Лекция 2. Высокотемпературные фазовые переходы в атомно-оптических системах

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Plan of Lecture 2

1. Critical phenomena for coupled atom-light system under the OC

   - ✓ Two-level Laser;
   - ✓ Superradiant phase transition;

2. True BECs in low dimensional gas of “light” particles.

   - ✓1D BEC with atomic polaritons in microtubes;
   - ✓2D BEC of photons

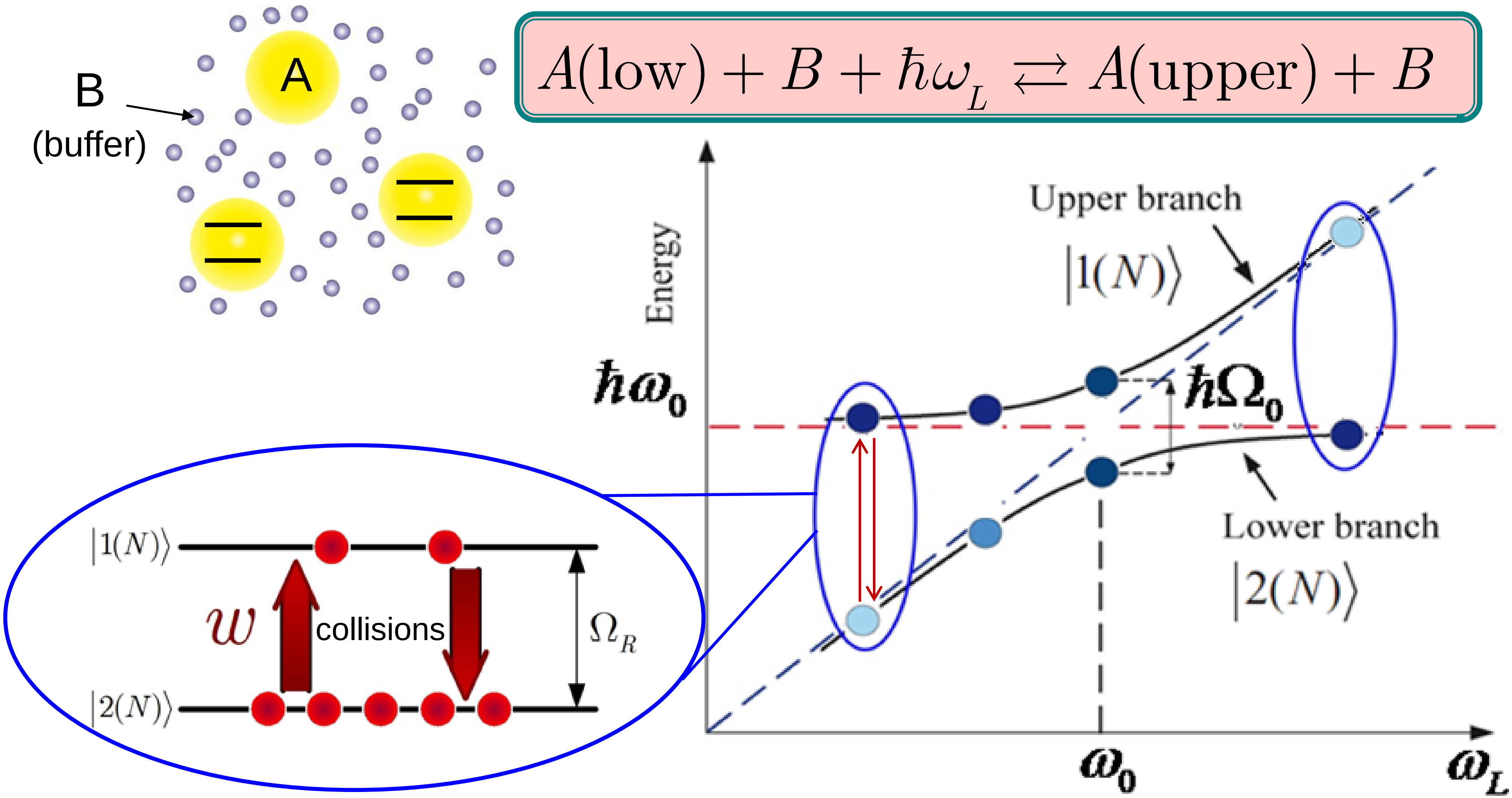
3. Some applications of OC for cooling

4. Outlook

