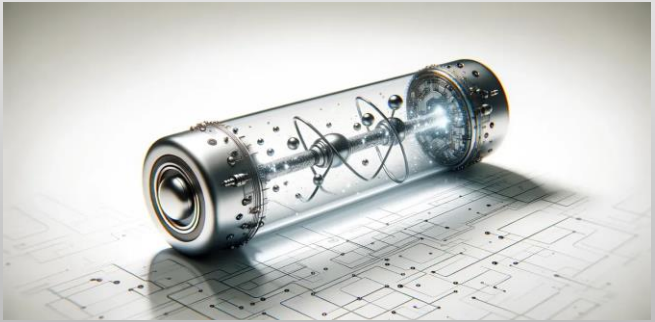
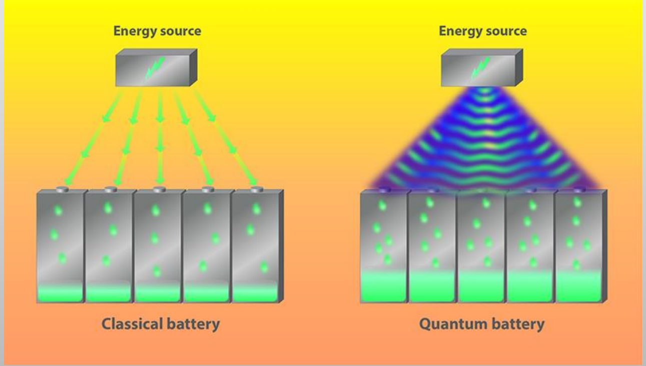
Dynamics of Quantum Battery:
Charging, Storing, Discharging and Degrading





2024 PHYS 596 **Group #7**

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Pirmoradian, F., & Mølmer, K. (2019). Aging of a quantum battery. *Physical Review A, 100*(4), 043833.

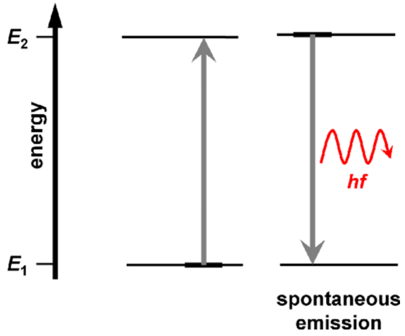
Quantum Batteries are energy storage systems

Quantum batteries are (typically) using two-level quantum systems, to achieve **storage** and **releasing** of radiative energy.

A collection of two-level systems, coupling to a single cavity mode.

By tuning the cavity frequency and/or damping rate, we can change the lifetime of the excited state of the emitters for charging, storage, and release of energy

which may coherently couple to other quantum systems.

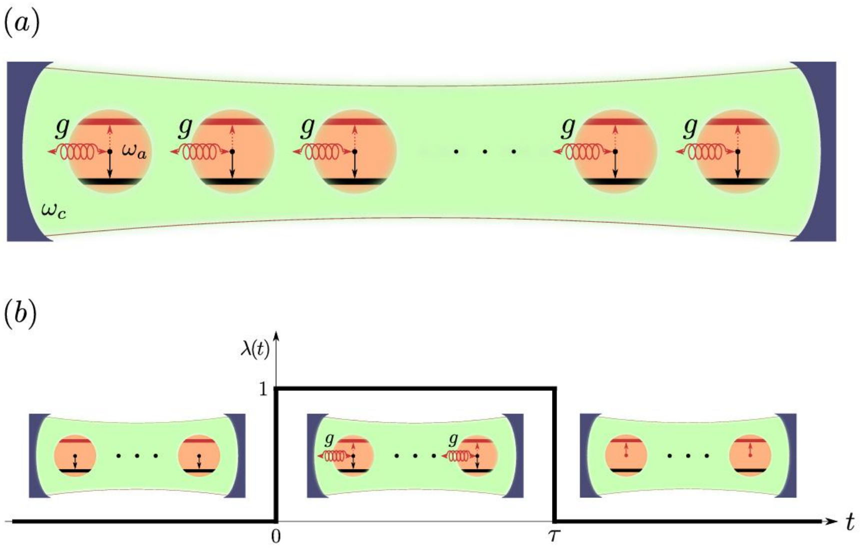


Purcell effect: the enhancement of a quantum system's spontaneous emission rate using a driven resonant cavity.

