Interference and dynamics of light from a distance-controlled atom pair in an optical cavity

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About the paper

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Interference and dynamics of light from a distance-controlled atom pair in an optical cavity

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Interference is central to quantum physics and occurs when indistinguishable paths exist, as in a double-slit experiment. Replacing the two slits with single atoms[1] introduces optical nonlinearities for which non-trivial interference phenomena are predicted[2, 3, 4, 5, 6]. Their observation, however, has been hampered by difficulties in preparing the required atomic distribution, controlling the optical phases and detecting the faint light. Here we overcome all of these experimental challenges by combining an optical lattice for atom localization, an imaging system with single-site resolution and an optical resonator for light steering. We observe resonator-induced saturation of resonance fluorescence[7, 8] for constructive interference and non-zero emission with huge photon bunching for destructive interference. The latter is explained by atomic saturation and photon-pair generation, similar to predictions for free-space atoms[3, 4, 5, 9]. Our experimental setting allows realization of the Tavis–Cummings model[10] for any number of atoms and photons, exploration of fundamental aspects of light–matter interaction[11, 12, 13, 14, 15] and implementation of new quantum information processing protocols[16, 17, 18, 19].

Who is the author?

Gerhard Rempe

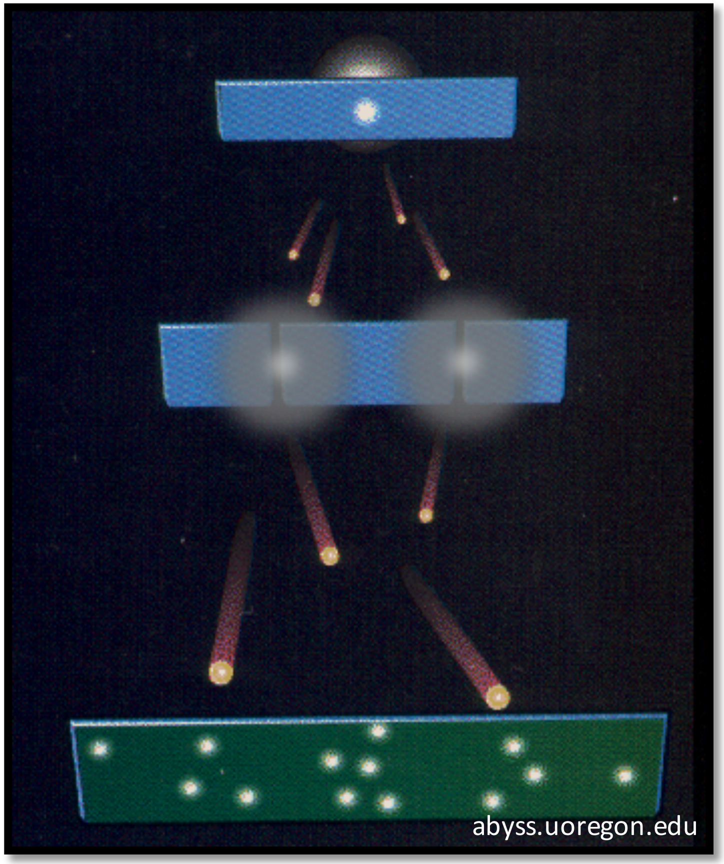
Stephan Ritter

Who is the author?

Gerhard Rempe

- Study of Physics and Mathematics
  at the Universities of Essen and Munich (1976-1982)
- Doctorate at the Ludwig-Maximilians-Universität
  Munich (1986)
- Habilitation at the Ludwig-Maximilians-Universität
  Munich (1990)
- Robert Andrews Millikan Fellow,
  California Institute of Technology, Pasadena, USA (1990-1992)
- Professor of Physics at the University of Konstanz (1992-1999)
- Director and Scientific Member at the Max-Planck-Institut
  of Quantum Optics and Professor at the Technical University
  of Munich (since 1999)

Introduction



Introduction

To observation..

- Preparing the required atomic distribution
- Controlling the optical phases
- Detecting the faint light

This experiment

- Optical lattice (for atom localization)
- Imaging system w/ single-site resolution
- Optical resonator (for light steering)

Introduction

- Tavis-Cummings model
- Fundamental aspects of light-matter interaction
- New quantum information processing protocols

Background history

Non-classical radiation effect

Free space

Optical resonator

Single emitter

Multiple emitter

RELATIVE OPTICAL PHASES

Subwavelength localization

Relative position

Background history

PRL 114, 023601 (2015) PHYSICAL REVIEW LETTERS week ending 16 JANUARY 2015

Cavity-Modified Collective Rayleigh Scattering of Two Atoms

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(Received 26 August 2014; published 14 January 2015)

We report on the observation of cooperative radiation of exactly two neutral atoms strongly coupled to the single mode field of an optical cavity, which is close to the lossless-cavity limit. Monitoring the cavity output power, we observe constructive and destructive interference of collective Rayleigh scattering for certain relative di
output power for t
which is in contr
quantitatively exp
states. We extract
advanced cooling
Thereby we imp
entanglement sch

