Unlocking ultra-short time-scale many-body entanglement generation through atom-pair coupling to cavity photons

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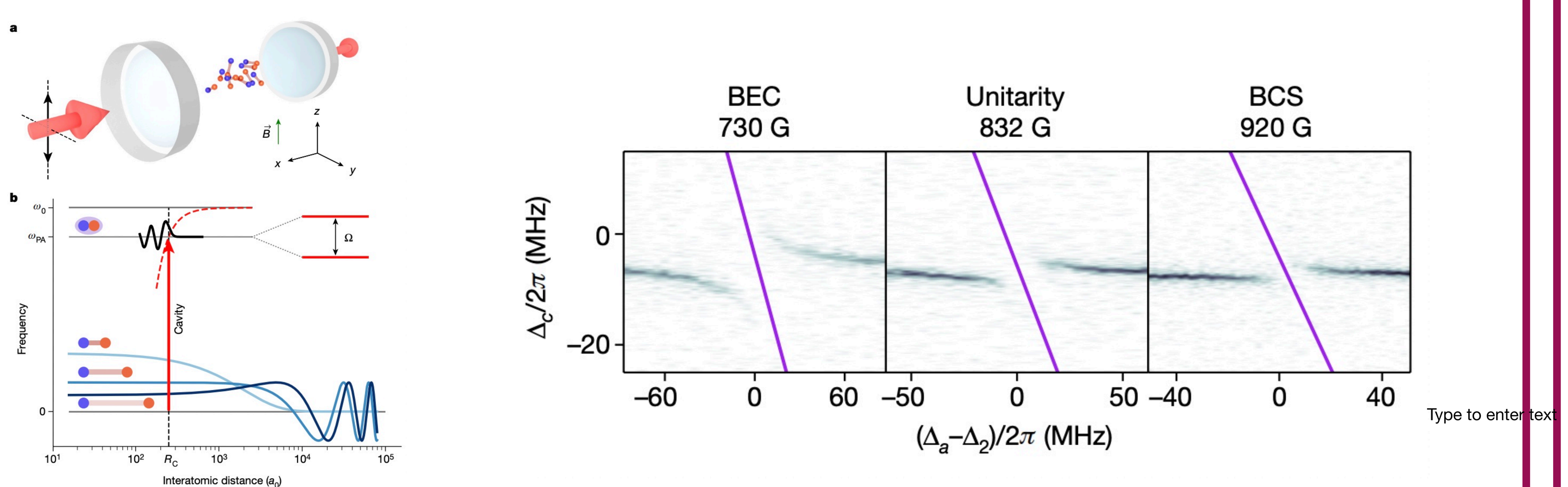
1. INTRODUCTION

- Hybrid light-matter systems: cavity photons + ultracold atomic gas.
- Photon-induced tuneable-range interaction potentials: novel states of matter.
- Atom-photon interactions lead to non-classical states of matter or light.
- Promising way for tuning interaction between atoms via photon exchange in cavity.
- Recently the formation of pair-polaritons was experimentally demonstrated [1].



Pair-Polaritons in a strongly interacting Fermi Gas

2. NOVEL APPROACH

- Atom-pair interaction with a single photon.
- Laser pumping: Cavity laser, frequency ω_L and amplitude η through one of its mirrors.
- Atomic states: Electronic ground and optically accessible molecular state ($E_\Delta = \hbar\omega_b$).
- Atomic confinement: Confined by a double-well potential, $V_{DW}(x)$, along x direction.
- Confinement is harmonic, frequency ω_H in the y-z plane.