The decay via a cavity mode can be Purcell enhanced (by several orders of magnitude) compared to single emitter radiative decay in free space.

(much slower) process of individual decoherence and decay of the individual components of the battery.

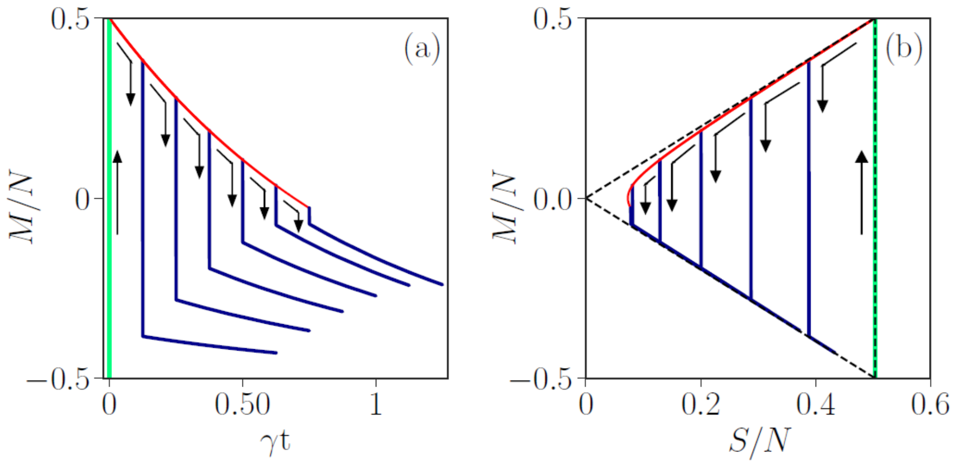
Comparison with Previous Works (Degrading of QB)



- Collective many-body system constitutes an attractive model for energy storage: Quantum Battery (QB) [1, 2]
- Spins can be used for charging, storage, and release of energy
- Individual decay of emitters degrades the battery just like household batteries.

1. Zhang, Yu-Yu, et al. "Powerful harmonic charging in a quantum battery." Physical Review E 99.5 (2019): 052106.
2. Zhang, Xiang, and Miriam Blaauboer. "Enhanced energy transfer in a Dicke quantum battery." Frontiers in Physics 10 (2023): 1097564.

Comparison with Previous Works (Discharging Dynamics)



Green: Rapid excitation (Charging)
Red: Slow individual decay (Storing)
Blue: Rapid collective deacy (Discharging)

- [1, 2] focused on charging of QB vs. this work explains storing (decaying) & discharging dynamics.
- N = # of emitters
- M = <S_z> (Stored energy)
- S = Collective spin quantum number

1. Zhang, Yu-Yu, et al. "Powerful harmonic charging in a quantum battery." Physical Review E 99.5 (2019): 052106.
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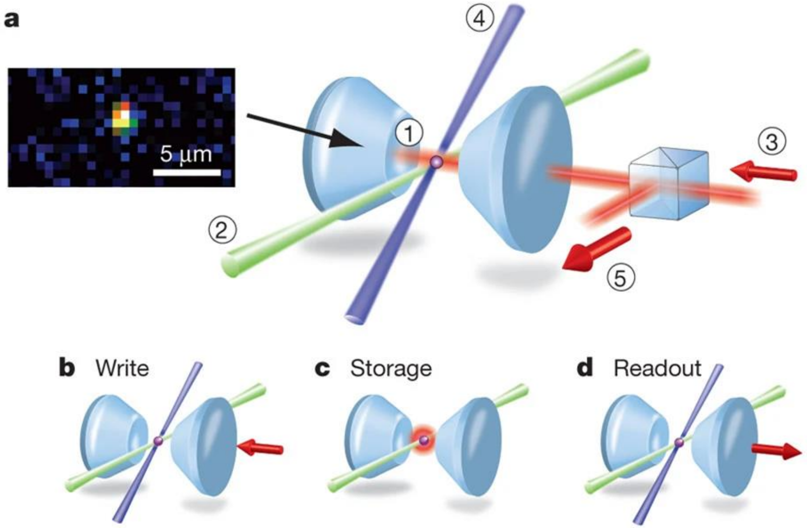
Similarity with Quantum Memories