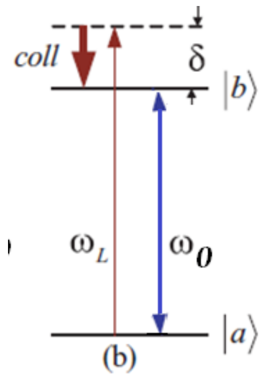
Thermalization of coupled atomic states

Optical collisions process

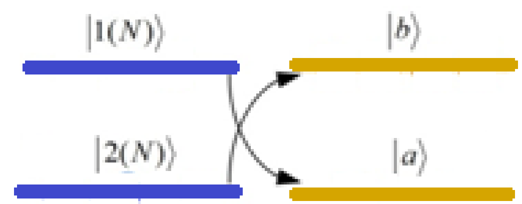
$$A(\text{low}) + B + \hbar\omega_L \rightleftarrows A(\text{upper}) + B$$

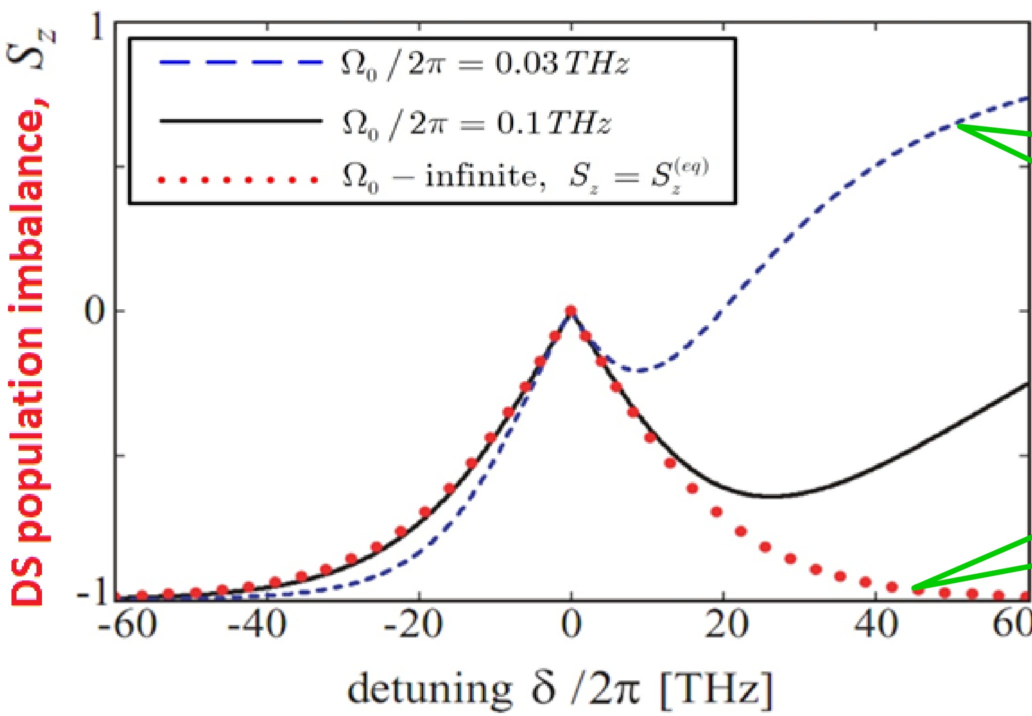


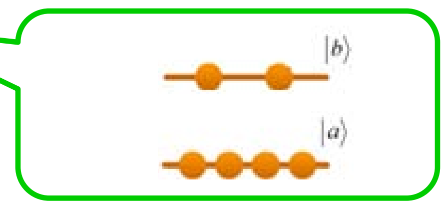
Quasi-thermalization at positive detuning



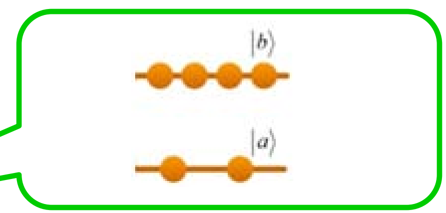
For $\delta > 0$ we have







No inversion due to spontaneous emission

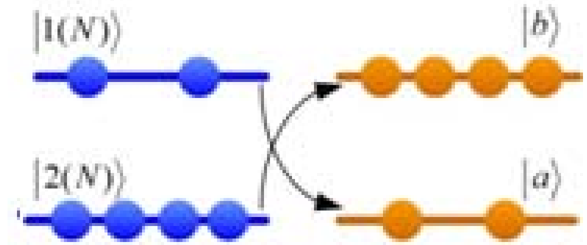


Inversion!