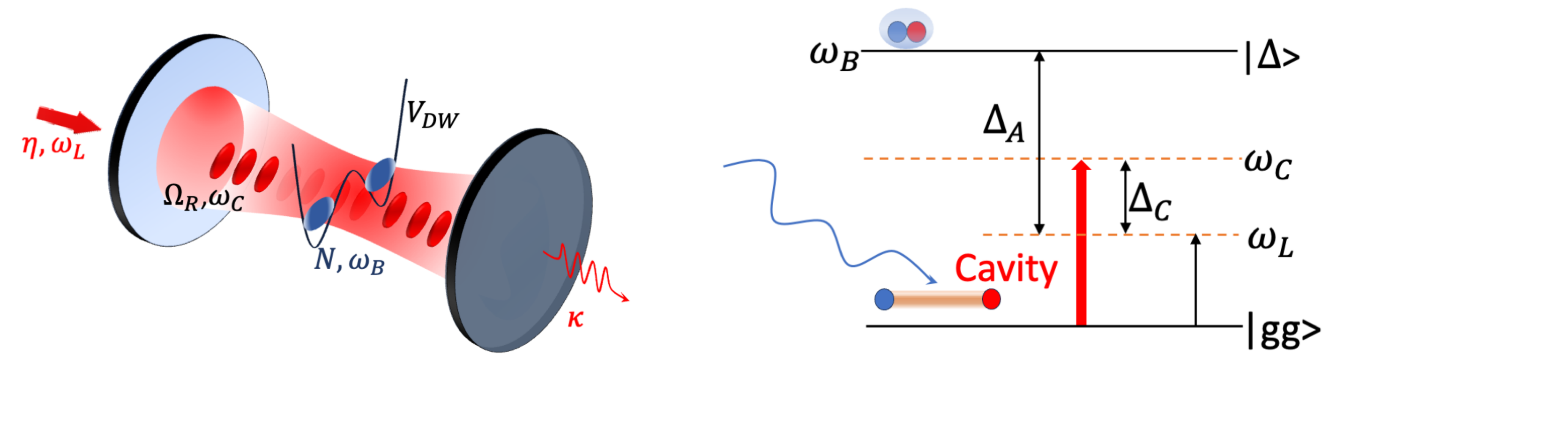


Illustration of the setup

3a. HAMILTONIAN &TWO MODE APPROXIMATION

The Hamiltonian for hybrid light-matter system is:

$$\hat{H} = \hat{H}_{atomic} + \hat{H}_{molecule} + \hat{H}_{photon} + \hat{H}_{atom-light}$$

$$\hat{H}_{atomic} = \int d^3r \Psi_g^\dagger(r)\left[\frac{\nabla^2}{2m} + V(r)\right]\Psi_g(r) + \frac{1}{2}\int d^3r\, g\, \Psi_g^\dagger(r)\Psi_g^\dagger(r)\Psi_g(r)\Psi_g(r)$$

$$\hat{H}_{molecule} = \int d^3r \Psi_\Delta^\dagger\left[\frac{-\nabla^2}{2M} + V(r) - \Delta_A\right]\Psi_\Delta$$

$$\hat{H}_{photon} = -\Delta_c a^\dagger a + \eta\left(a^\dagger + a\right)$$

$$\hat{H}_{atom-light} = -i\Omega_R\int d^3r f(r)\left[a\Psi_\Delta^\dagger(r)\Psi_g^2(r) - a^\dagger\left(\Psi_g^2(r)\right)^\dagger\Psi_\Delta(r)\right]$$

For large atom detuning, we can adiabatically eliminate the molecular state.

Using two mode approximation: $\hat{H}_{\text{eff}} \approx \hat{H}_L + \hat{H}_J + \hat{H}_{JL}$

$$\hat{H}_{eff} = -\tilde{\Delta}_C a^\dagger a + \eta\left(a^\dagger + a\right) - 2J\hat{J}_x + U\hat{J}_z^2 + 2W_0 a^\dagger a \hat{J}_z^2$$