- By allowing sufficient discharging, QB can be rejuvenated to their full capacity.
- This is similar to the resetting protocol of quantum memories [3, 4].
- Storing Information vs. Energy.

Quantum memories can write, store, and readout quantum information.

3. Wesenberg, Janus H., et al. "Quantum computing with an electron spin ensemble." Physical Review Letters 103.7 (2009): 070502.
4. Specht, H., Nölleke, C., Reiserer, A. et al. A single-atom quantum memory. Nature 473, 190–193 (2011).

QB Model: Do the parameters make sense?

Two modes:

- **Storage:** Energy decays at a rate of $1/\gamma$
- **Emission:** Energy emitted at rate $1/\Gamma$

$$\overset{\text{Time evolution}}{d\rho_S/dt} = \sum_{i=1}^{N} \overset{\text{Decay rate}}{\gamma}\mathcal{D}[\sigma_i^-]\rho_T + \overset{\text{Emission rate}}{\Gamma}\,\mathcal{D}[S^-]\rho_S$$

- Emission approximation: $\Gamma \gg \gamma$
  - Sensible since δ in denominator of Γ

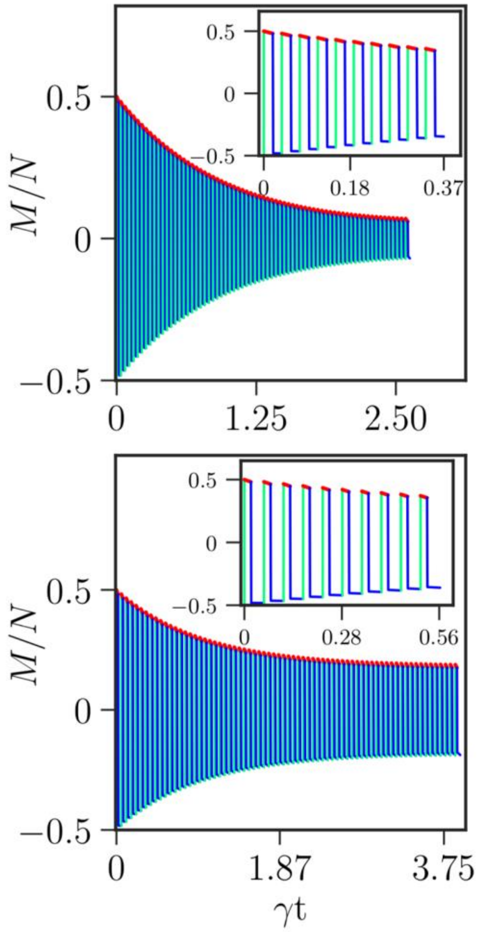
$$\Gamma = \kappa\frac{g^2}{\kappa^2/4+\underset{\omega(\text{Driving}) - \omega(\text{Resonant})}{\delta^2}}$$

- Storage assumption: $\Gamma = 0$
  - Claim Γ can be “turned off” by switching off cavity resonance far away - Not clear why this is a valid assumption
  - Practical battery also requires small γ (long storage time), unclear how freely this may be chosen

Conclusions

- Similar to conventional batteries, maximum storage of quantum batteries “ages” or “degrades”
  - **Individual decay** processes are the main driver
  - Limit cycle/capacity trajectory also depends on relative **storing and discharging durations**

- Dephasing effects could increase overall S and thus improve performance [5]



