原子集団のディッケ状態とその応用

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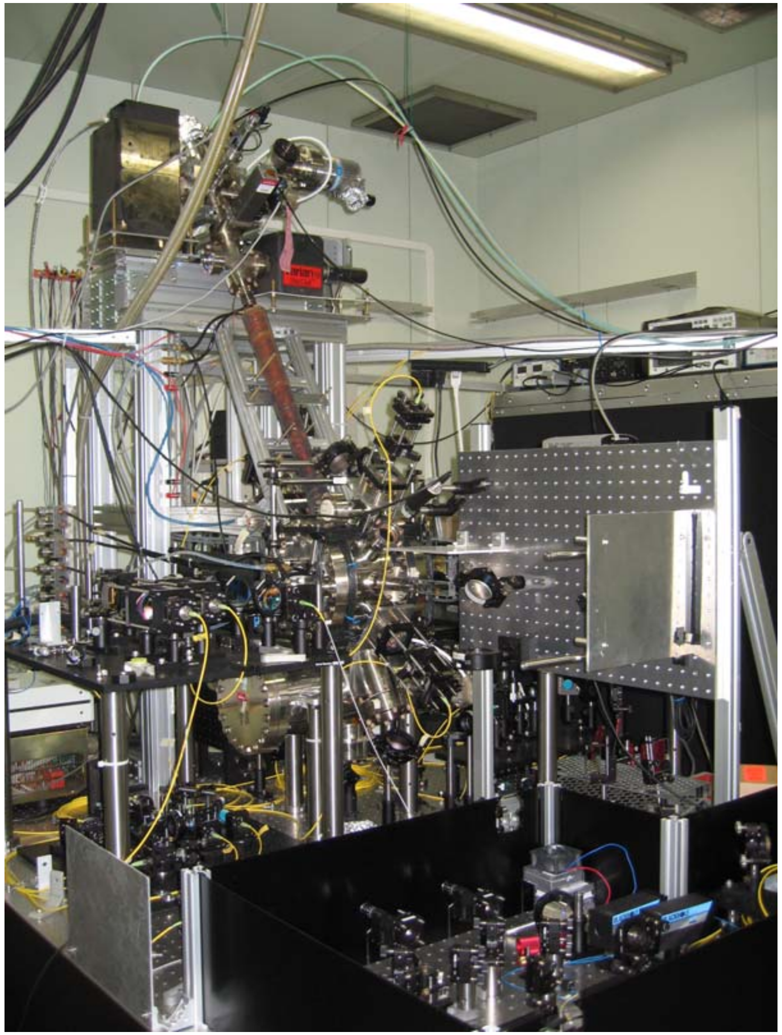
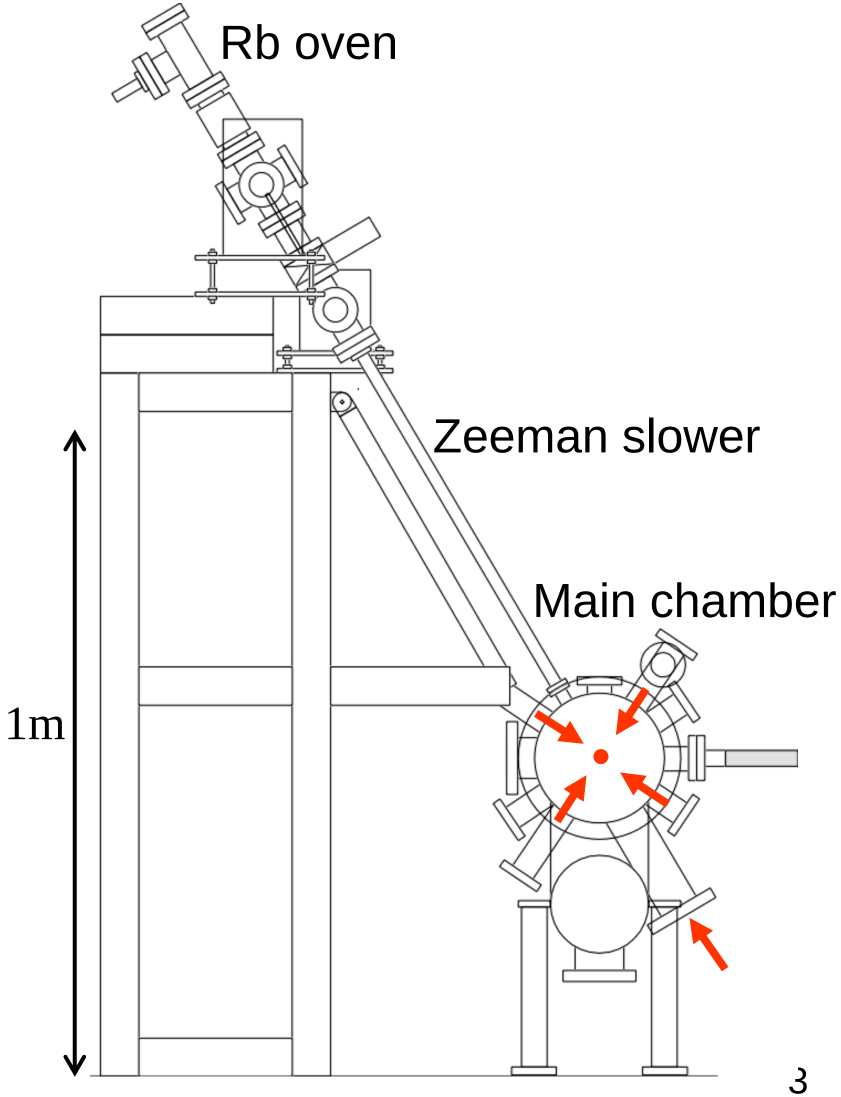
鳥井寿夫、吉川豊、中山和之、久我隆弘

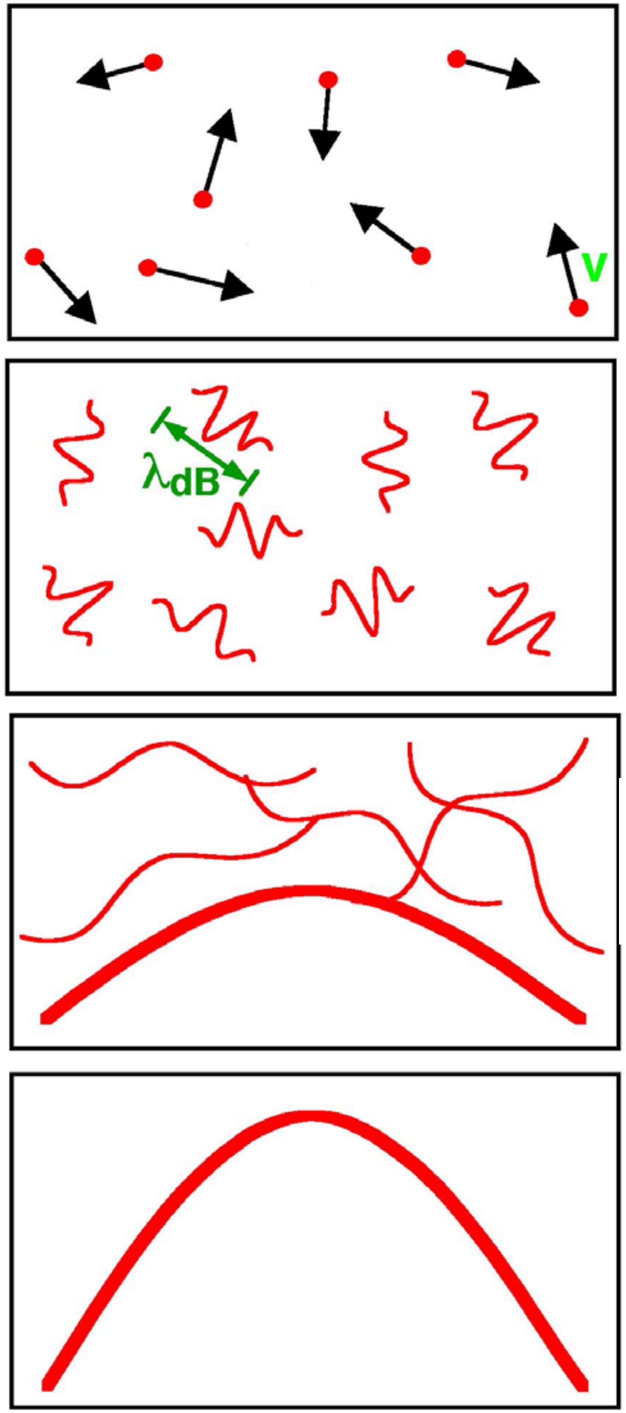
Outline

- 原子気体BECの作り方、観測法
- BECにおける超放射レイリー散乱
- Dicke状態による超放射の説明
- 熱的原子集団における超放射散乱
- BECの超放射（ディッケ状態）を利用した光パルスの多重保存