DOI: 10.1103/Phys

PRL 114, 023602 (2015) PHYSICAL REVIEW LETTERS week ending 16 JANUARY 2015

Enhanced Quantum Interface with Collective Ion-Cavity Coupling

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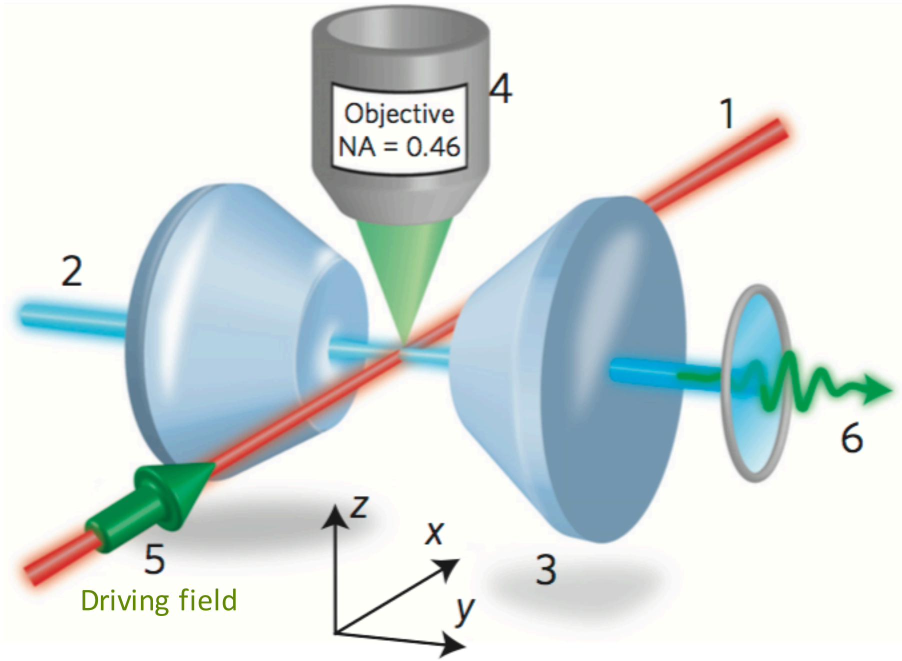
(Received 26 August 2014; published 14 January 2015)

We prepare a maximally entangled state of two ions and couple both ions to the mode of an optical cavity. The phase of the entangled state determines the collective interaction of the ions with the cavity mode, that is, whether the emission of a single photon into the cavity is suppressed or enhanced. By adjusting this phase, we tune the ion-cavity system from sub- to superradiance. We then encode a single qubit in the two-ion superradiant state and show that this encoding enhances the transfer of quantum information onto a photon.

DOI: 10.1103/PhysRevLett.114.023602 PACS numbers: 42.50.Nn, 42.50.Dv, 42.50.Pq

Experimental set-up

Atom pair(^{87}Rb) coupled permanently (~10s)