$$\frac{\Gamma}{\gamma} << \frac{\Omega_0^2}{\delta^2} << 1$$

Laser

For $\delta > 0$ we have



Experiment (Р.В. Марков, А.И. Пархоменко, А.И. Плеханов, А.М. Шалагин, *ЖЭТФ*, **136,** 211 (2009))

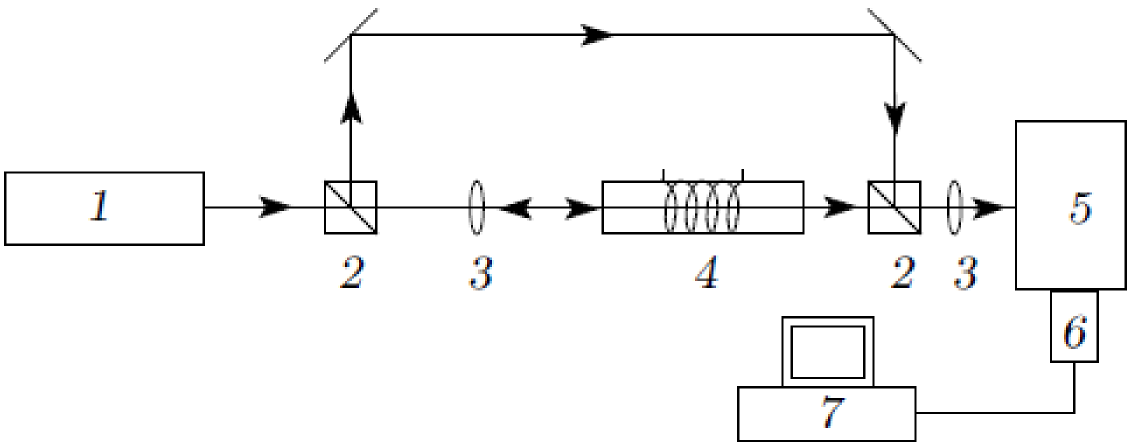


Схема экспериментальной установки: *1* — импульсный лазер на красителе, *2* — светоделительные кубики, *3* — фокусирующие линзы, *4* — ячейка с парами натрия, *5* — монохроматор, *6* — приемник излучения, *7* — компьютер

Температура газа

$T = 580\, K$

Давление

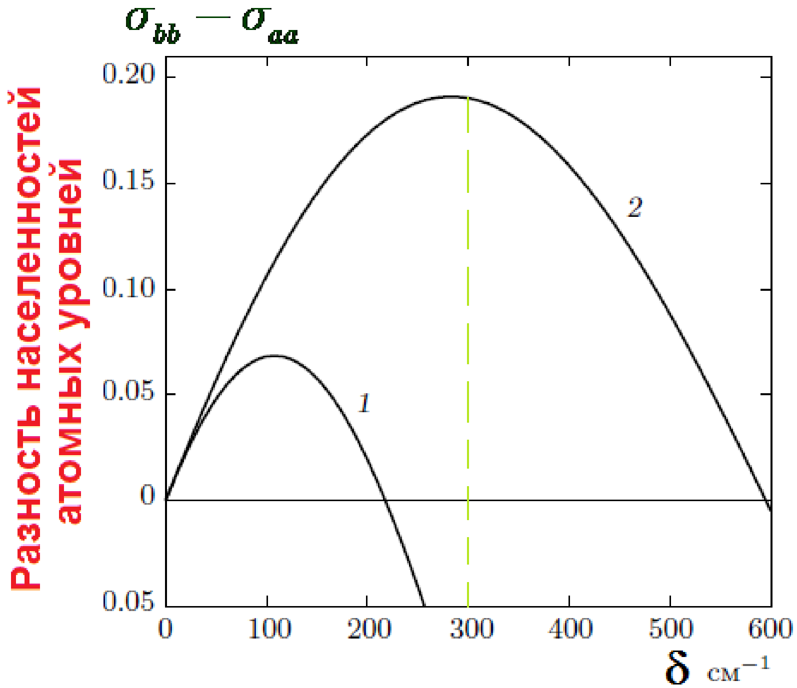
P=4атм.