Rb原子ボース凝縮体生成装置@駒場







T～300K
λdB～0.1Å
ρ～10^{-12}

原子は粒子のように振舞う

↓ **レーザー冷却**

T～10μK
λdB～10nm
ρ～10^{-6}

粒子の波動性が顕著になる

↓ **蒸発冷却**

T～1μK
λdB～100nm
ρ～1

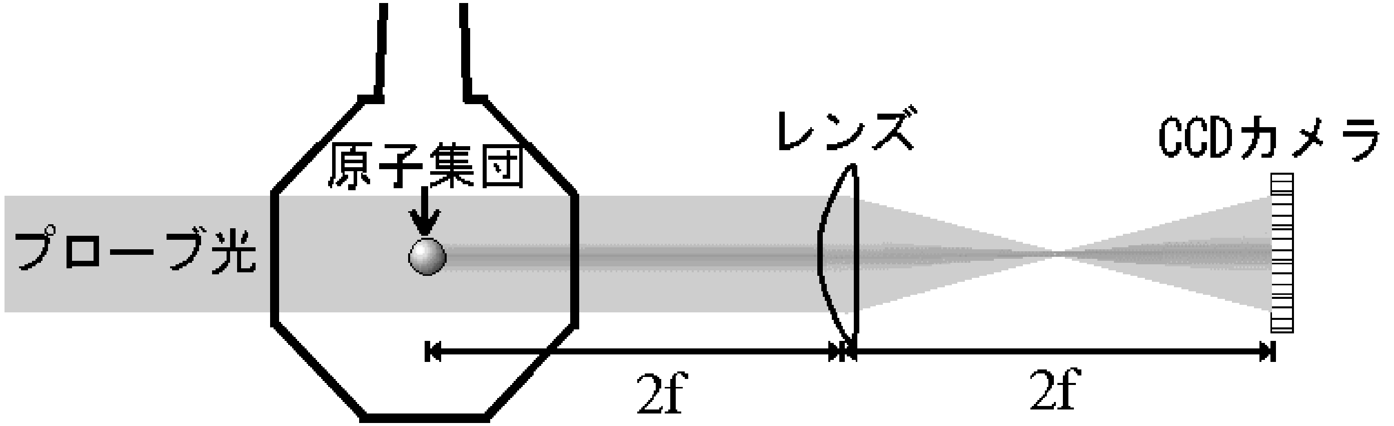
波が重なり始める
（ボース統計性が顕著になる）

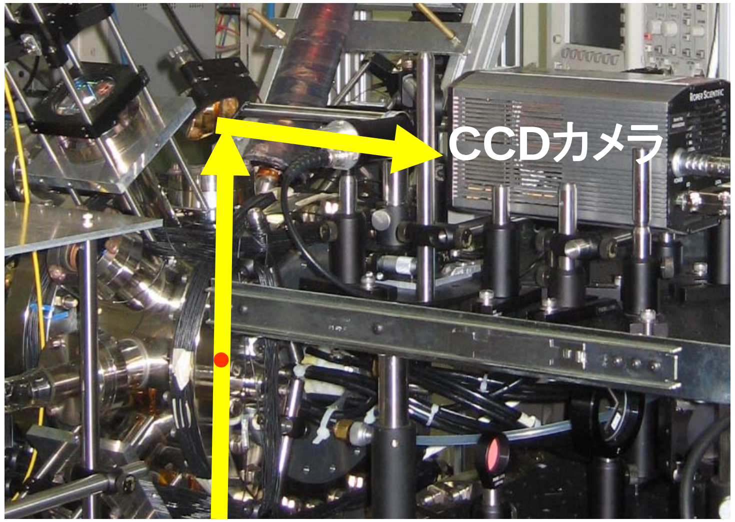
↓

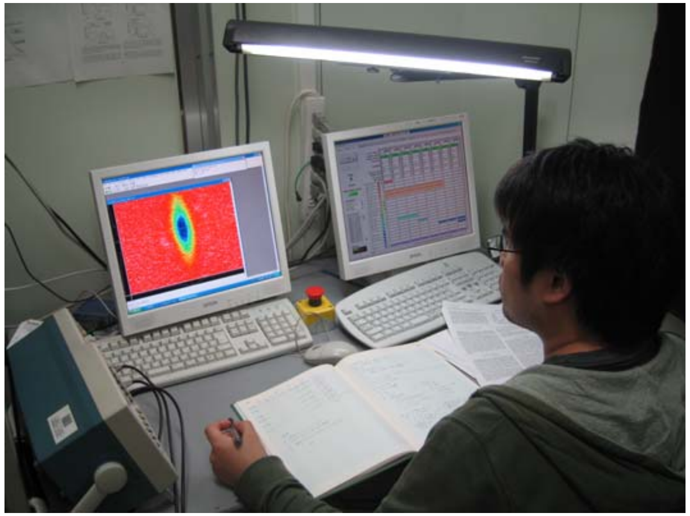
T～100nK
λdB～1μm
ρ～10^{6}

一つの巨大な波
（ボース・アインシュタイン凝縮）

BEC相転移の確認（吸収イメージング法）

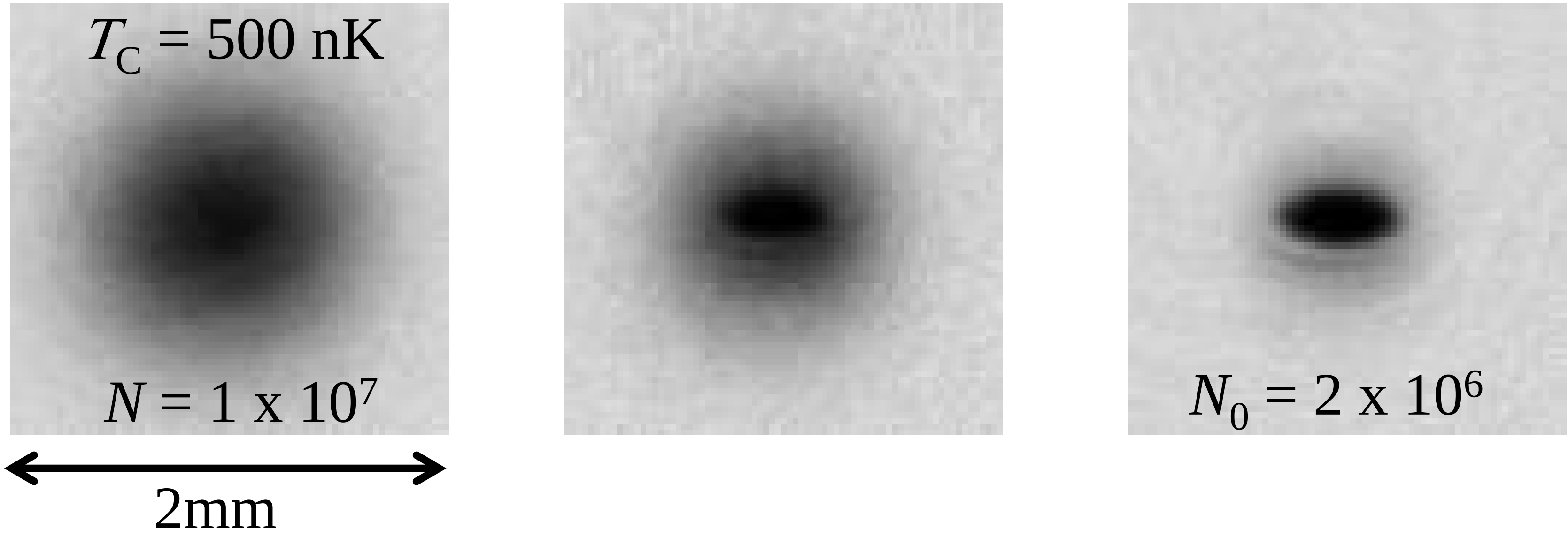






BEC Phase Transition

(52-ms time-of-flight absorption images)