2D optical lattice

$$\frac{\lambda_{trap,x}}{2} = 532nm \qquad \frac{\lambda_{trap,y}}{2} = 386nm$$

Image of an atom pair

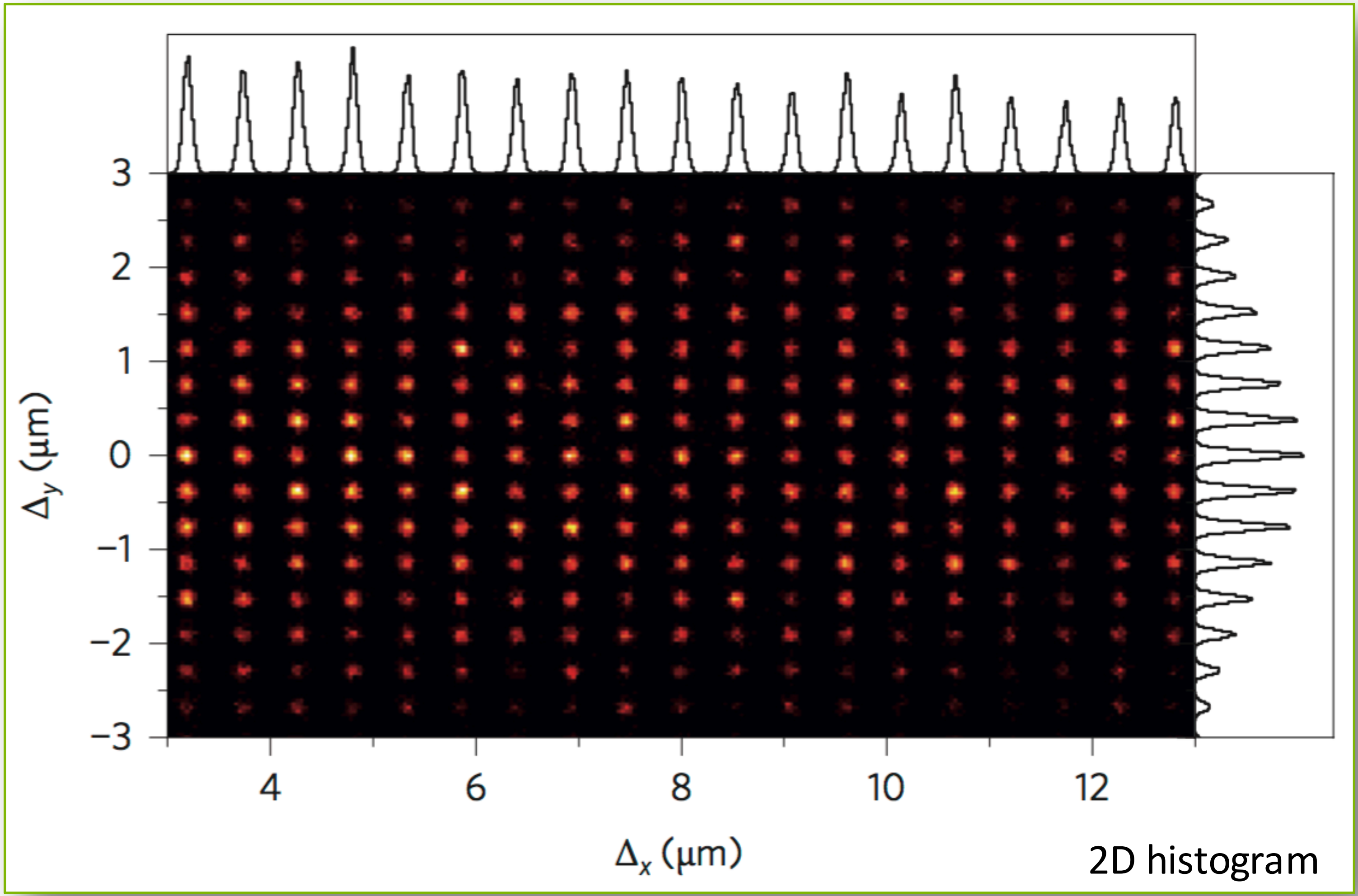


Image of an atom pair

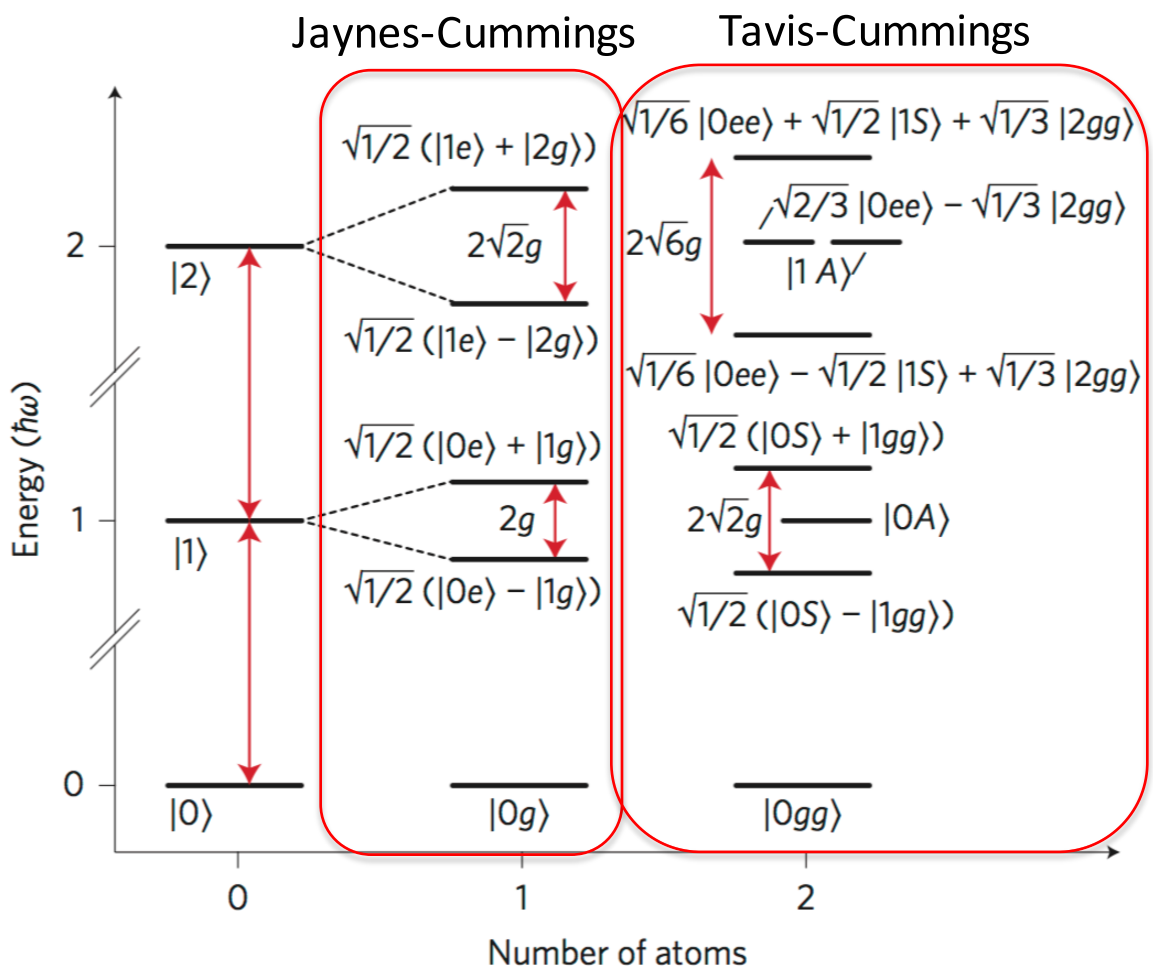
Difference phase are ***discrete*** due to the presence of the ***optical lattice***

$$\phi = \Delta n_x \frac{\lambda_{trap,x}}{\lambda_{atom}}\pi + \left(n_{y_1} - n_{y_2}\right)\pi$$

for $\left|n_{y_1}\right|, \left|n_{y_2}\right| < \frac{\lambda_{atom}}{2\left(\lambda_{atom} - \lambda_{trap,y}\right)}$

This is the region where the optical lattice field(772nm) and cavity mode field(780nm) gets less difference so that the phase difference along the y-axis can be evaluated as 0 or π. And the experiment is done in that region.