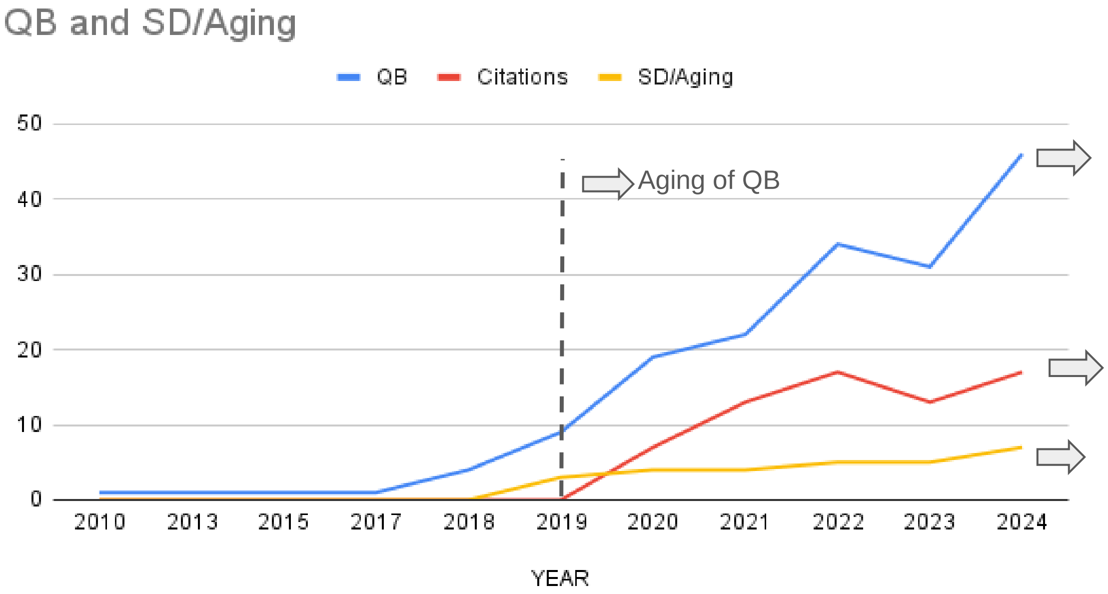
5. Y. Zhang, Y. Xiang Zhang, and K. Mølmer, New J. Phys. 20,112001 (2018).

Our Assessment

- Mechanisms are promising, but the magnitudes of values seem uncertain
    - “The decay via a cavity mode can be **Purcell enhanced** by several orders of magnitude compared to single emitter radiative decay in free space”
    - Shows relation of decay rate to other parameters, but without quantifying (horizontal scale γt)
- Use of **Dicke superradiance** for improved charging power (Dicke quantum batteries) more established [6, 7]
- Number of particles N must be very large to generate meaningful energy
- The relations between parameters have been studied but they are **potential limiting factors**

6. X. Zhang and M. Blaauboer. "Enhanced energy transfer in a Dicke quantum battery." Frontiers in Physics, arXiv:1812.10139v1
7. Zhang, Yu-Yu and Yang, Tian-Ran and Fu, Libin and Wang, Xiaoguang , Phys. Rev. E, 052106 (2019).

How has “Aging of a QB” Aged?