thermal cloud at Tc — bimodal (thermal + BEC) — Pure BEC

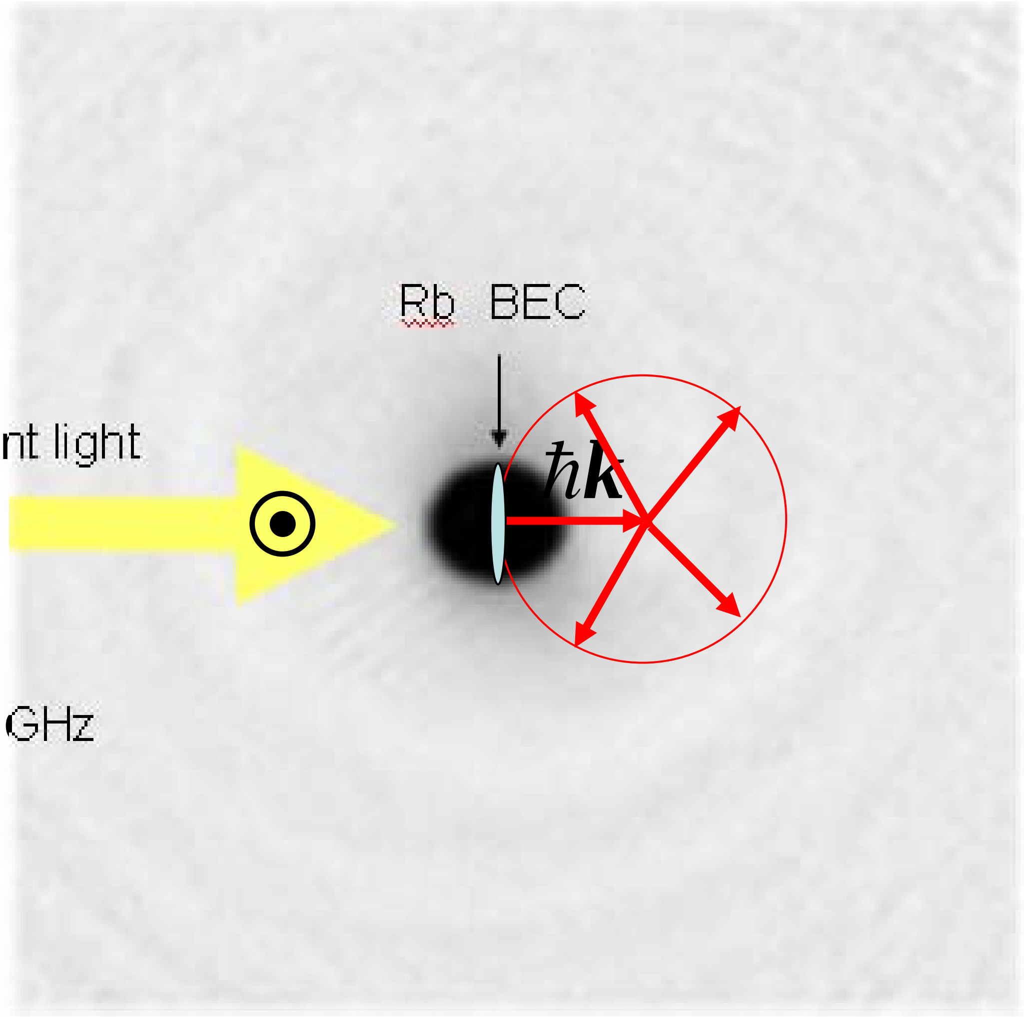
ν_{rf} = 1.24 MHz

ν_{rf} = 1.20 MHz

ν_{rf} = 1.16 MHz

BECにおける
超放射レイリー散乱

Rayleigh scattering in a Rb BEC



Off-resonant light

63 mW/cm^2

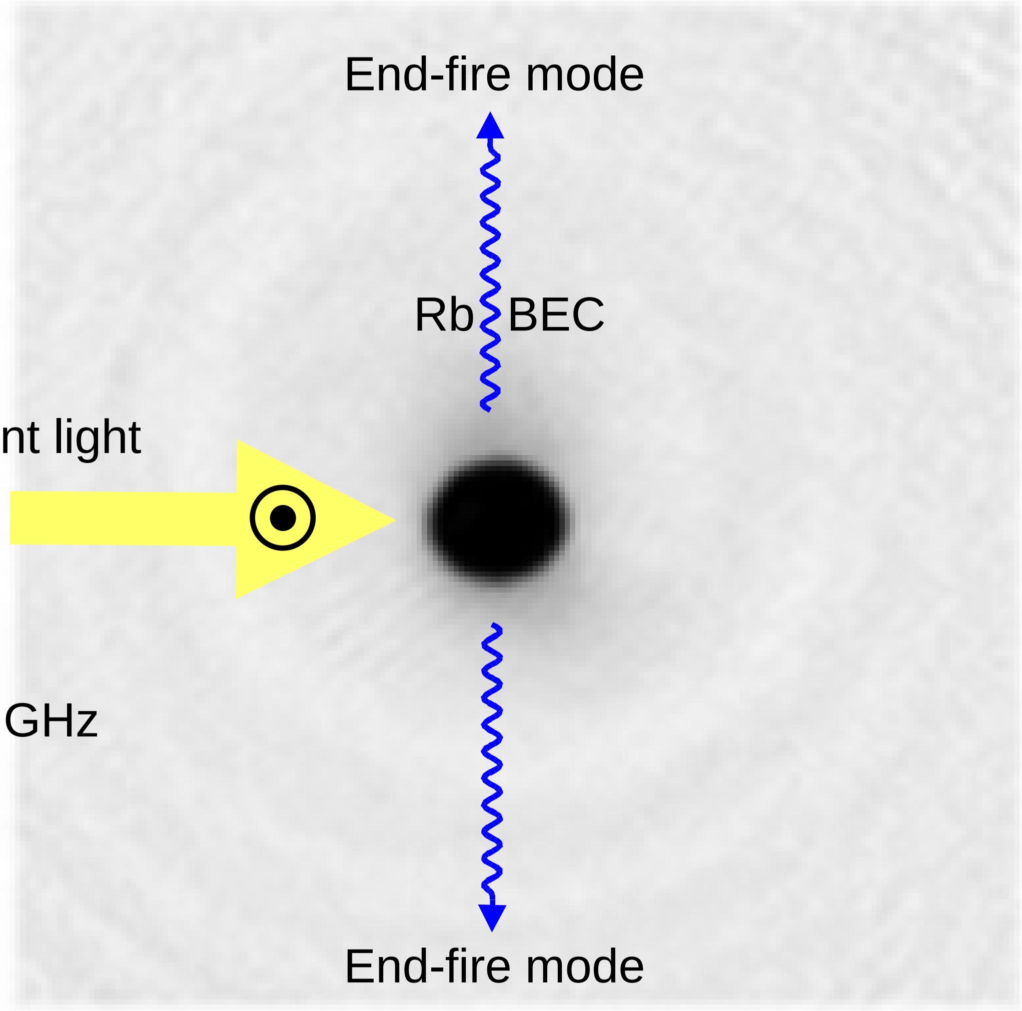
detuning: -4.4 GHz

Pulse duration:
25 μs-3200 μs

30 ms TOF

D. Schneble, Y.T., M. Boyd, E. W. Streed, D. E. Pritchard, and W. Ketterle, Science **300**, 475 (2003)

Rayleigh scattering in a Rb BEC



Off-resonant light

63 mW/cm^2

detuning: -4.4 GHz

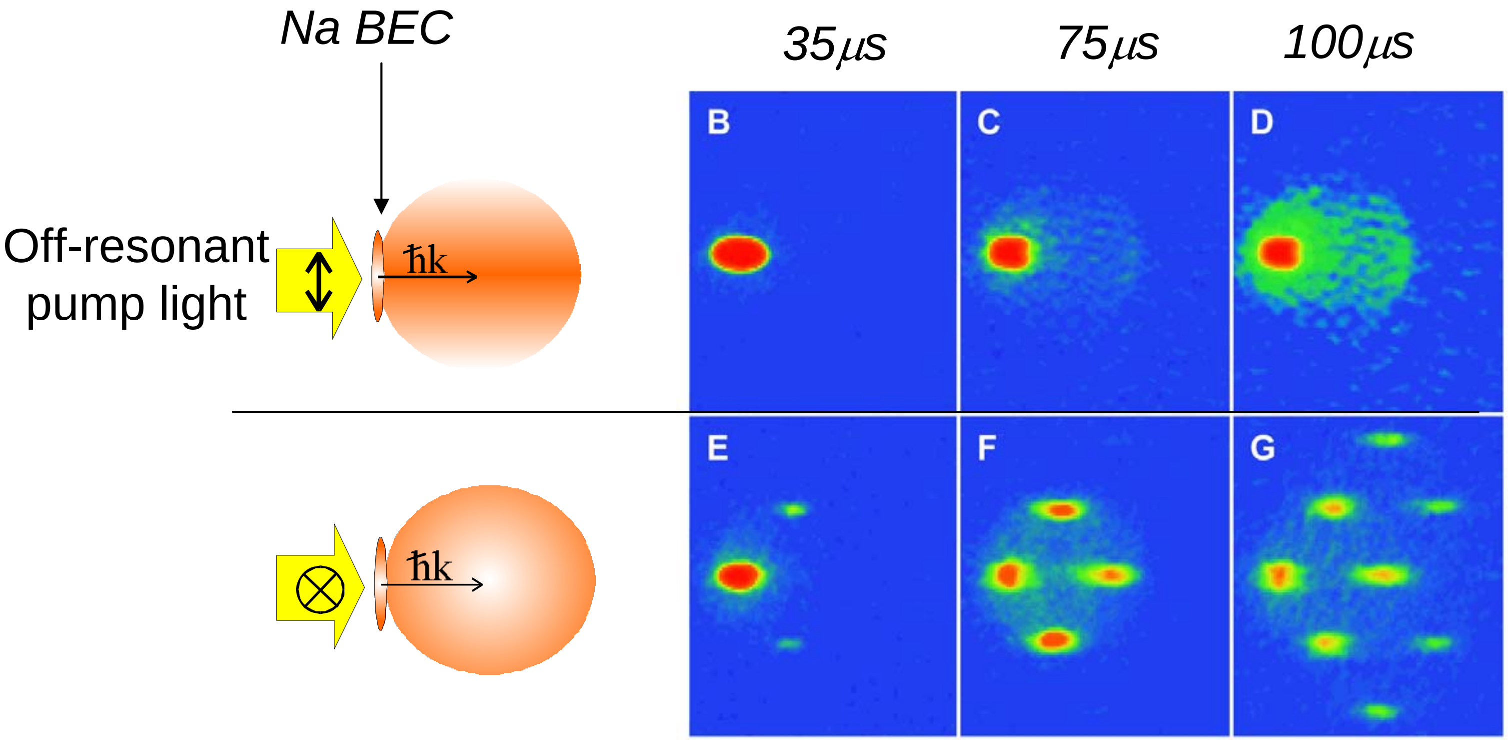
Pulse duration:
25 μs-3200 μs

30 ms TOF

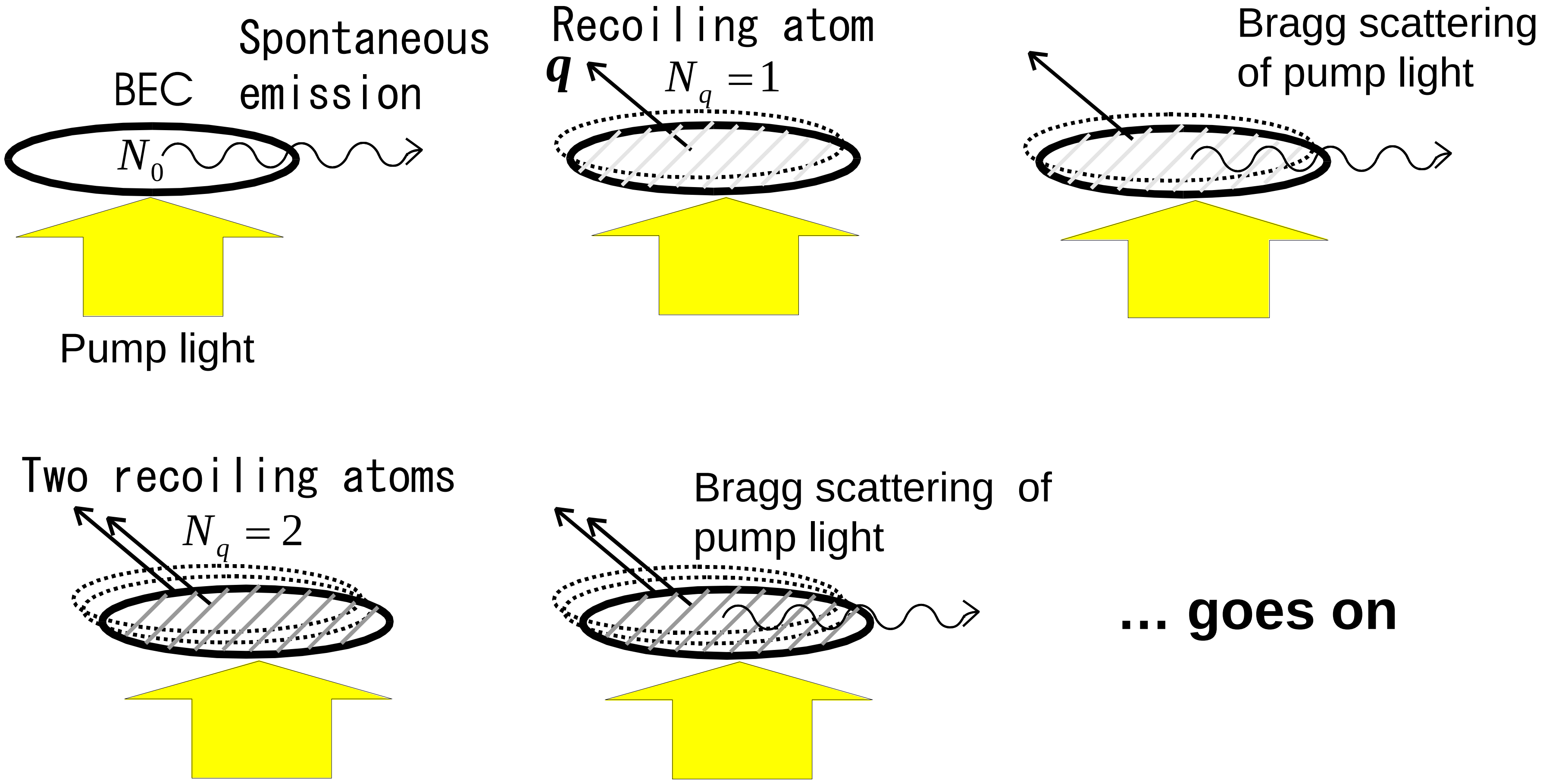
D. Schneble, Y.T., M. Boyd, E. W. Streed, D. E. Pritchard, and W. Ketterle, Science **300**, 475 (2003)

Superradiant Rayleigh scattering from a Bose-Einstein condensate

S. Inouye, et. al., Science **285**, 571 (1999)



Semiclassical interpretation of superradiance



BEC

N_0

Spontaneous emission

Pump light

Recoiling atom

$\boldsymbol{q}$

$N_q = 1$

Bragg scattering of pump light

Two recoiling atoms

$N_q = 2$

Bragg scattering of pump light

… goes on

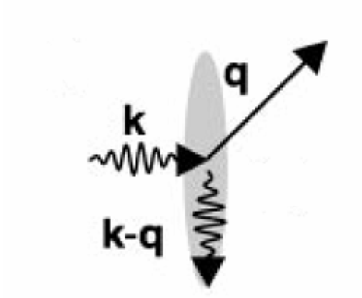
The rate of light scattering is enhanced by the number of recoiling atoms

$$\dot{N}_q \propto N_0 N_q$$

Amplification of matter-wave

Full quantum picture
(Fermi's Golden Rule)

Scattering process:



Condensate

Recoiling atoms

$$|N_0, n_k; N_q, n_{k-q}> \xrightarrow[\hat{H}=\hat{a}_q^+\hat{c}_{k-q}^+\hat{a}_0\hat{c}_k]{} |N_0-1, n_k-1; N_q+1, n_{k-q}+1>$$

Incident photon

Scattered photon

Scattering rate:

$$W \propto |< N_0-1, n_k-1; N_q+1, n_{q-k}+1|\hat{H}|N_0, n_k; N_q, n_{k-q}>|^2$$

$$= N_0 n_k (N_q+1)(\cancel{n_{k-q}}+1) \propto N_0(N_q+1)$$

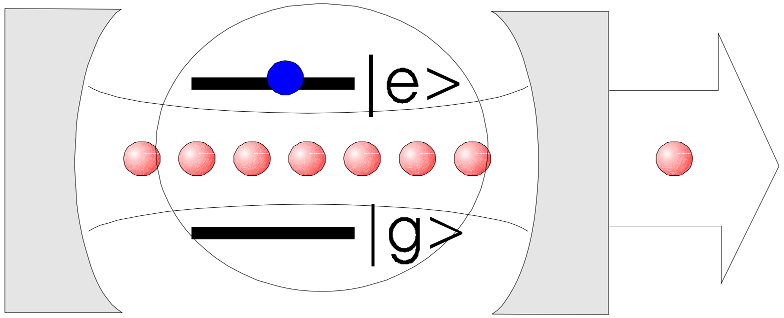
neglect

Stimulated scattering (Bosonic enhancement)

Spontaneous scattering

Analogy with the laser principle

N photons in the cavity



The interaction Hamiltonian
(after rotating-wave approx.)

$$\hbar g(a\sigma^{+} + a^{+}\sigma^{-})$$

$$\left(g = \sqrt{d^{2}\omega/2\varepsilon_{0}V}\right)$$

The emission rate of the atom

$$R \propto \left| < g, N-1 \,|\, (a\sigma^{+} + a^{+}\sigma^{-}) \,|\, e, N > \right|^{2}$$

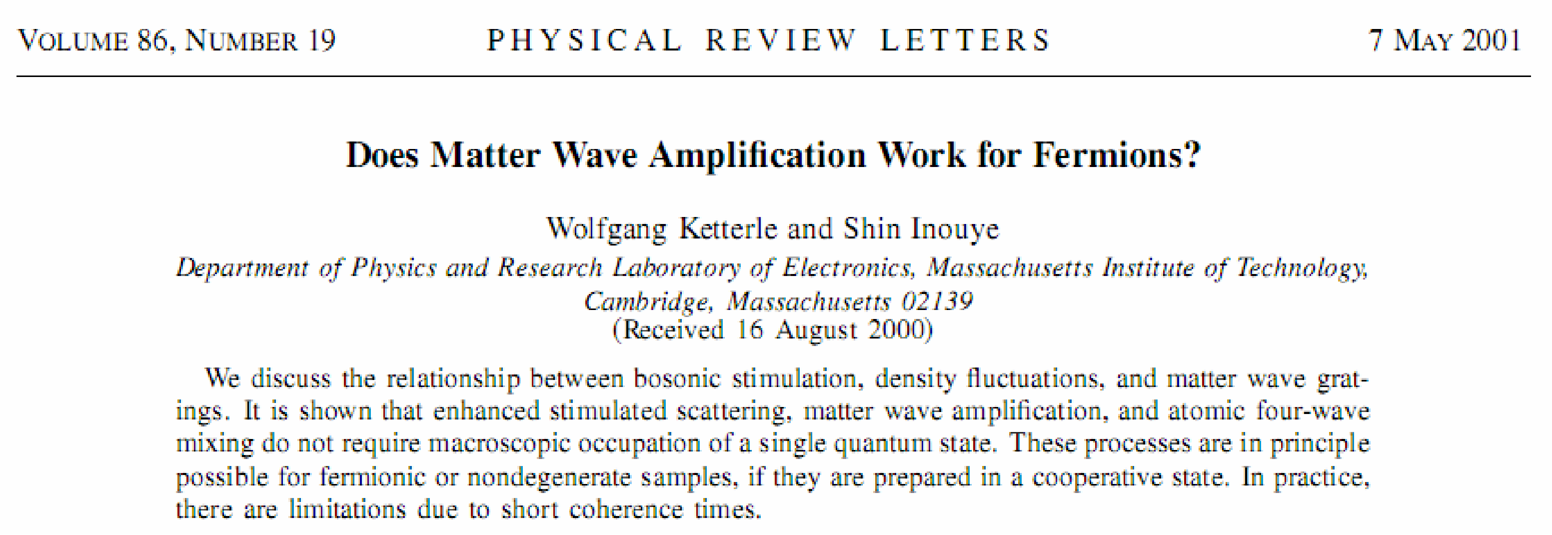
$$= \left(\underbrace{N}_{\text{Stimulated emission}} + \underbrace{1}_{\text{Spontaneous emission}}\right)$$

Stimulated emission

Spontaneous emission

LASER: Light Amplification by Stimulated Emission of Radiation

原子波増幅（超放射）はフェルミオンでも熱的原子でも起こる



VOLUME 86, NUMBER 19 PHYSICAL REVIEW LETTERS 7 MAY 2001

Does Matter Wave Amplification Work for Fermions?

Wolfgang Ketterle and Shin Inouye
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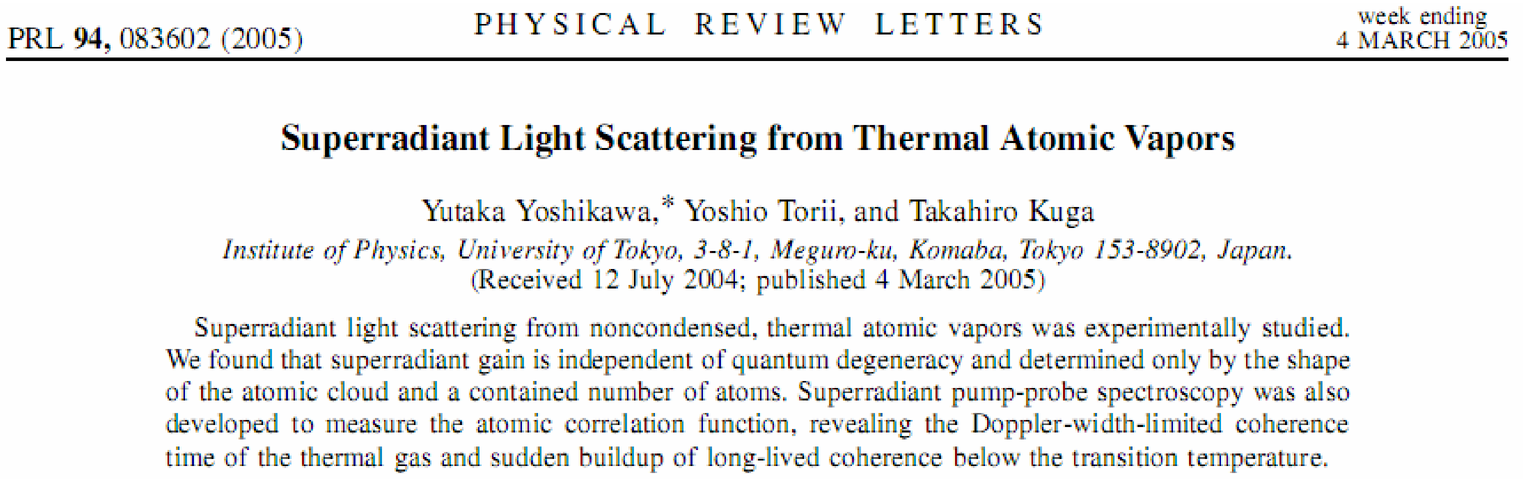
Cambridge, Massachusetts 02139

(Received 16 August 2000)

We discuss the relationship between bosonic stimulation, density fluctuations, and matter wave gratings. It is shown that enhanced stimulated scattering, matter wave amplification, and atomic four-wave mixing do not require macroscopic occupation of a single quantum state. These processes are in principle possible for fermionic or nondegenerate samples, if they are prepared in a cooperative state. In practice, there are limitations due to short coherence times.