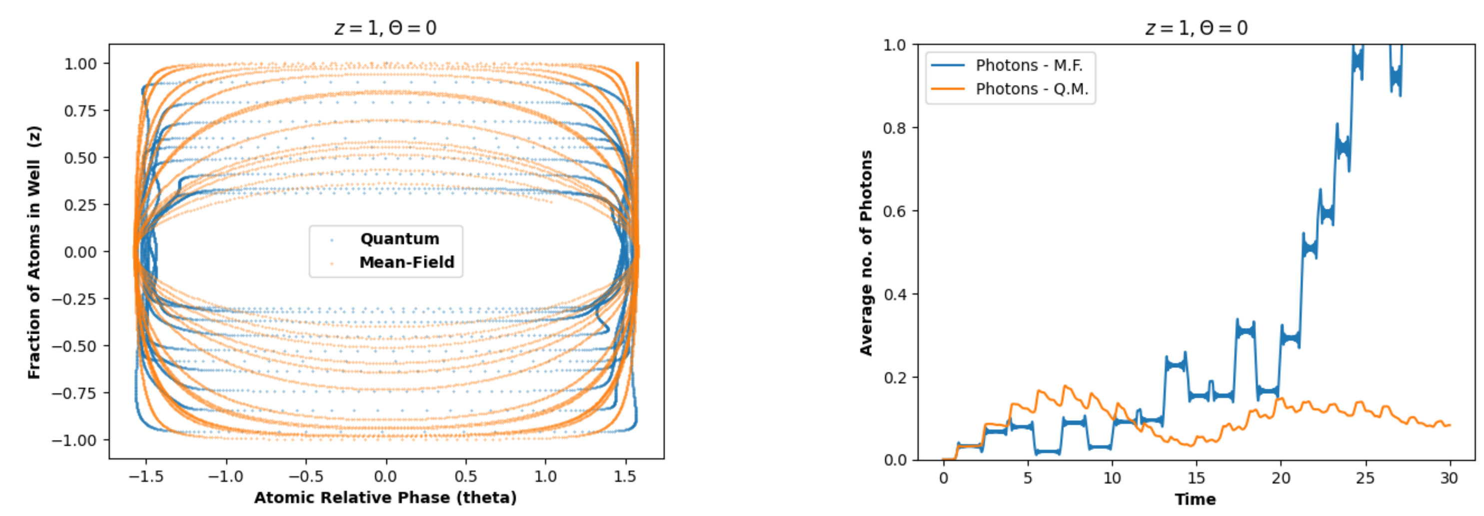
Atom-atom interaction depends on *quantum state* of cavity photons

3b. SYMBOLS USED

- ϵ = Single-well energy
- g = Atom-Atom interaction
- J = Tunneling Energy
- U = On-site Interaction strength
- W_0 = Pair-light Interaction
- Δ_A, Δ_C = detuning from: molecular state, cavity photon
- Ω_R = Single mode Rabi frequency

4. MEAN-FIELD vs EXACT DIAGONALIZATION

We can approximate the system in the full coherent state:
$|FCS\rangle = |\beta_1\rangle_A \otimes |\beta_2\rangle_A \otimes |\alpha\rangle_L$



Comparison of quantum and classical trajectories.
Divergence between the two at shorter times* → *buildup of correlations

5. QUANTUM CORRELATIONS

1. Atoms: Spin-squeezing

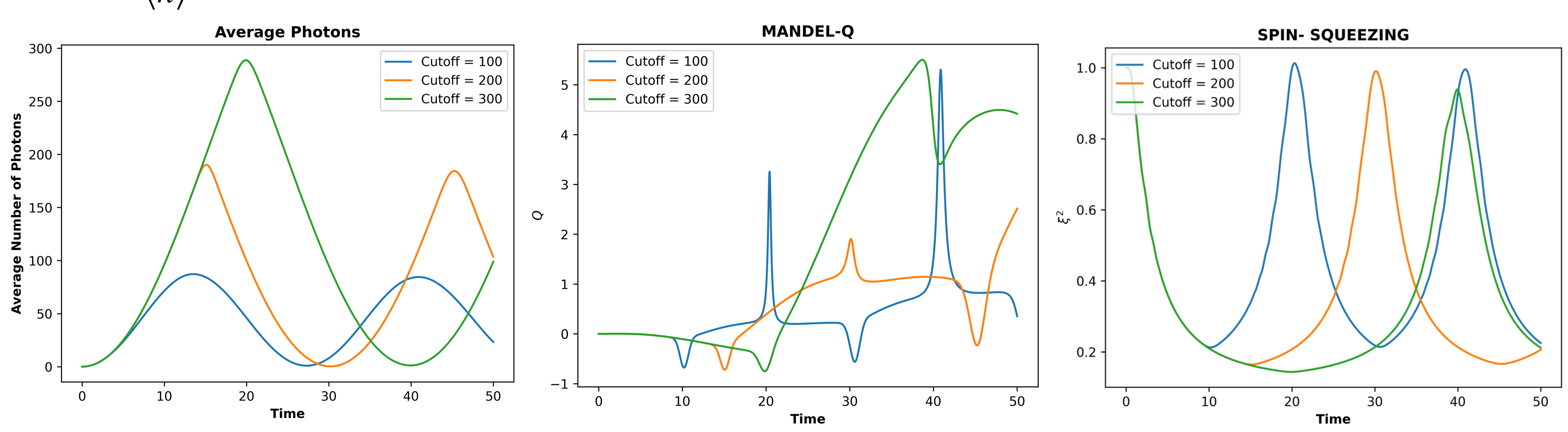
$$\xi^2 = N\frac{\Delta\hat{J}_z^2}{\langle\hat{J}_x\rangle^2 + \langle\hat{J}_y\rangle^2}$$