Буферный газ - гелий

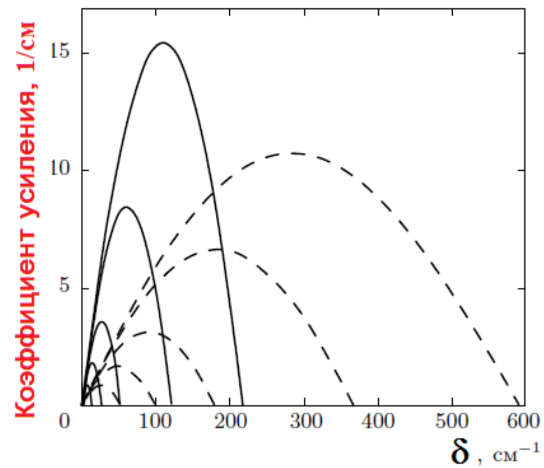
Интенсивность

$130\, MBm/cm^2$

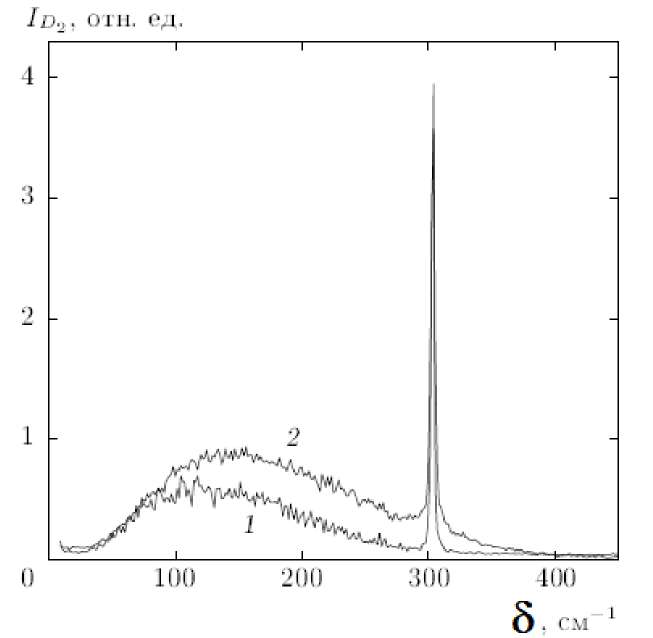
Experiment results



Зависимости инверсии населенностей в двухуровневой системе от отстройки частоты возбуждающего излучения; $I = 100$ МВт/см^2, $T = 600$ К, $\lambda = 0.6$ мкм, $\Gamma_l = 10$ МГц, $\Gamma_{oc} = \Gamma$, $\Gamma/P = 10$ МГц/Торр, давление буферного газа $P = 1$ (*1*), 4 (*2*) атм



Коэффициент усиления на резонансной частоте перехода в зависимости от отстройки частоты возбуждающего излучения δ

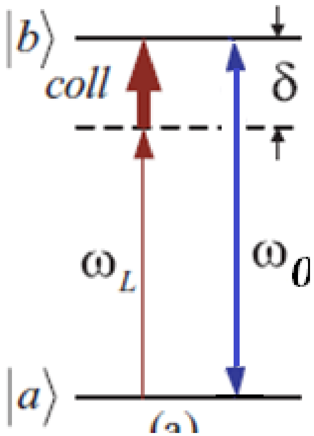


Интенсивность излучения на частоте ω_{D_2} резонансного перехода натрия $3P_{3/2}$–$3S_{1/2}$ (D_2-линия, $\lambda = 5890$ Å) в зависимости от отстройки частоты возбуждающего излучения $\delta = \omega - \omega_{D_2}$. $I = 50$ (*1*), 130 (*2*) МВт/см^2