PRL **94,** 083602 (2005) PHYSICAL REVIEW LETTERS week ending 4 MARCH 2005

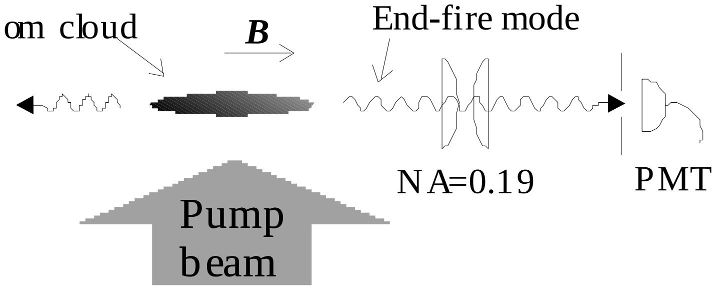
Superradiant Light Scattering from Thermal Atomic Vapors

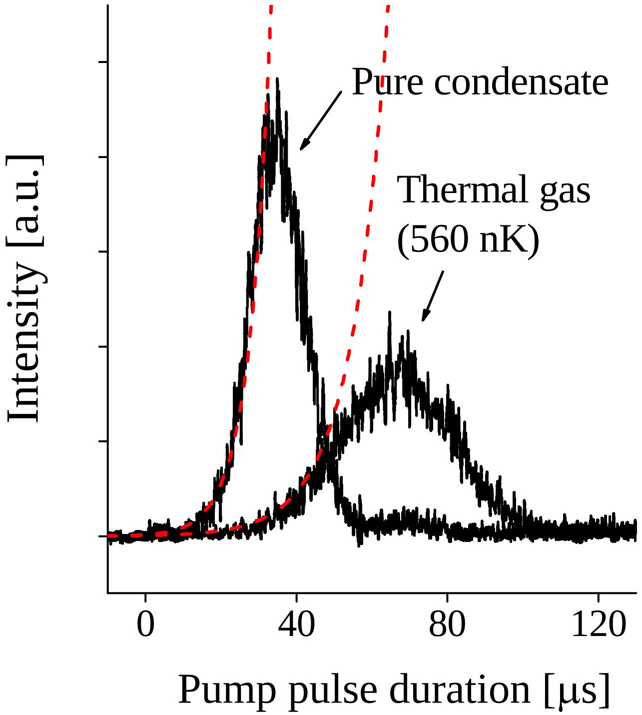
Yutaka Yoshikawa,* Yoshio Torii, and Takahiro Kuga
Institute of Physics, University of Tokyo, 3-8-1, Meguro-ku, Komaba, Tokyo 153-8902, Japan.

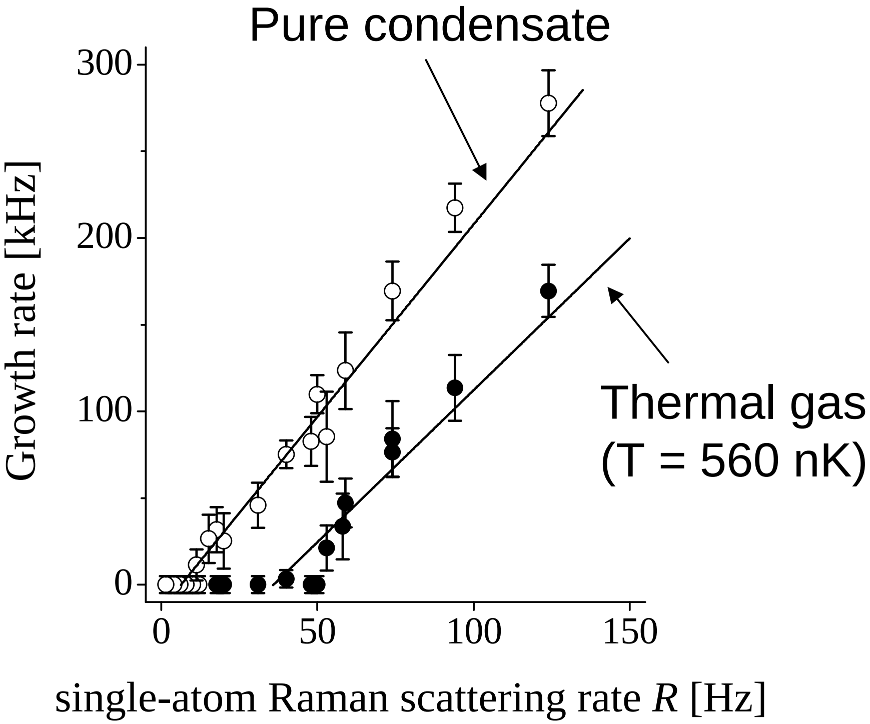
(Received 12 July 2004; published 4 March 2005)

Superradiant light scattering from noncondensed, thermal atomic vapors was experimentally studied. We found that superradiant gain is independent of quantum degeneracy and determined only by the shape of the atomic cloud and a contained number of atoms. Superradiant pump-probe spectroscopy was also developed to measure the atomic correlation function, revealing the Doppler-width-limited coherence time of the thermal gas and sudden buildup of long-lived coherence below the transition temperature.

Superradiance in a Thermal gas

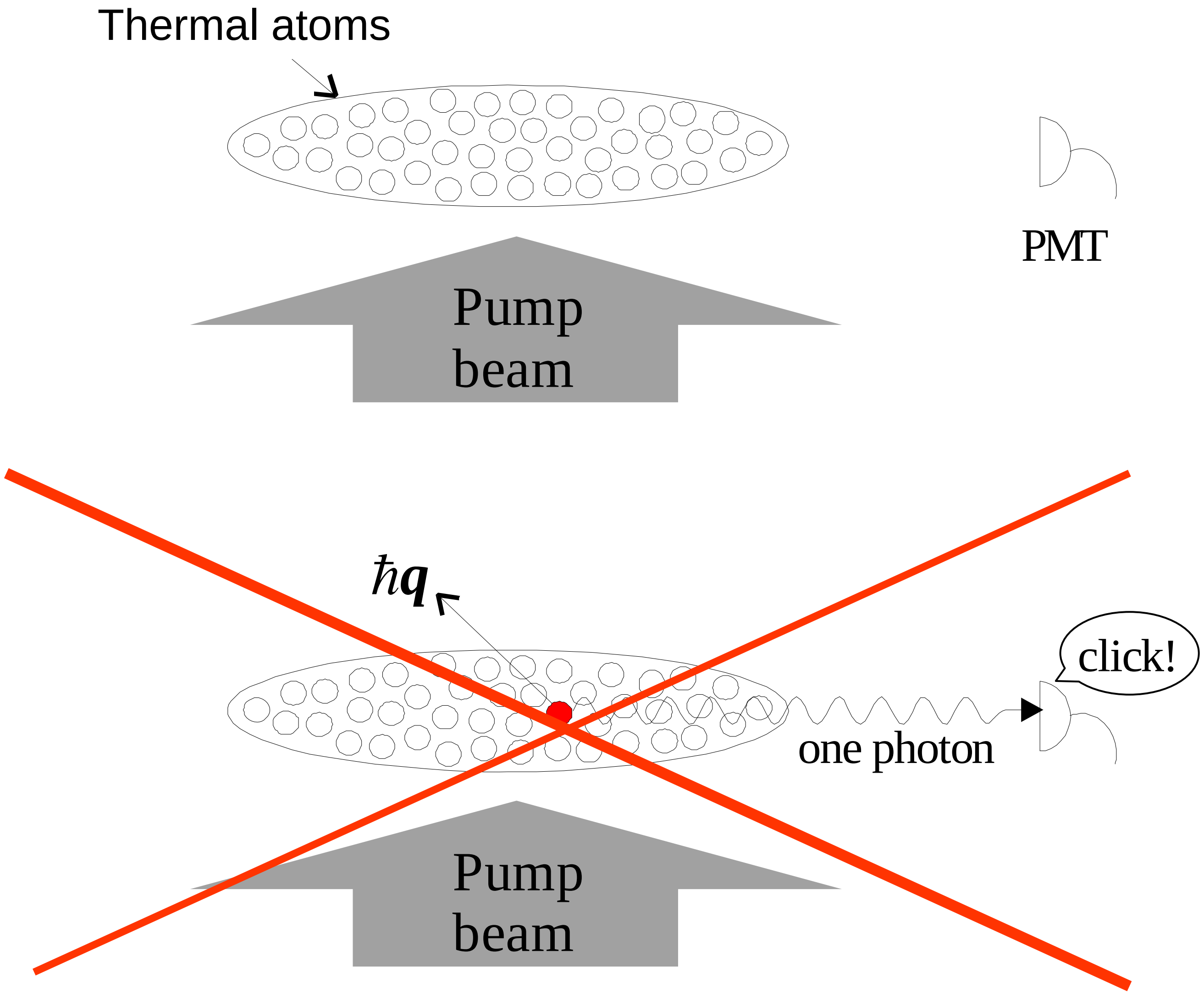




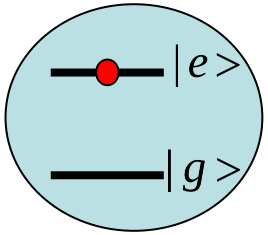


Y. Yoshikawa, Y. T. and T. Kuga, PRL **94** 083602 (2005)

Where is a grating?



One-atom spontaneous emission



The electric dipole operator

$$\hat{d} = d(\sigma^+ + \sigma^-) \quad \left(\sigma^+ = |e><g|, \sigma^- = |g><e|\right)$$

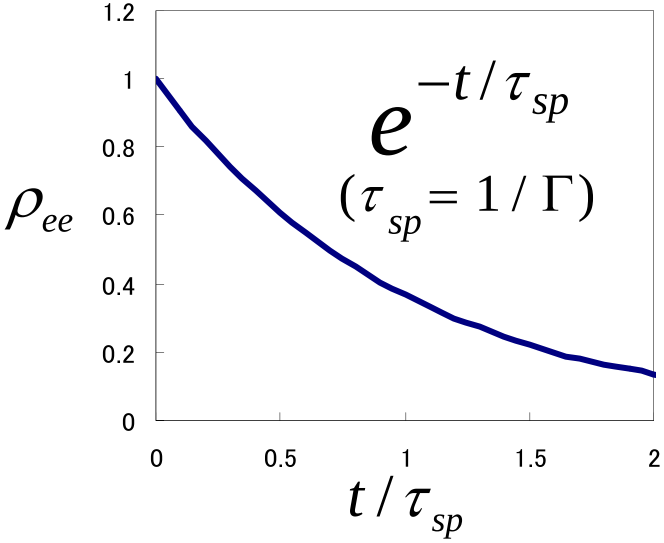
The atom-field interaction Hamiltonian

$$\hat{H}_{\text{int}} = -\hat{d}\cdot\hat{E}_{rad} = \sum \hbar g_i (a_i\sigma^+ + a_i^+\sigma^-) \quad \left(g_i = \sqrt{d^2\omega_i/2\varepsilon_0 V}\right)$$

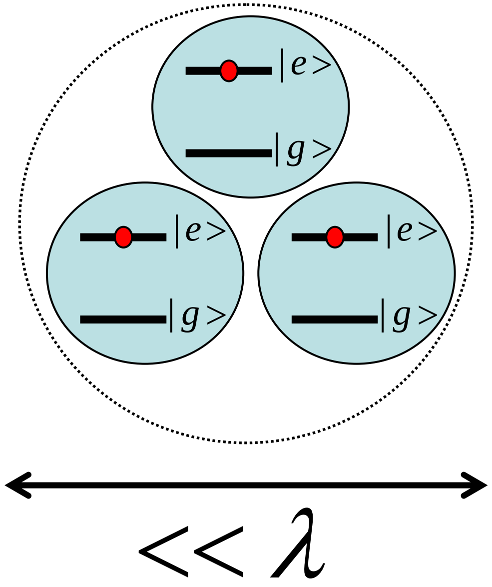
The rate of spontaneous emission

$$R = \Gamma\langle\sigma^+\sigma^-\rangle \left(\Gamma = \frac{d^2\omega^3}{3\pi\hbar\varepsilon_0 c^3}\right)$$

Wigner and Weisskopf (1930)



Three-atom spontaneous emission



The (total) electric dipole operator

$$\hat{d} = d\sum_{i=1}^{3}(\sigma_i^+ + \sigma_i^-) \equiv d(\sigma^+ + \sigma^-)$$

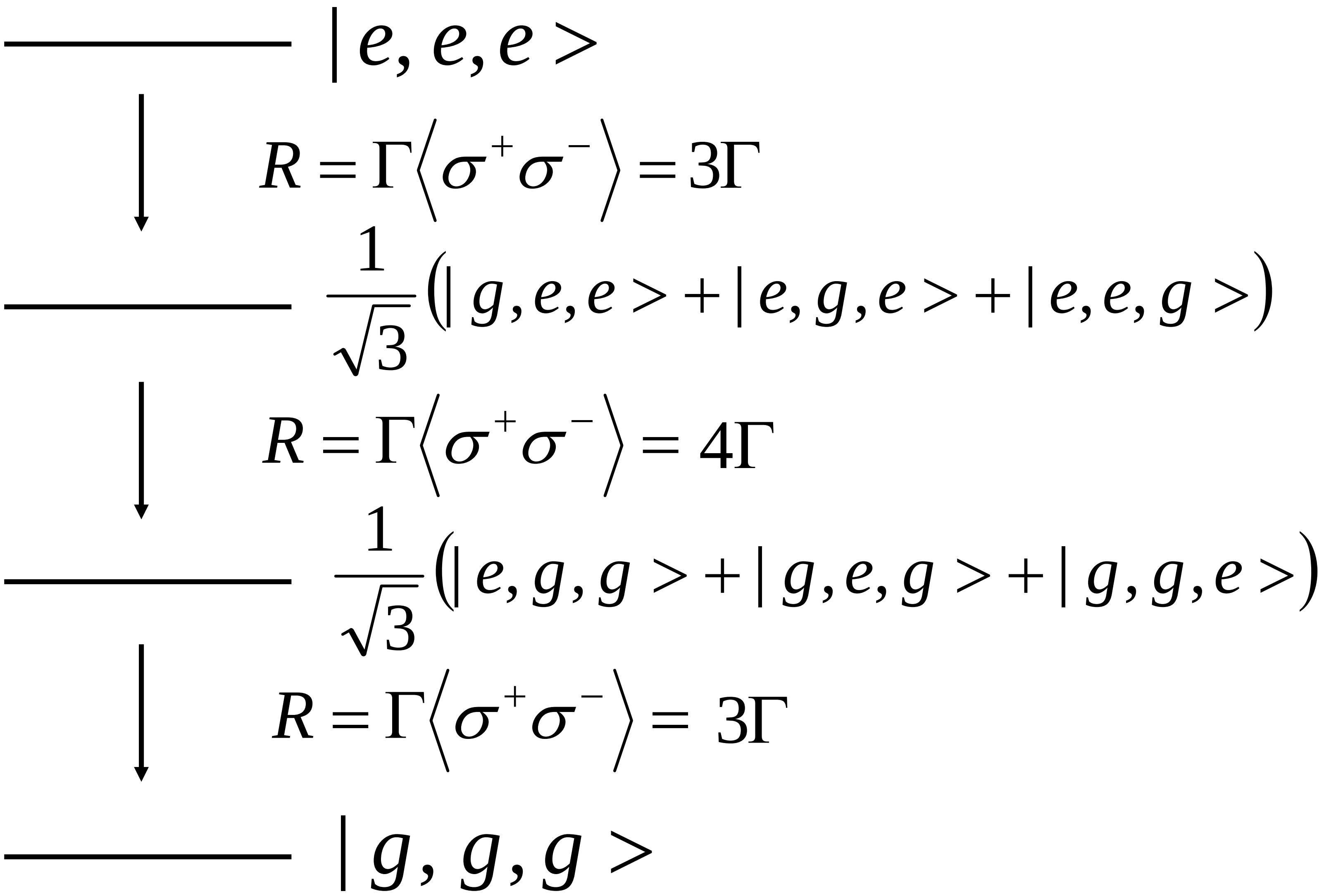
$$\left(\sigma^+ \equiv \sum_{i=1}^{3} |e>_i\,_i<g|,\ \sigma^+ \equiv \sum_{i=1}^{3} |g>_i\,_i<e| \right)$$

