\Omega_{\rm dm}}{N}t} \quad \text{with} \quad A(n) = \frac{2\sin^2(n\pi/N)}{2\sin^2(n\pi/N) + N\gamma\tau}.$$

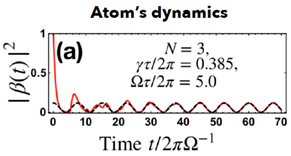
Bound states only exist in the non-Markovian regime $\gamma\tau \neq > 0$!

Oscillating bound states for a multi-leg giant atom

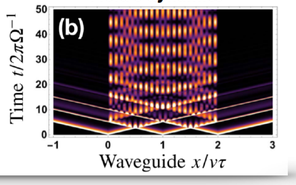
$\gamma T/2\pi = 0.385,\ \Omega T/2\pi = 5.0$



Atom's dynamics



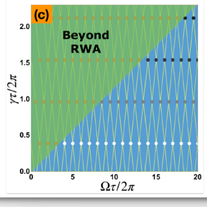
Field's dynamics

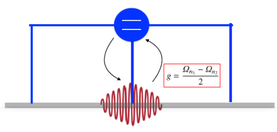


$$\begin{cases} \Omega\tau = \frac{2n_1\pi}{N} - \frac{2(n_1-n_2)\pi}{N}\frac{\cot\left(\frac{n_1\pi}{N}\right)}{\cot\left(\frac{n_1\pi}{N}\right)-\cot\left(\frac{n_2\pi}{N}\right)} > 0, \\ \gamma\tau = \frac{4(n_1-n_2)\pi}{N^2}\frac{1}{\cot\left(\frac{n_1\pi}{N}\right)-\cot\left(\frac{n_2\pi}{N}\right)} > 0. \end{cases}$$

Here, n_1 , n_2 are integers .

L. Guo et al, arXiv:1911.13028 (2019) [Accepted by PRR]





Oscillating bound states only exist for $N \geq 3$

Summary and Outlook

Summary

- **Giant atom**: single quantum system with deterministic time delay
- Theory and Experiment on **non-exponential decay** of two-leg giant atom
- **Discover** existence of *oscillating bound states* in continuous spectrum for a multi-leg giant atom

Outlook

- Beyond single-excitation approximation
- Multiple giant atoms
- Multi-dimensional bath
- Possible application for quantum information, e.g., photon tweezer