Energy spectrum of the atom-cavity system



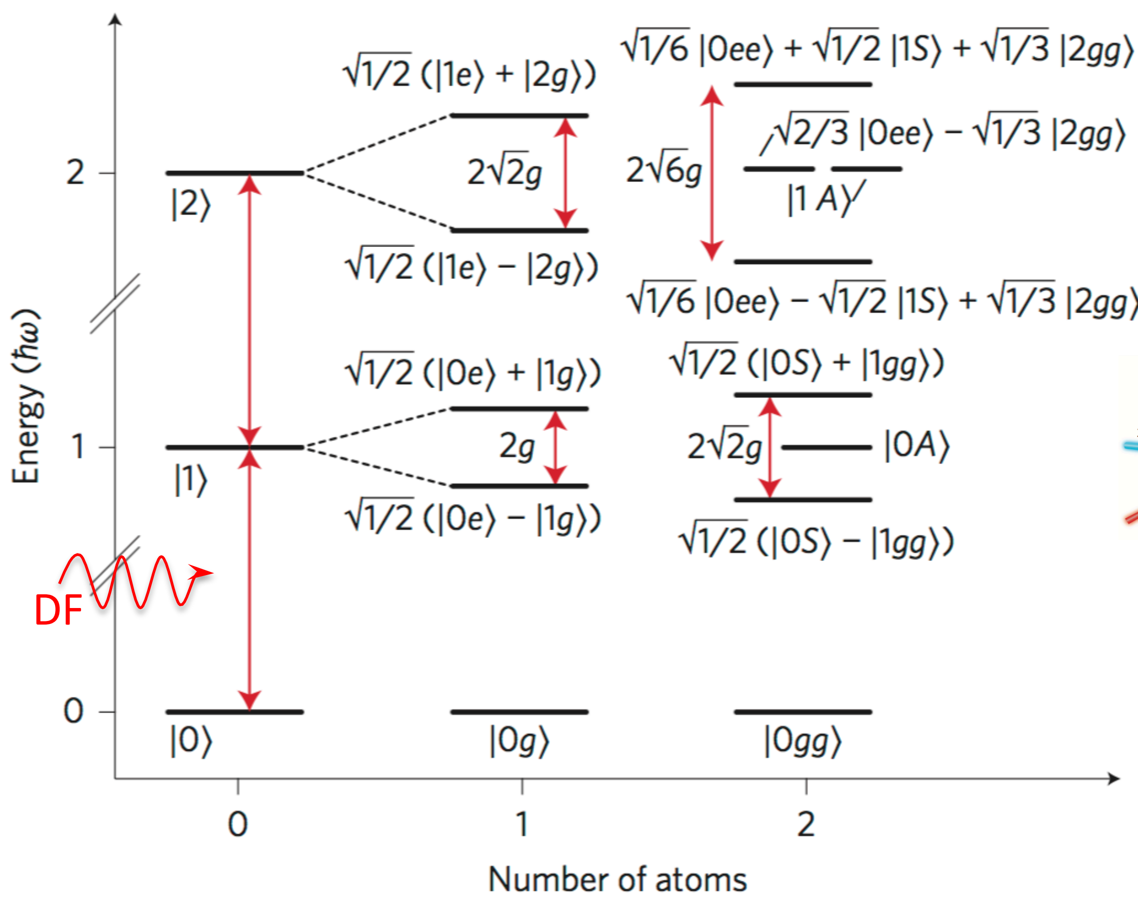
$$|S\rangle = \left(|eg\rangle + |ge\rangle\right)/\sqrt{2}$$

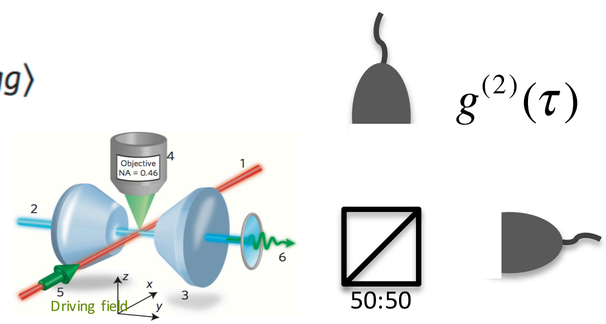
$$|A\rangle = \left(|eg\rangle - |ge\rangle\right)/\sqrt{2}$$

$$|e\rangle = |5P_{3/2}, F=3, m_F=3\rangle$$

$$|g\rangle = |5S_{1/2}, F=2, m_F=2\rangle$$

Energy spectrum of the atom-cavity system





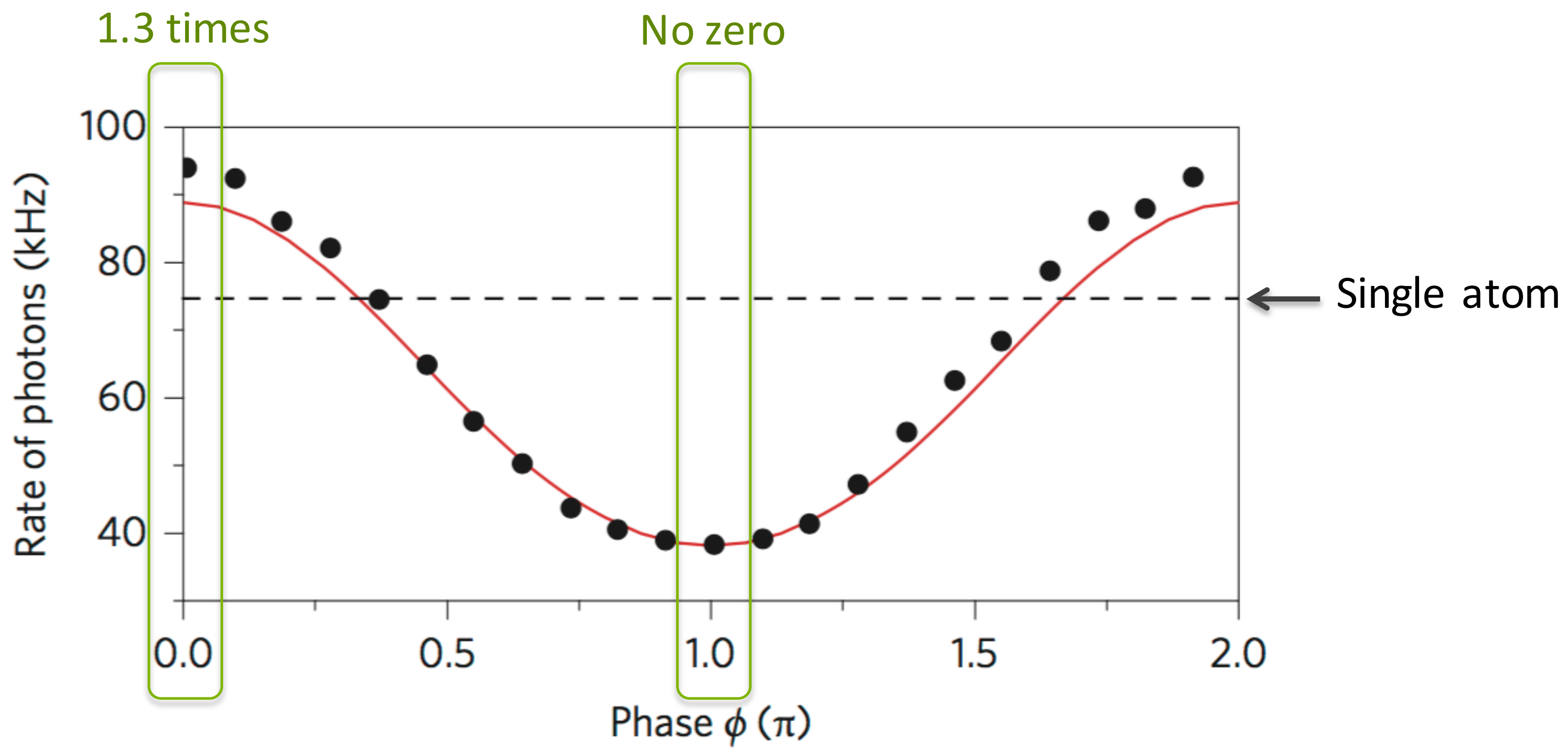
$$|S\rangle = (|eg\rangle + |ge\rangle)/\sqrt{2}$$