The rate of spontaneous emission

$$R = \Gamma\left\langle \sigma^+\sigma^- \right\rangle$$

Same form as the single-atom case, but $\sigma^+(\sigma^-)$ is the sum of each raising (lowering) operator

Evolution of the three-atom system



$$|e,e,e>$$

$$R=\Gamma\left\langle \sigma^{+}\sigma^{-}\right\rangle =3\Gamma$$

$$\frac{1}{\sqrt{3}}\left(|g,e,e>+|e,g,e>+|e,e,g>\right)$$

$$R=\Gamma\left\langle \sigma^{+}\sigma^{-}\right\rangle =4\Gamma$$

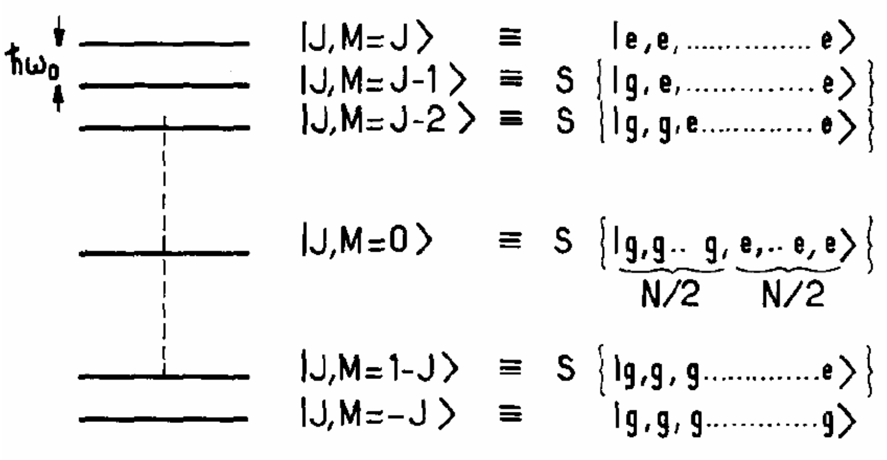
$$\frac{1}{\sqrt{3}}\left(|e,g,g>+|g,e,g>+|g,g,e>\right)$$

$$R=\Gamma\left\langle \sigma^{+}\sigma^{-}\right\rangle =3\Gamma$$

$$|g,g,g>$$

N-atom spontaneous emission

N-atom system ⇔ N spin-1/2 system with the total spin J = N/2 (assumption: *Indiscernability* of the atoms with respect to photon emission)



R. H. Dicke, Phys. Rev. **93**, 99 (1954)

Spontaneous emission rate of the N-atom system:

$$\begin{aligned}\Gamma_N &= \Gamma\langle J,M\,|\,J_+J_-\,|\,J,M\rangle \\ &= \Gamma(J+M)(J-M+1) \\ &= \Gamma N_e(N_g+1)\end{aligned}$$

↑

Enhancement by the number of photons already emitted

Comparison between ordinary and superradiant emission

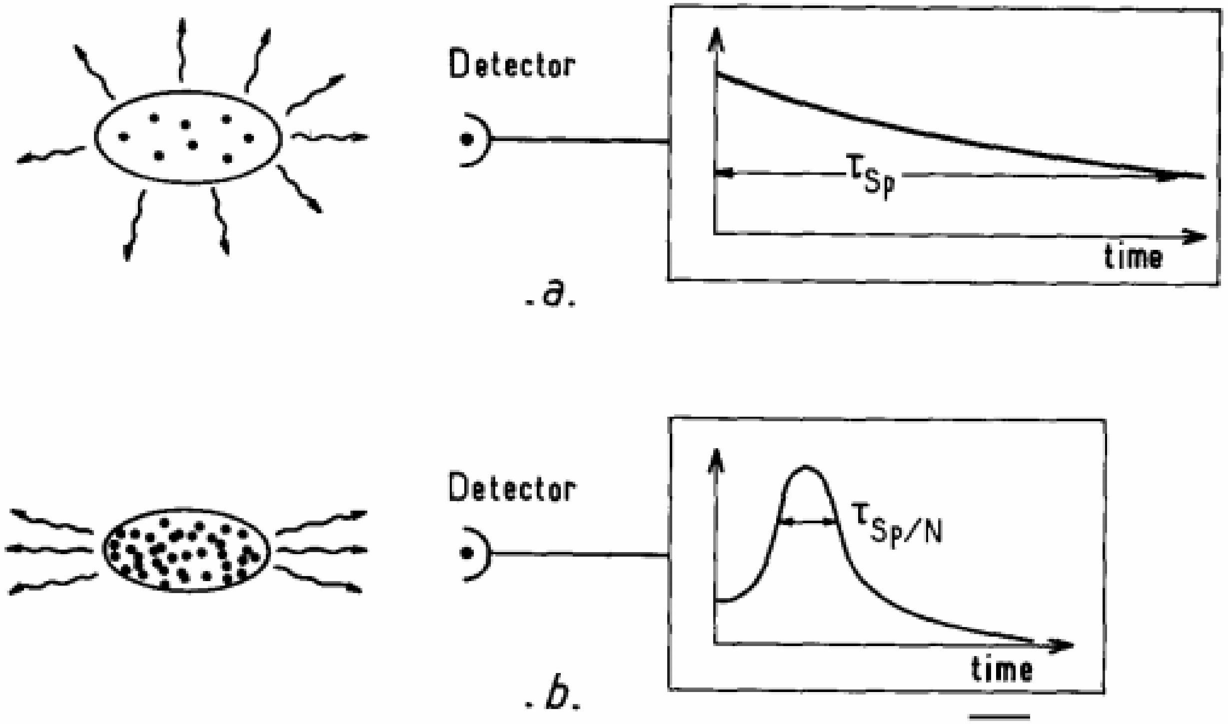
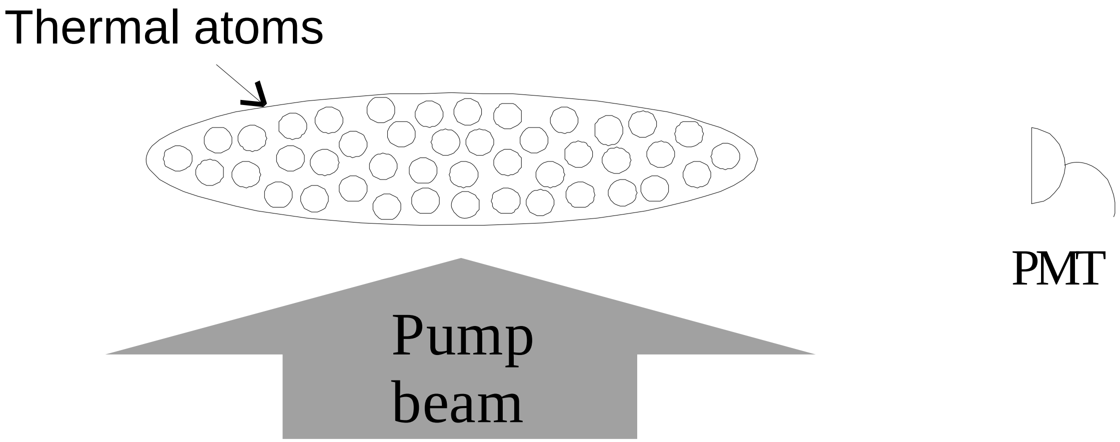
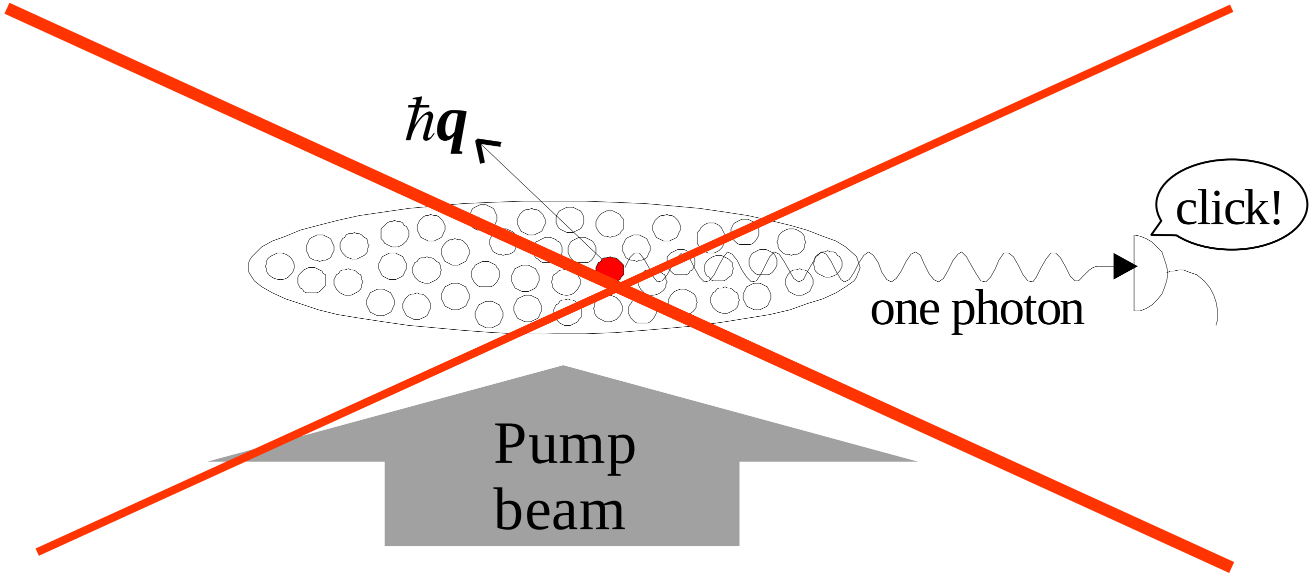


Fig. 1. Comparison between the general characteristics of ordinary fluorescence and superradiance experiments. (a) Ordinary spontaneous emission is essentially isotropic with an exponentially decaying intensity (time constant τ_{sp}). (b) Superradiance is anisotropic with an emission occurring in a short burst of duration $\sim \tau_{sp}/N$.