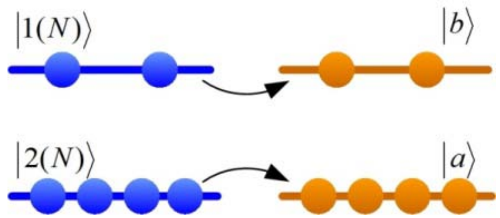
При $\hbar|\delta| \simeq k_B T$

Коэф. усиления ≈ 45

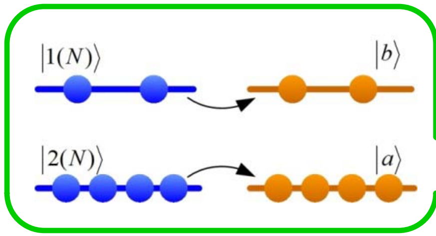
Thermalization at negative detuning



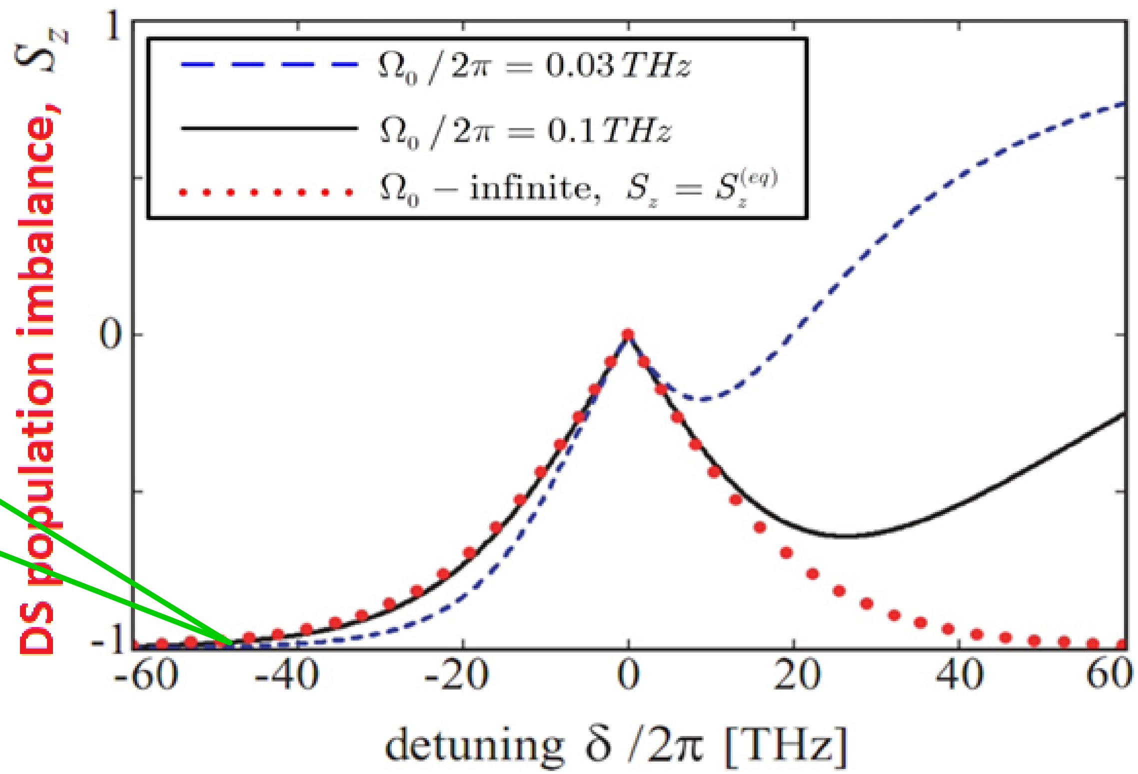
For $\delta < 0$ we have



No inversion



$$\frac{\Gamma}{\gamma} << \frac{\Omega_0^2}{\delta^2} << 1$$



Thermodynamic Approach For Atom-Field Interaction

Hamiltonian of collective atom-field interaction

$$H = \hbar\omega_L f^\dagger f + \frac{\hbar\omega_0}{2}\sum_j S_{z,j} + \frac{\hbar\kappa}{\sqrt{N_{at}}}\sum_j \left(S_{-,j} f^\dagger + S_{-,j}^\dagger f\right)$$

where $S_{z,j} = 0.5\left(|b\rangle\langle b| - |a\rangle\langle a|\right)$ **is operator of population imbalance,**

$\kappa = g\sqrt{N_{at}}$ **is collective atom-field interaction parameter, is** N_{at} **a number of atoms.**