$$|A\rangle = (|eg\rangle - |ge\rangle)/\sqrt{2}$$

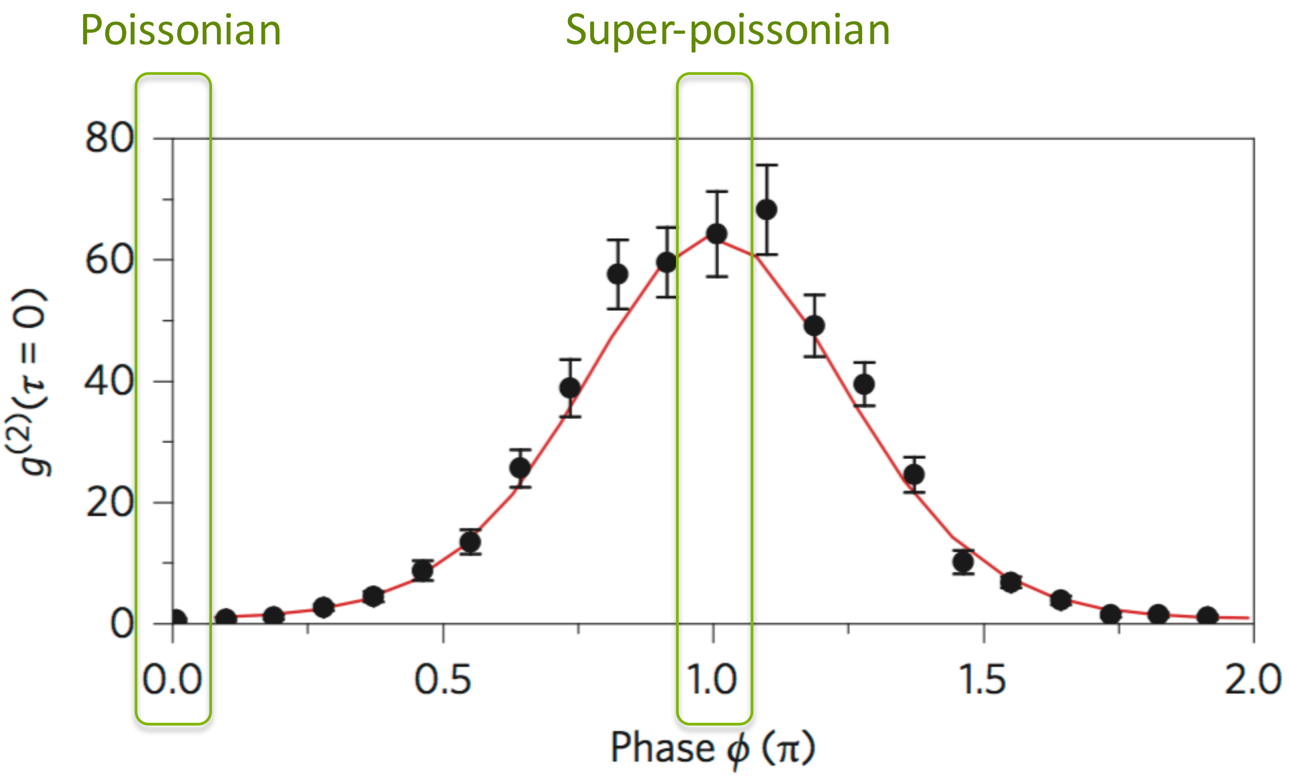
$$|e\rangle = |5P_{3/2}, F=3, m_F=3\rangle$$

$$|g\rangle = |5S_{1/2}, F=2, m_F=2\rangle$$

Photon emission rate



$g^{(2)}(0)$


Poissonian
Super-poissonian
80
60
40
20
0
0.0
0.5
1.0
1.5
2.0
$g^{(2)}(\tau = 0)$
Phase ϕ (π)