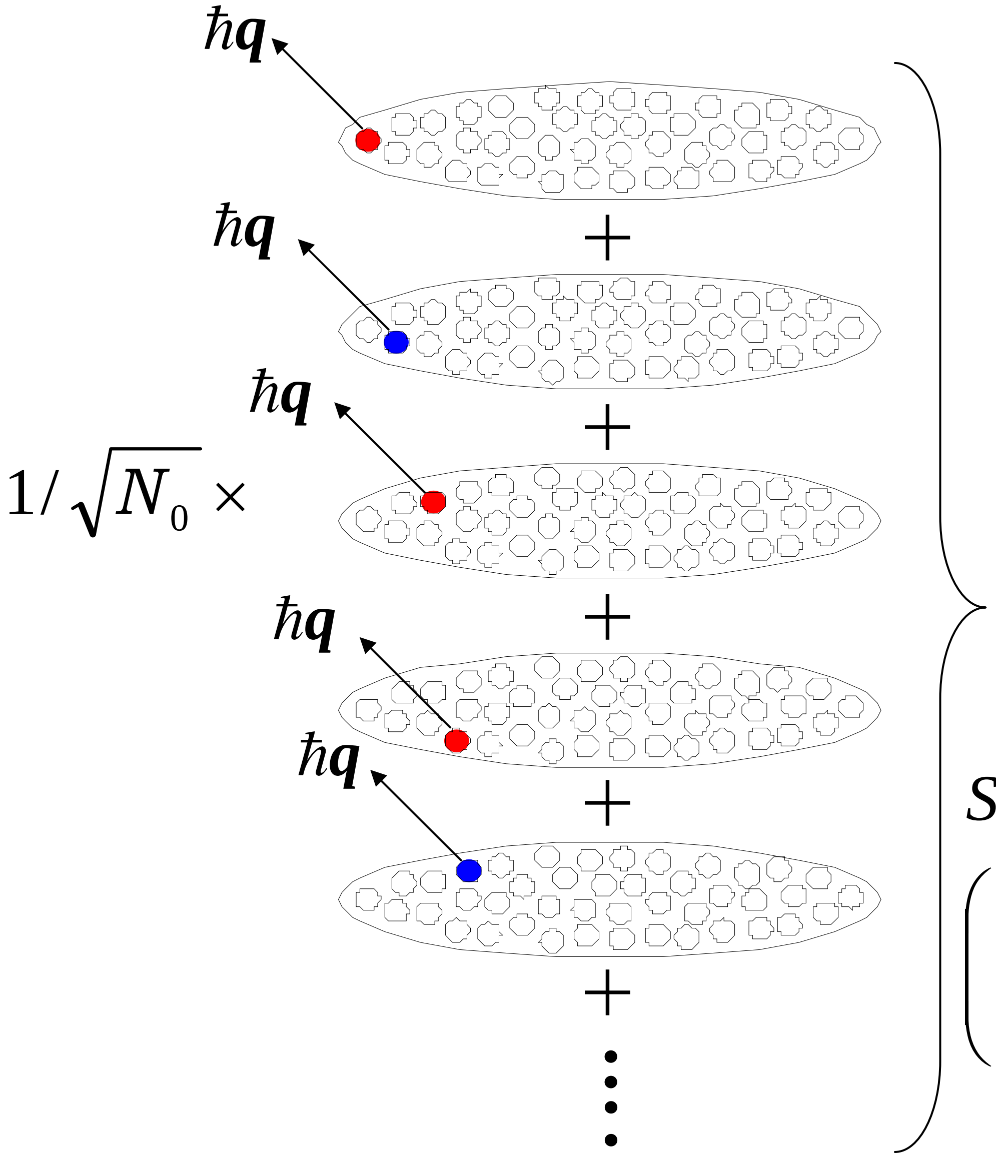
From M. Gross and S. Haroche, Phys. Rep. **93**, 301 (1982)

Where is a grating?

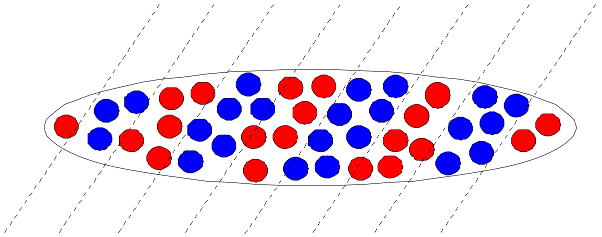




The origin of a grating (Collective mode excitation)



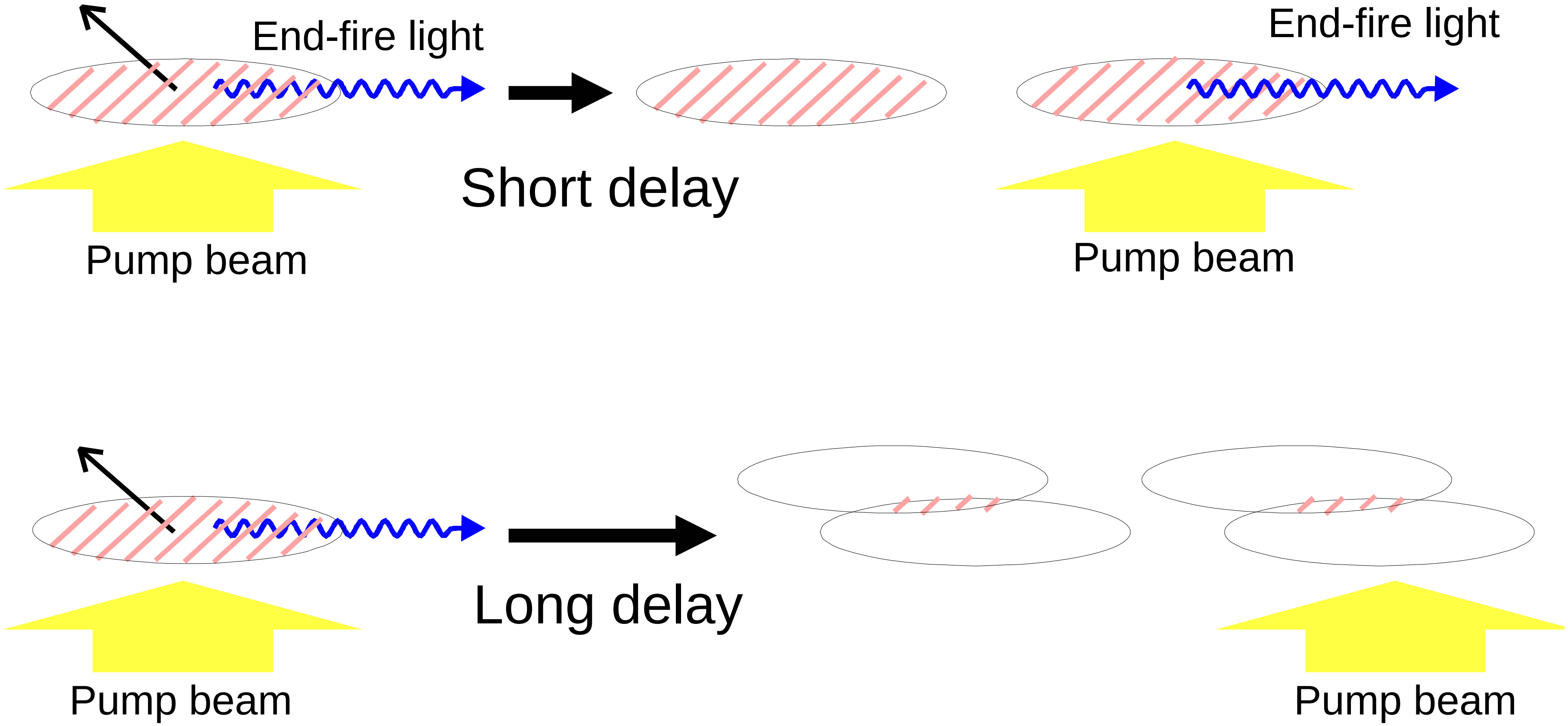
One atom is excited to the collective atomic mode defined by S⁺



$$S^+ \,|\, J, M = -J > \,=\, |\, J, M = -J + 1 >$$

$$\left(S^+ \equiv \frac{1}{\sqrt{N_0}} \sum_{i=1}^{N_0} |\, \hbar q >_i < 0 \,| \right)$$

How long does the grating survive?