, N = total number of atoms. $\xi^2 < 1$ → entanglement between the atoms

2. Photons : Mandel-Q parameter

$$Q = \frac{\langle(\Delta\hat{n})^2\rangle - \langle\hat{n}\rangle}{\langle\hat{n}\rangle}$$

$\hat{n}$ = number operator. $-1 \leqslant Q < 0$ → non-classical light



***Non-classical* light and *entanglement* between atoms**

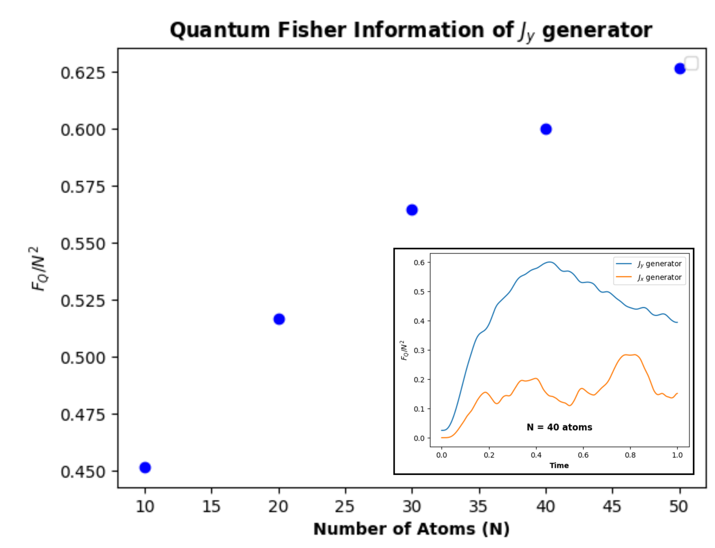
3. Quantum Fisher information

$$F_q = 2\sum_{i,j}\frac{\left(\lambda_i - \lambda_j\right)^2}{\lambda_i + \lambda_j}|\langle\psi_i|\hat{h}|\psi_j\rangle|^2$$

$\hat{h}$ is the interferometric generator.

$\lambda's$ and $|\psi\rangle's$ comes from the spectral decomposition of the density matrix

$$\hat{\rho} = \sum_i \lambda_i|\Psi_i\rangle\langle\Psi_i|$$



Superlinear scaling of quantum Fisher information for J=0

6. CONCLUSIONS

- Photon-atom-pair interaction → effective atom-atom interaction.
- Dependence on quantum state of cavity photons.
- Non-classical correlations of photons.
- Strong entanglement between atoms.
- Controlled by: detuning, pump, initial photonic state.

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8. REFERENCES

1. Konishi, H., Roux, K., Helson, V. *et al.* Universal pair polaritons in a strongly interacting Fermi gas. *Nature* **596**, 509–513 (2021). https://doi.org/10.1038/s41586-021-03731-9
2. 2. G. Szirmai, G. Mazzarella, and L. Salasnich Phys. Rev. A **91**, 023601

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