IN-phase

PHYSICAL REVIEW A VOLUME 45, NUMBER 3 1 FEBRUARY 1992

Suppression of fluorescence in a lossless cavity

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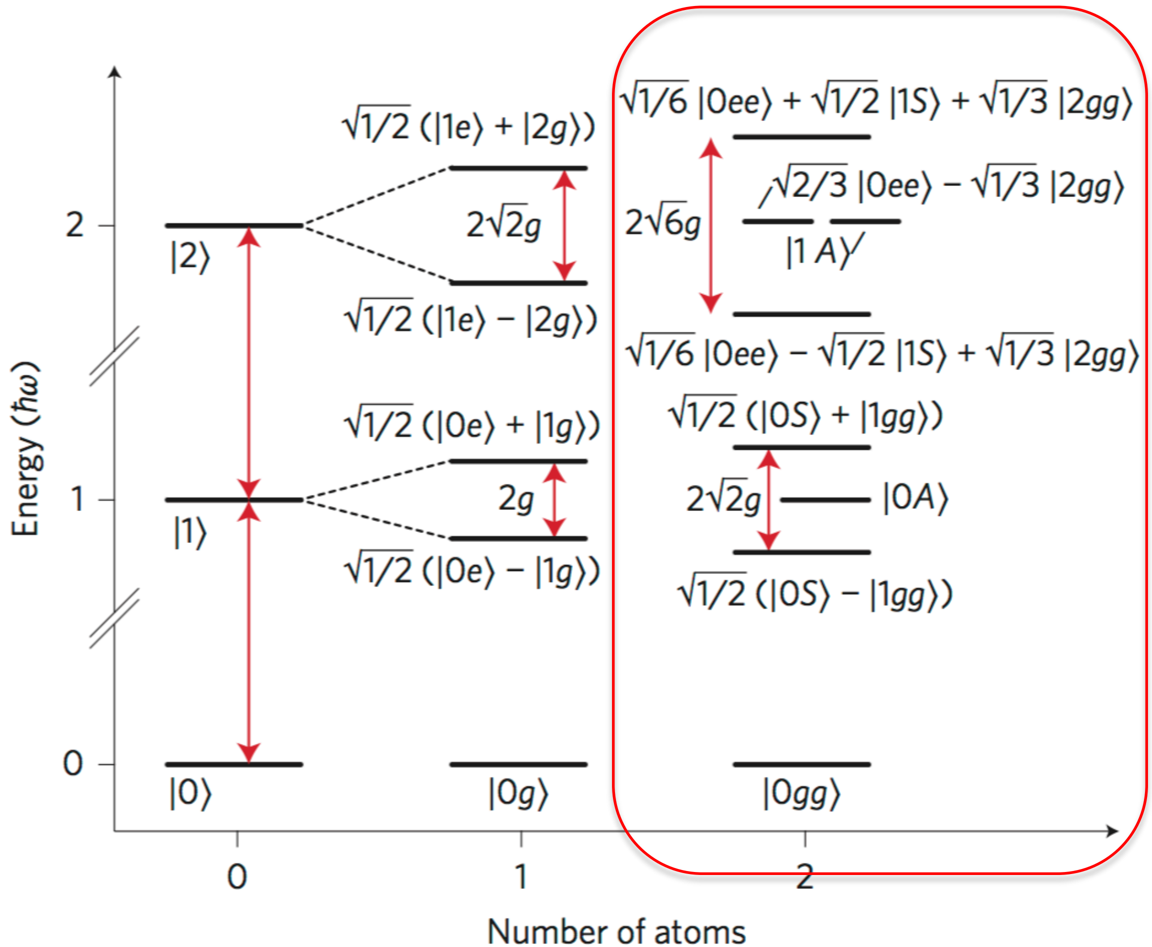
In this paper we theoretically investigate the behavior of a two-level atom in a lossless cavity driven by an external field. Using classical electrodynamics to describe the external field while quantizing the cavity field, we find that the cavity field is excited to a coherent state whose amplitude is equal to that of the external field, but shifted 180° in phase. This results in the disappearance of the atomic resonance fluorescence (i.e., the atom stops interacting with the fields). When we quantize the external field the effect persists. A fully quantized dressed-state approach provides some helpful insight and a nice analogy to another problem in which the resonance fluorescence vanishes.

PACS number(s): 42.50.−p

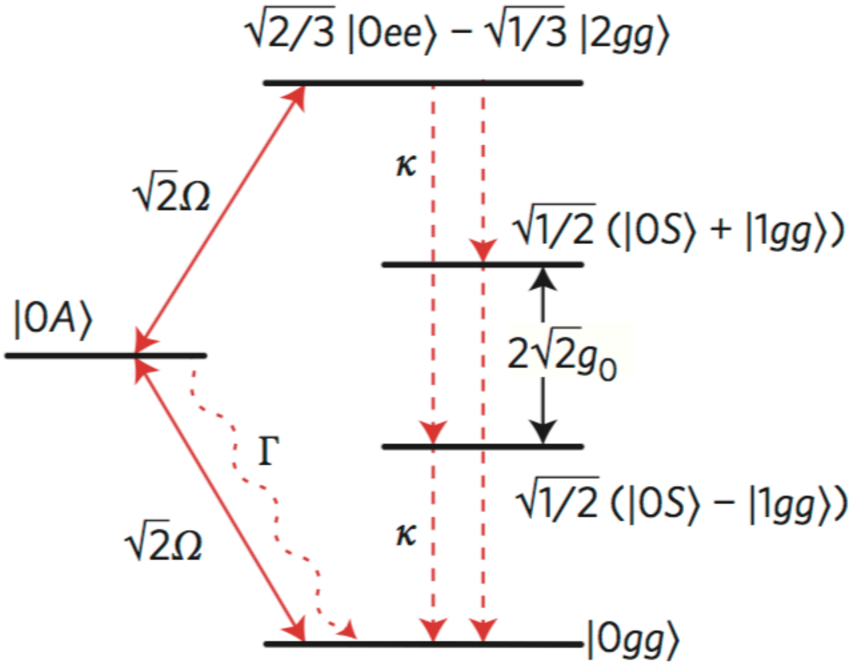
The intracavity power is ***independent*** of the number of atoms!!