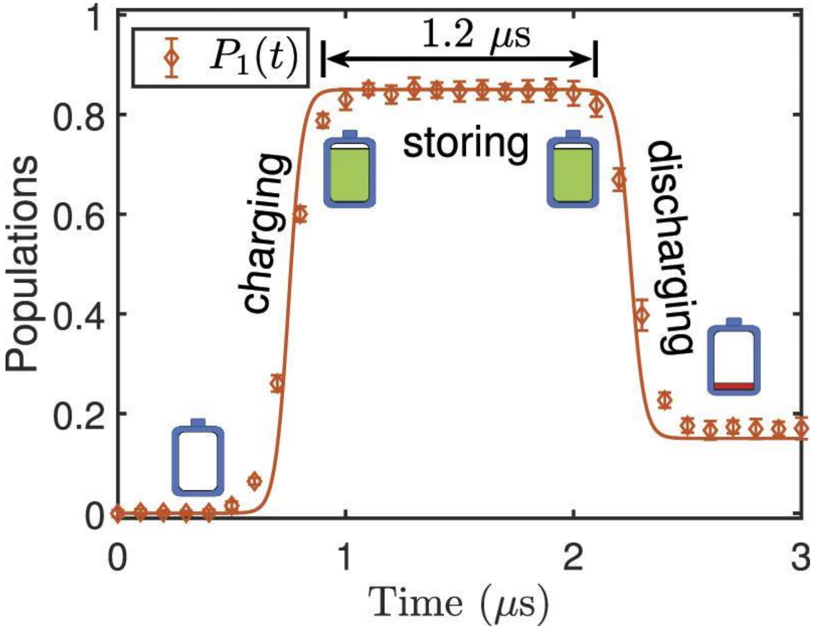
The field of QB has been growing steadily since 2010

“Aging of QB” has been cited 67 times since 2019

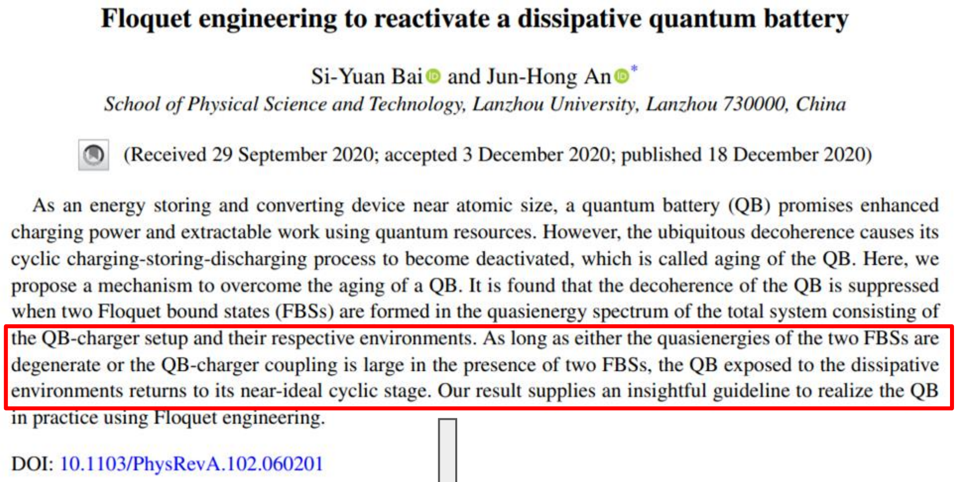
Since this paper, 28 articles have mentioned aging or self-discharge in QBs

A line chart depicting the growth of the field of Quantum Batteries (QB) (depicted in blue) per year, and the subfield of “aging” and “self-discharge” (depicted in yellow). The red line indicates the total number of citations of the paper per year. Data adapted from Scopus.

Developments in the QB literature



Experimental realization of a QB using a three-level open system using superconducting qutrit. Ri-Hua Zheng et al 2022 New J. Phys. 24 063031 https://doi.org/10.1088/1367-2630/ac788f



Floquet engineering to reactivate a dissipative quantum battery

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As an energy storing and converting device near atomic size, a quantum battery (QB) promises enhanced charging power and extractable work using quantum resources. However, the ubiquitous decoherence causes its cyclic charging-storing-discharging process to become deactivated, which is called aging of the QB. Here, we propose a mechanism to overcome the aging of a QB. It is found that the decoherence of the QB is suppressed when two Floquet bound states (FBSs) are formed in the quasienergy spectrum of the total system consisting of the QB-charger setup and their respective environments. As long as either the quasienergies of the two FBSs are degenerate or the QB-charger coupling is large in the presence of two FBSs, the QB exposed to the dissipative environments returns to its near-ideal cyclic stage. Our result supplies an insightful guideline to realize the QB in practice using Floquet engineering.

DOI: 10.1103/PhysRevA.102.060201

Future avenue: Build a QB that doesn’t age!

QUESTIONS?