End-fire light

End-fire light

Short delay

Pump beam

Pump beam

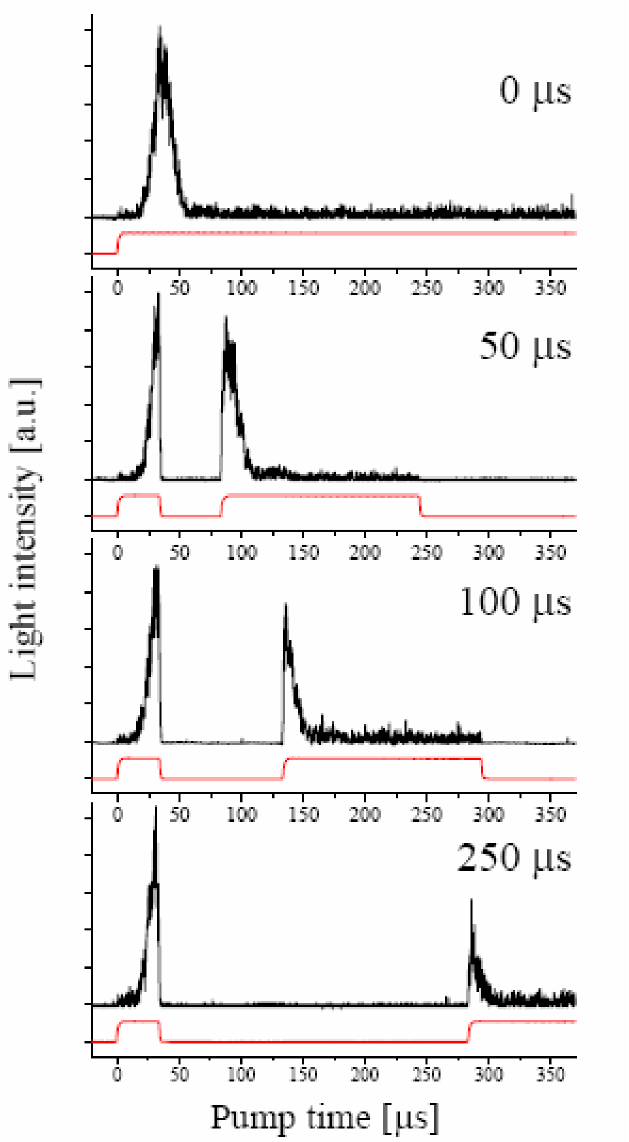
Long delay

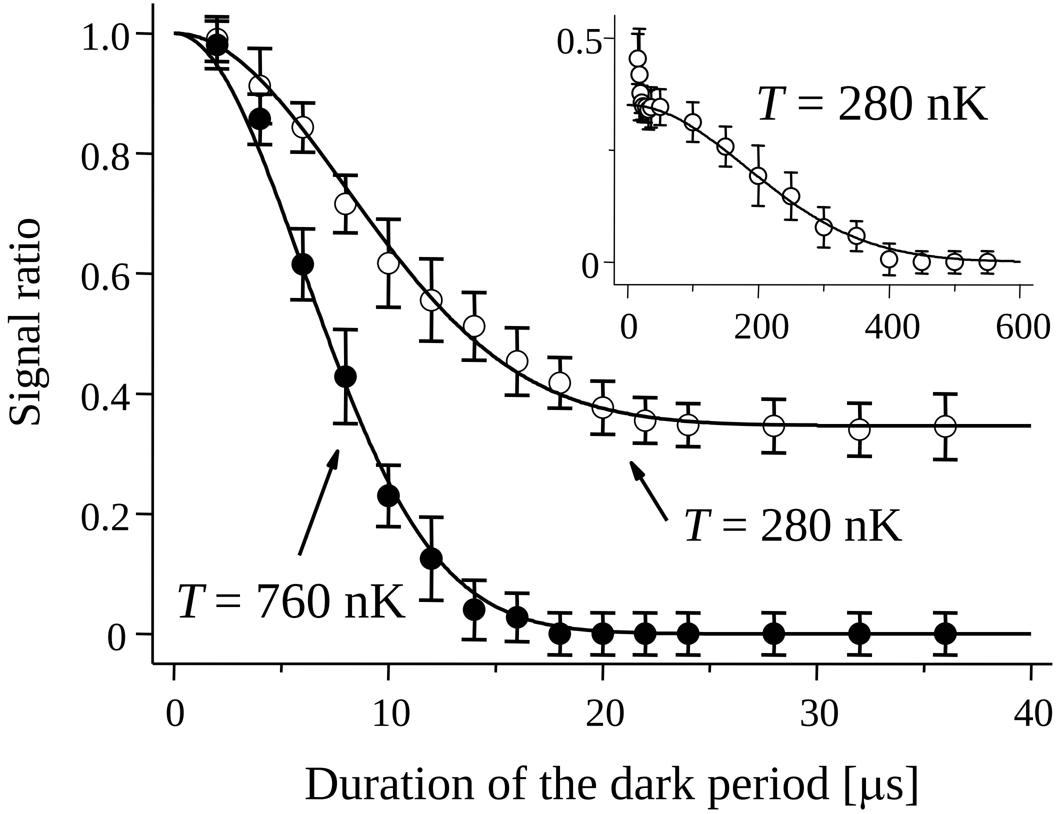
Pump beam

Pump beam

Storage (coherent) time of the grating is limited by the size of the wavepacket

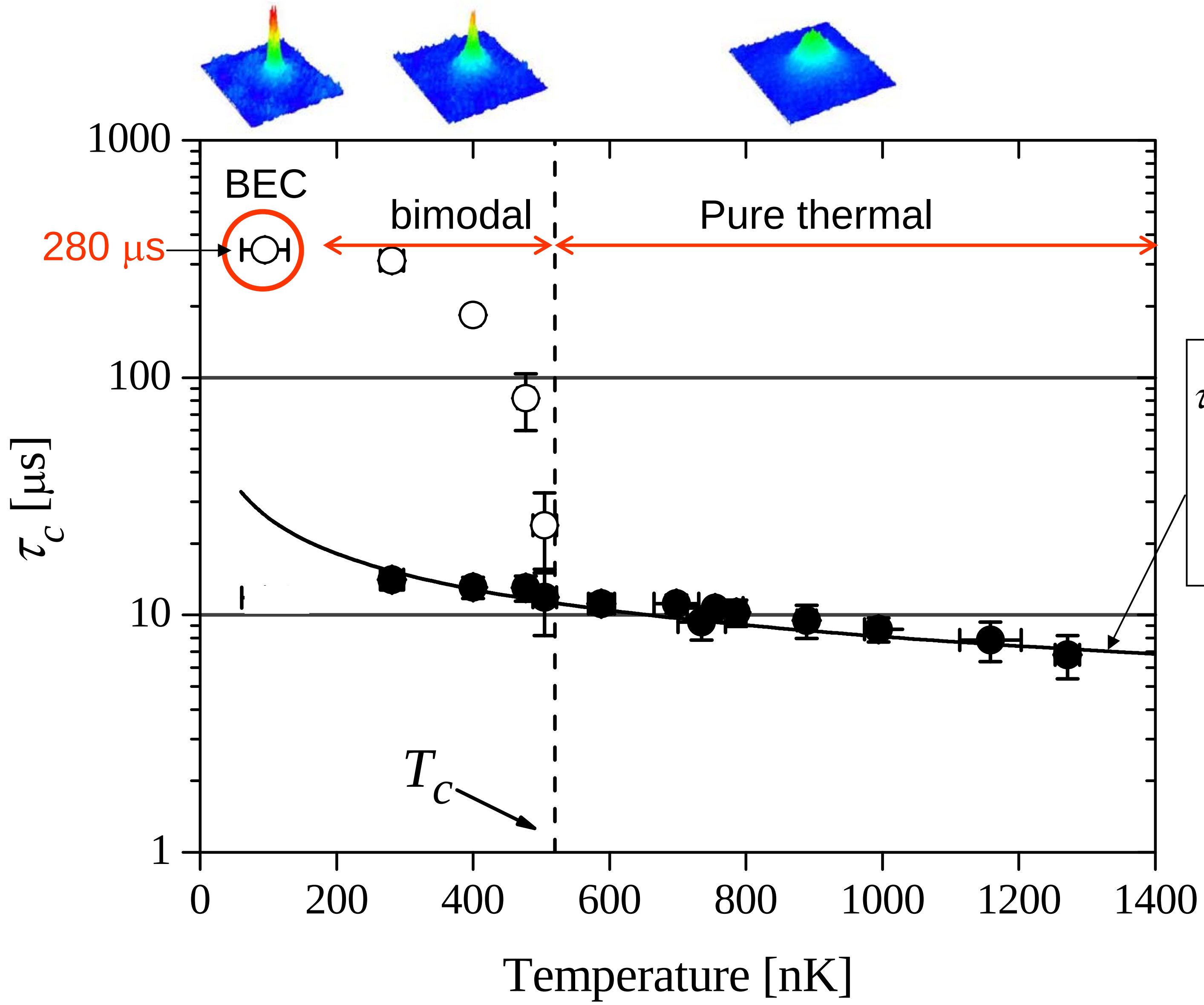
Storage (coherence) time measurement





Y. Yoshikawa, Y. T. and T. Kuga, PRL **94** 083602 (2005)

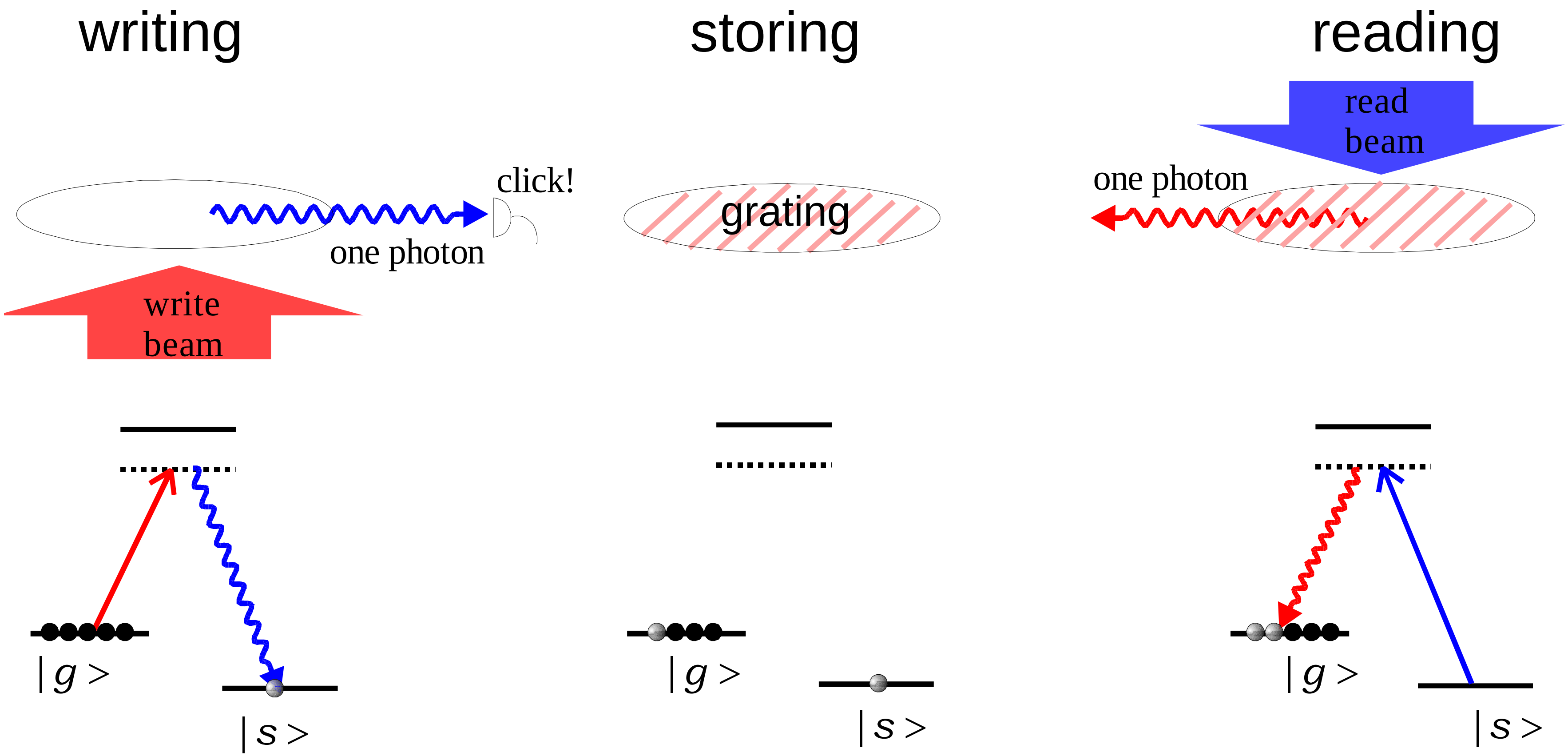
Storage time vs. temperature



$$\tau_\mathrm{c} = \frac{1}{2k\bar{\upsilon}} = \frac{\lambda}{4\pi}\sqrt{\frac{m}{k_\mathrm{B}T}}$$

Dicke状態の応用
単一光子の保存と再生

Writing, storing, and reading of a single photon

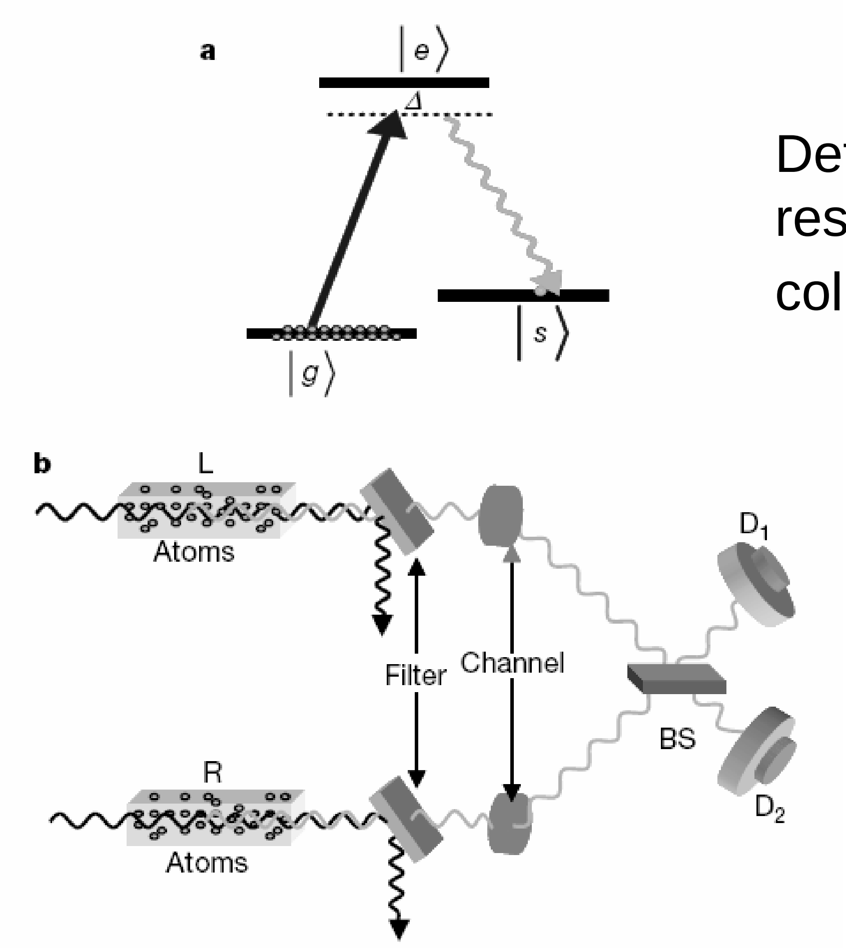


writing

storing

reading

Motivation: DLCZ protocol
(long distance quantum network)



Detection of a forward-scattered photon results in the excitation of the symmetric collective mode defined by

$$S^{+} \equiv \frac{1}{\sqrt{N}} \sum_{i=1}^{N} | s >_i < g |$$

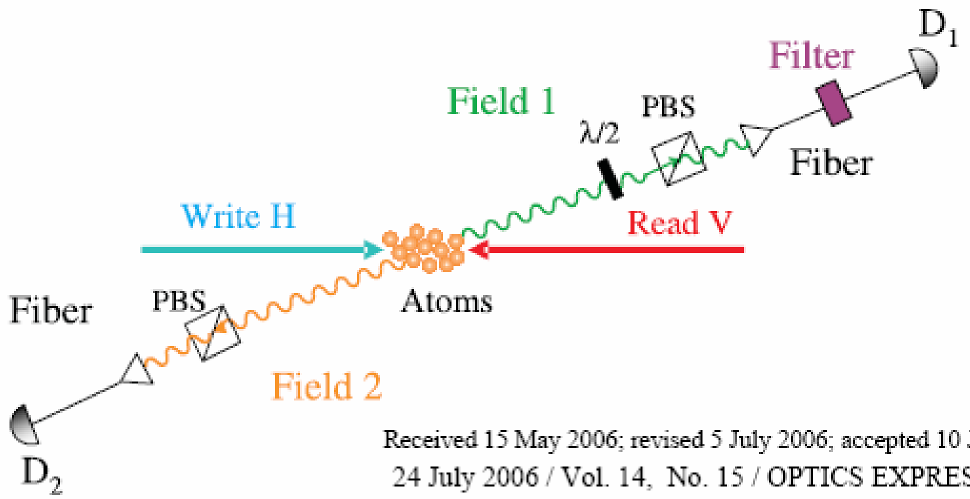
L.-M. Duan, M. D. Lukin, J. I. Cirac,and P. Zoller, Nature. **414**, 413 (2001)

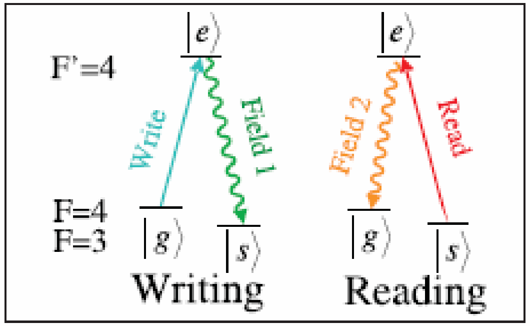
Efficient retrieval of a single excitation stored in an atomic ensemble

Julien Laurat, Hugues de Riedmatten, Daniel Felinto, Chin-Wen Chou, Erik W. Schomburg, and H. Jeff Kimble

Norman Bridge Laboratory of Physics 12-33, California Institute of Technology, Pasadena, California 91125, USA

Abstract: We report significant improvements in the retrieval efficiency of a single excitation stored in an atomic ensemble and in the subsequent generation of strongly correlated pairs of photons. A 50% probability of transforming the stored excitation into one photon in a well-defined spatio-temporal mode at the output of the ensemble is demonstrated. These improvements are illustrated by the generation of high-quality heralded single photons with a suppression of the two-photon component below 1% of the value for a coherent state. A broad characterization of our system is performed for different parameters in order to provide input for the future design of realistic quantum networks.