OUT-of-phase

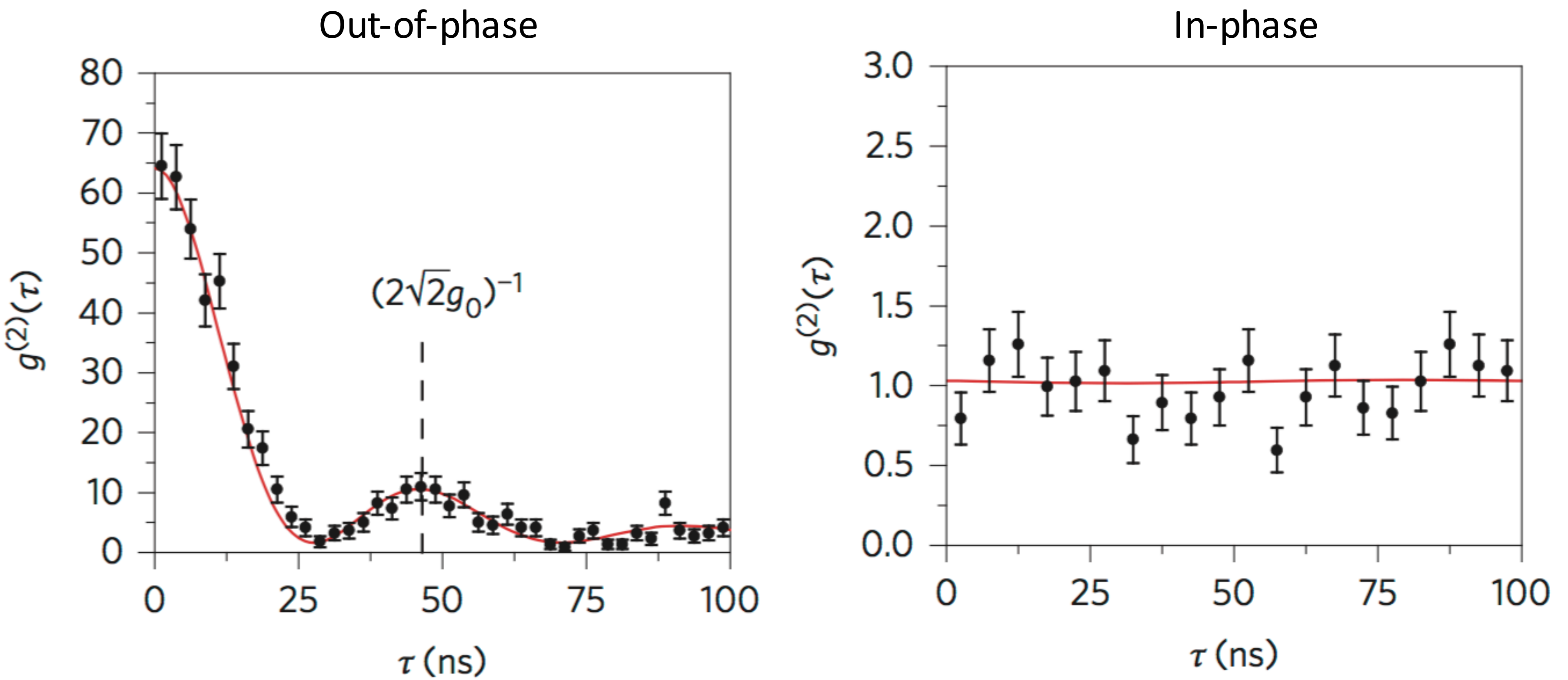


Energy ($\hbar\omega$)
2
1
0
|2⟩
|1⟩
|0⟩
√1/2 (|1e⟩ + |2g⟩)
2√2g
√1/2 (|1e⟩ − |2g⟩)
√1/2 (|0e⟩ + |1g⟩)
2g
√1/2 (|0e⟩ − |1g⟩)
|0g⟩
√1/6 |0ee⟩ + √1/2 |1S⟩ + √1/3 |2gg⟩
2√6g
√2/3 |0ee⟩ − √1/3 |2gg⟩
|1 A⟩
√1/6 |0ee⟩ − √1/2 |1S⟩ + √1/3 |2gg⟩
√1/2 (|0S⟩ + |1gg⟩)
2√2g
|0A⟩
√1/2 (|0S⟩ − |1gg⟩)
|0gg⟩
0
1
2
Number of atoms

Emission dynamics



Emission dynamics



expecting

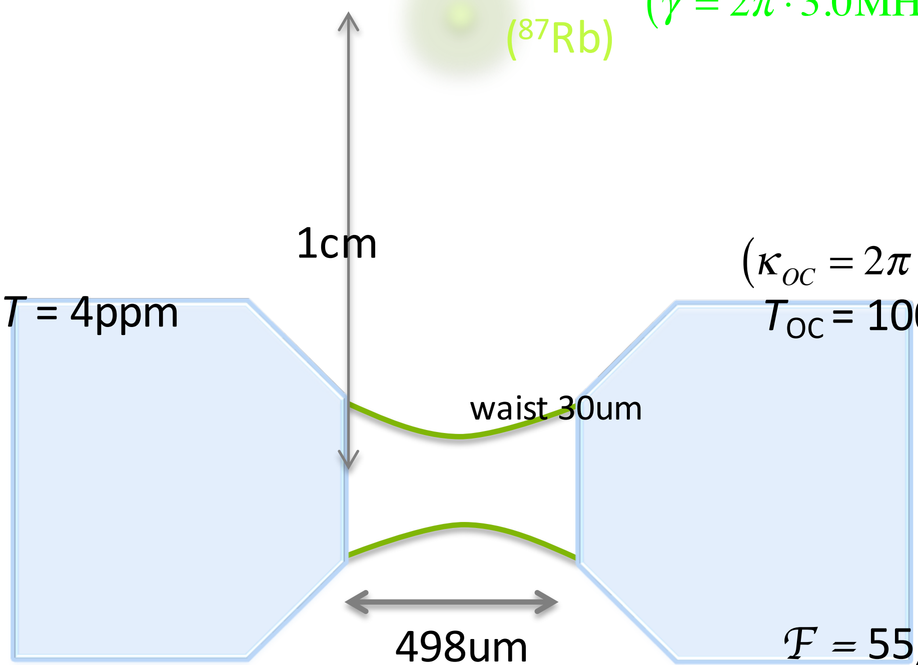
- Using this experimental technique
  - Explore the collective radiation effects predicted for multi-atom system
  - Implement novel entanglement
  - Quantum information processing schemes with several qubits

SUPPLEMENTARY

Apparatus

$$C = \frac{g^2}{2\kappa\gamma} = 3.7$$

$$(\gamma = 2\pi \cdot 3.0\text{MHz})$$

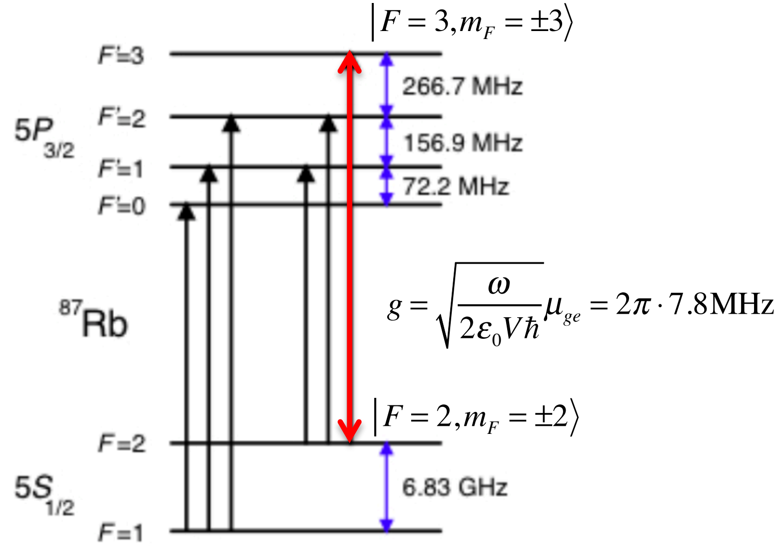


$$(\kappa_{OC} = 2\pi \cdot 2.4\text{MHz})$$

T_{OC} = 100ppm

$\mathcal{F} = 55{,}000$

$$(\kappa = 2\pi \cdot 2.8\text{MHz})$$



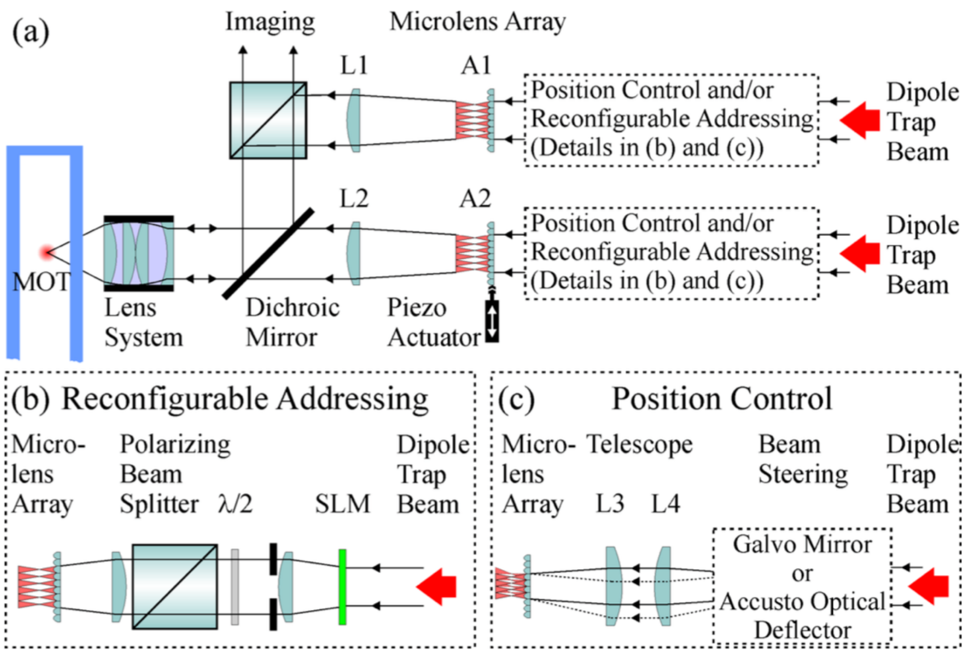


FIG. 2. (color online). Schematic view of the experimental setup. (a) The microlens arrays A1 and A2 are illuminated by two trapping laser beams. The resulting spot patterns are combined at a dichroic mirror and re-imaged into the vacuum chamber. The incident dipole trap beams can be position-controlled and site-selectively addressed. (b) A spatial light modulator (SLM) is used to control the light power addressing each microlens. (c) A galvo mirror or an acousto-optical beam deflector can be used to control the incident angle of the trapping laser beam on the microlens array A1 and/or A2 and therefore the position of the microtraps in the focal plane. Position control can be implemented through a piezo actuator in addition (shown for A2 in (a)).

PHYSICAL REVIEW A **85**, 023801 (2012)

Quantum statistics of the collective excitations of an atomic ensemble inside a cavity

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We study the quantum statistical properties of the collective excitations of an atomic ensemble inside a high-finesse cavity. In the large-detuning regime, it is found that the virtual photon exchange can induce a long-range interaction between atoms, which results in correlated excitations. In particular, the atomic blockade phenomenon occurs when the induced long-range interaction effectively suppresses the double atomic excitation, when the average photon number takes certain values, which makes the two nearest energy levels degenerate. We also show that quantum phase transitions occur in the indirectly interacting atomic ensemble when the average photon number reaches several critical points. In this sense, the quantum statistical properties of the collective excitations are very sensitive to the change of the average photon number. Our model exhibits quantum phase transitions similar to the ones in the Lipkin-Meshkov-Glick model. Our proposal could be implemented in a variety of systems including cavity quantum electrodynamics (QED), Bose-Einstein condensates, and circuit QED.

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