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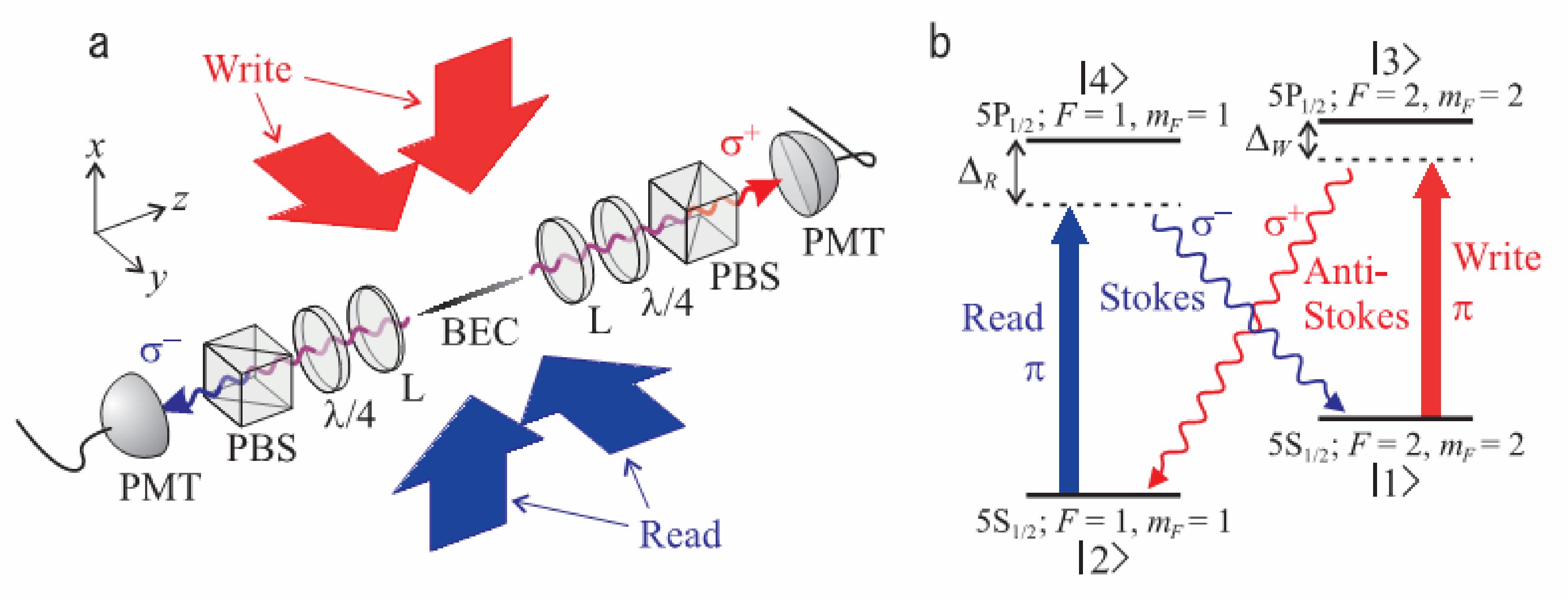
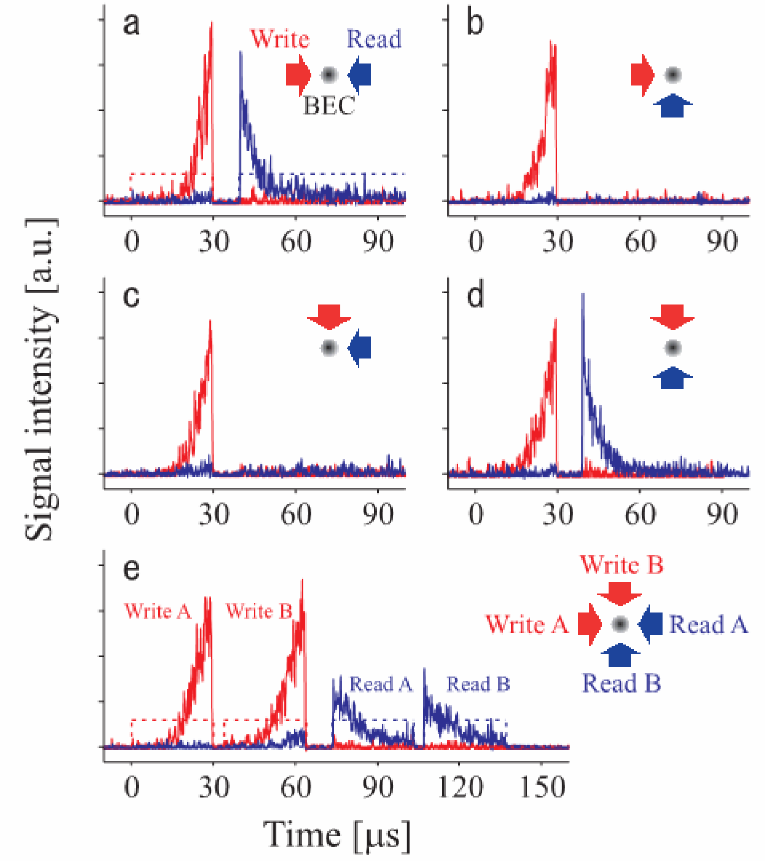
24 July 2006 / Vol. 14, No. 15 / OPTICS EXPRESS 6912

BECを用いた単一光子の保存と再生



予備実験：
BECを用いた光パルスの保存と再生



応用

- 任意光子発生器
- 多重量子メモリ
- 量子原子光学実験
  （2原子干渉など）

Y. Yoshikawa, K. Nakayama, Y. T. and T. Kuga,
Phys. Rev. Lett. **99**, 220407 (2007).

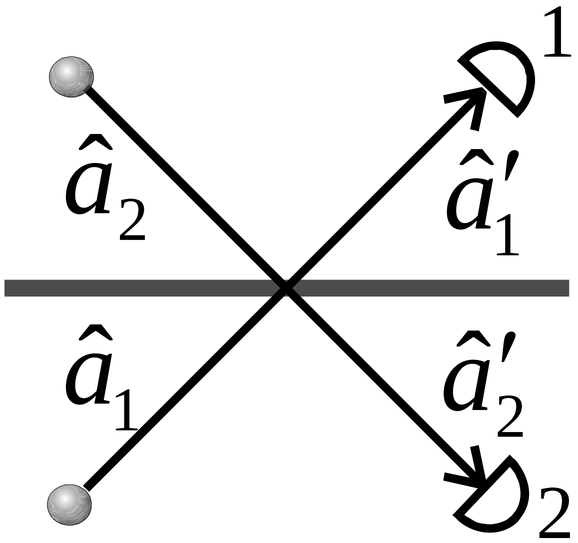
マンデルの2光子干渉

Input state

$$\hat{a}_1^+ \hat{a}_2^+ \,|\, 0, 0 >$$

Beam splitter operation

$$\begin{pmatrix} \hat{a}_1' \\ \hat{a}_2' \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \begin{pmatrix} \hat{a}_1 \\ \hat{a}_2 \end{pmatrix}$$



Output state

$$\frac{1}{2}\left(\hat{a}_1'^+ + \hat{a}_2'^+\right)\left(\hat{a}_1'^+ - \hat{a}_2'^+\right) |\, 0, 0 >$$

Bunching

$$= \frac{1}{2}\left(\left(\hat{a}_1'^+\right)^2 + \left(\hat{a}_2'^+\right)^2\right) |\, 0, 0 >= \boxed{\frac{1}{\sqrt{2}}\left(|\, 2, 0 > + \,|\, 0, 2 >\right)}$$

VOLUME 59, NUMBER 18 PHYSICAL REVIEW LETTERS 2 NOVEMBER 1987

Measurement of Subpicosecond Time Intervals between Two Photons by Interference

C. K. Hong, Z. Y. Ou, and L. Mandel
Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627

(Received 10 July 1987)

A fourth-order interference technique has been used to measure the time intervals between two photons, and by implication the length of the photon wave packet, produced in the process of parametric down-conversion. The width of the time-interval distribution, which is largely determined by an interference filter, is found to be about 100 fs, with an accuracy that could, in principle, be less than 1 fs.

PACS numbers: 42.50.Bs, 42.65.Re

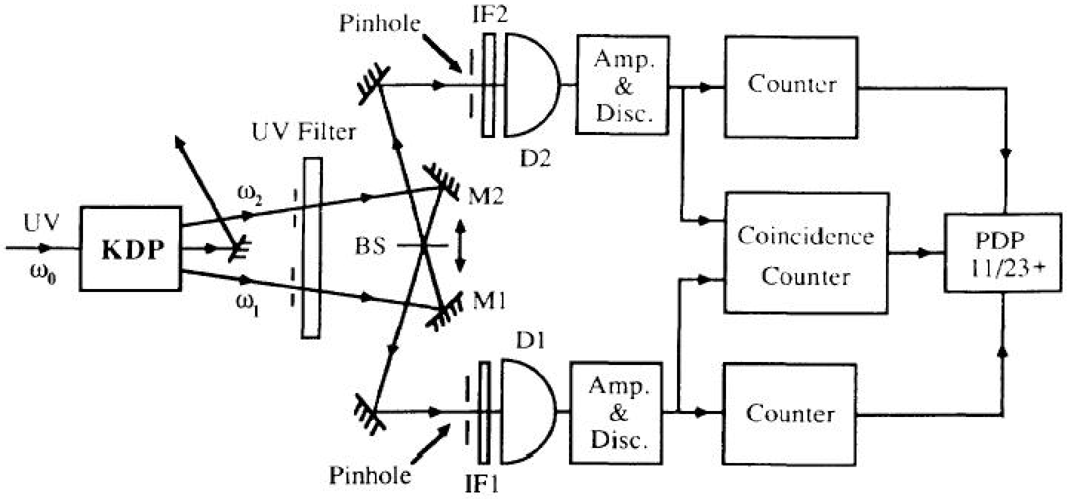


FIG. 1. Outline of the experimental setup.

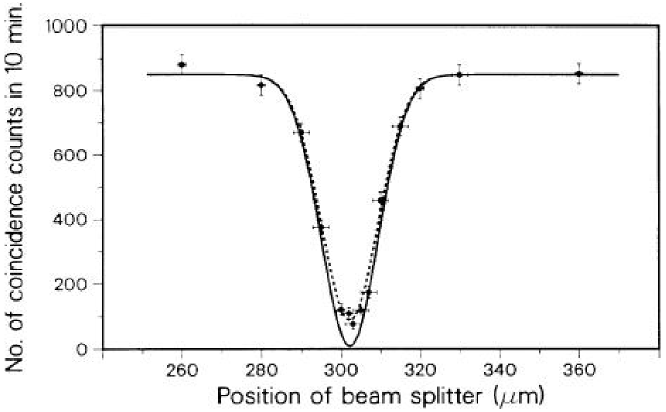
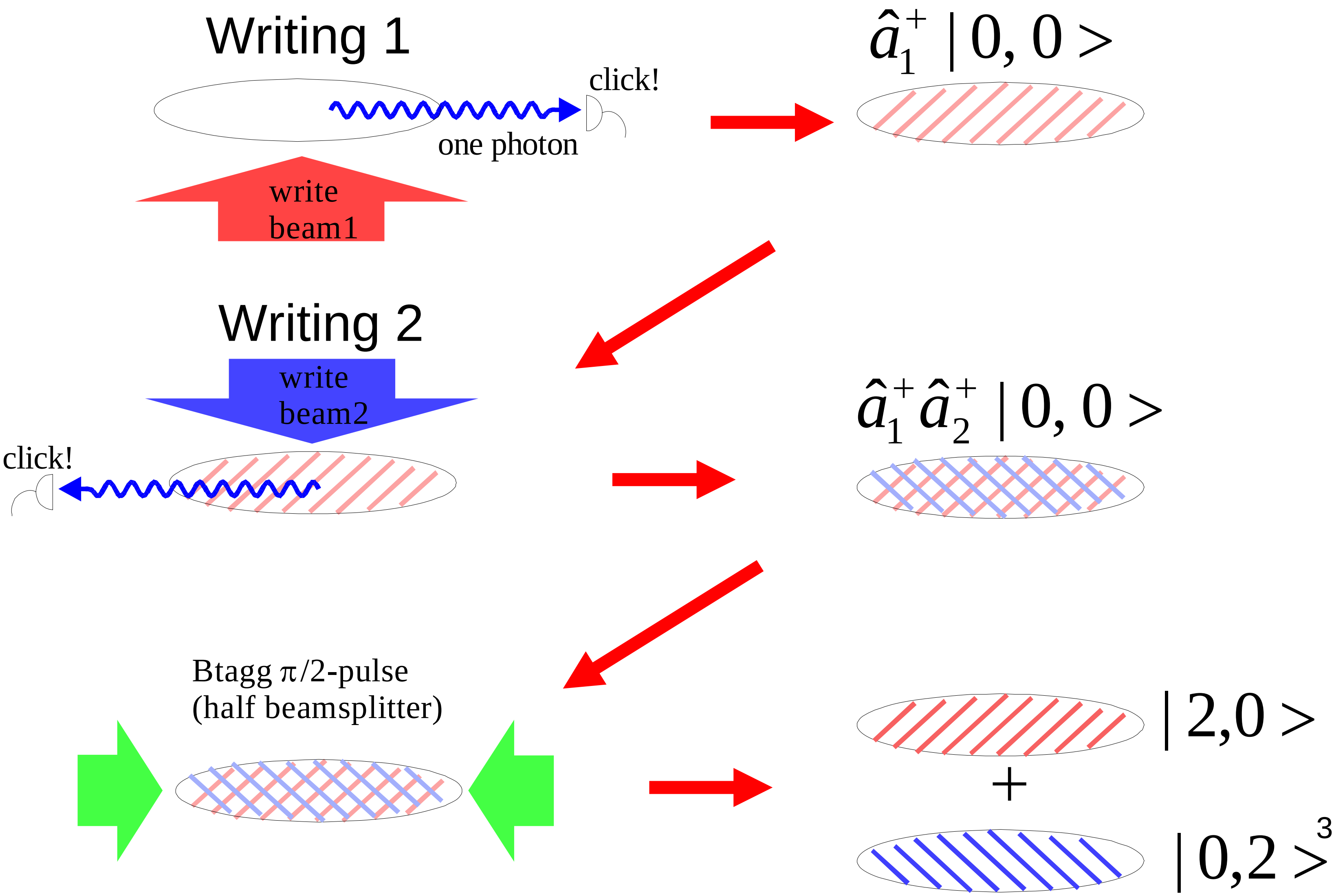


FIG. 2. The measured number of coincidences as a function of beam-splitter displacement $c\,\delta\tau$, superimposed on the solid theoretical curve derived from Eq. (11) with $R/T=0.95$, $\Delta\omega=3\times10^{13}$ rad s^{-1}. For the dashed curve the factor $2RT/(R^2+T^2)$ in Eq. (11) was multiplied by 0.9. The vertical error bars correspond to one standard deviation, whereas horizontal error bars are based on estimates of the measurement accuracy.

2原子（準粒子）の2粒子干渉



Writing 1

click!

one photon

write beam1

$\hat{a}_1^+ \,|0, 0>$

Writing 2

write beam2

click!

$\hat{a}_1^+ \hat{a}_2^+ \,|0, 0>$

Btagg π/2-pulse
(half beamsplitter)

$|2,0>$

$+$

$|0,2>$

まとめ

- 超放射（もしくは物質波増幅）は、ボーズ粒子系に特有の現象ではない。（位相整合を満たす方向への）散乱レートがコヒーレンス時間の逆数を上回ればよい。
- ディッケ状態は、単一（もしくは任意）光子発生器として量子情報処理の分野でも重要なツールの一つである。また量子原子光学の開拓にとっても重要なツールである。