Total number of atom-field excitations

$$N_{ex} = f^\dagger f + \frac{1}{2}\sum_j S_{z,j}$$

Thermodynamic approach implies calculation of partition function

$$Z(N_{at}, T) = \mathrm{Tr}\left[e^{-H'/k_B T}\right]$$

where $H' = H - \mu N_{ex}$, μ **is chemical potential,**

cf. *K. Hepp, E. H. Lieb, Ann. Phys. (NY) 76, 360 (1973); Y. K. Wang ,F. T. Hioe, Phys. Rev. A 7, 831 (1973).*

Calculations

PHYSICAL REVIEW A
GENERAL PHYSICS

THIRD SERIES, VOL. 7, NO. 3 — MARCH 1973

Phase Transition in the Dicke Model of Superradiance*

Y. K. Wang and F. T. Hioe

Расчет проводим в базисе когерентных состояний $a|\alpha\rangle = \alpha|\alpha\rangle; \quad \langle\alpha|a^\dagger = \langle\alpha|\alpha^*$

$$Z(N,T) = \sum_{s_1=\pm 1} \cdots \sum_{s_N=\pm 1} \int \frac{d^2\alpha}{\pi} \langle s_1 \cdots s_N | \langle \alpha | e^{-\beta H} | \alpha \rangle | s_1 \cdots s_N \rangle ,$$

$$\begin{aligned} Z(N,T) &= \int \frac{d^2\alpha}{\pi} \sum_{s_1=\pm 1} \cdots \sum_{s_N=\pm 1} e^{-\beta|\alpha|^2} \left(\prod_{j=1}^{N} \langle s_j | e^{-\beta h_j} | s_j \rangle \right) \\ &= \int \frac{d^2\alpha}{\pi} e^{-\beta|\alpha|^2} \left(\langle +1 | e^{-\beta h} | +1 \rangle + \langle -1 | e^{-\beta h} | -1 \rangle \right)^N \\ &= \int \frac{d^2\alpha}{\pi} e^{-\beta|\alpha|^2} (\mathrm{Tr}\, e^{-\beta h})^N , \end{aligned} \qquad (15)$$

where

$$h = (\tfrac{1}{2}\epsilon)\sigma^z + (\lambda/2\sqrt{N})(\alpha^*\sigma^- + \alpha\sigma^+) . \qquad (16)$$

$$Z(N,T) = 2\int_0^\infty r\,dr\, e^{-\beta r^2} \times \{2\cosh[(\tfrac{1}{2}\beta\epsilon)(1 + 4\lambda^2 r^2/\epsilon^2 N)]\}^N . \qquad (23)$$

Метод Лапласа

$$Z(N,T) = N \frac{C}{\sqrt{N}} \max_{0 \le y \le \infty} \exp\left\{N\left[-\beta y + \ln\left(2\cosh\{(\tfrac{1}{2}\beta\epsilon)[1 + (4\lambda^2/\epsilon^2)y]^{1/2}\}\right)\right]\right\}$$

Equation for Order Parameter

BCS-type equation

$$\lambda\tilde{\omega}_L = \lambda \frac{\kappa^2 \tanh\left(\frac{\hbar}{2k_B T}\left(\tilde{\omega}_{at}^2 + 4\kappa^2\lambda^2\right)^{1/2}\right)}{\left(\tilde{\omega}_{at}^2 + 4\kappa^2\lambda^2\right)^{1/2}}$$

$$\tilde{\omega}_{at} = \omega_{at} - \mu, \quad \tilde{\omega}_L = \omega_L - \mu$$

$\lambda^2 = \left\langle f^\dagger f \right\rangle / N_{at}$ **is normalized average photon number (order parameter),**

Normal phase solution is $\lambda = 0,$

Superradiant phase solution is $\lambda \neq 0.$

Polaritons

Definition of polariton annihilation operators

$$\Phi_{UP} = Cf + Xp$$ - upper branch polaritons

$$\Phi_{LP} = Xp - Cf$$ - lower branch polaritons

where p is an operator of atomic collective polarization, $C,\quad X$

are Hopfield coefficients;

$$C^2 = \frac{1}{2}\left(1 + \frac{\delta}{\sqrt{\delta^2 + \kappa^2}}\right) \qquad X^2 = \frac{1}{2}\left(1 - \frac{\delta}{\sqrt{\delta^2 + \kappa^2}}\right)$$

Bosonic commutation relations

Lets suppose that $\left[f, f^{+}\right] = 1 \quad \left[p, p^{+}\right] = 1$ ⇒ $\sigma_{bb} << \sigma_{aa} \simeq 1$

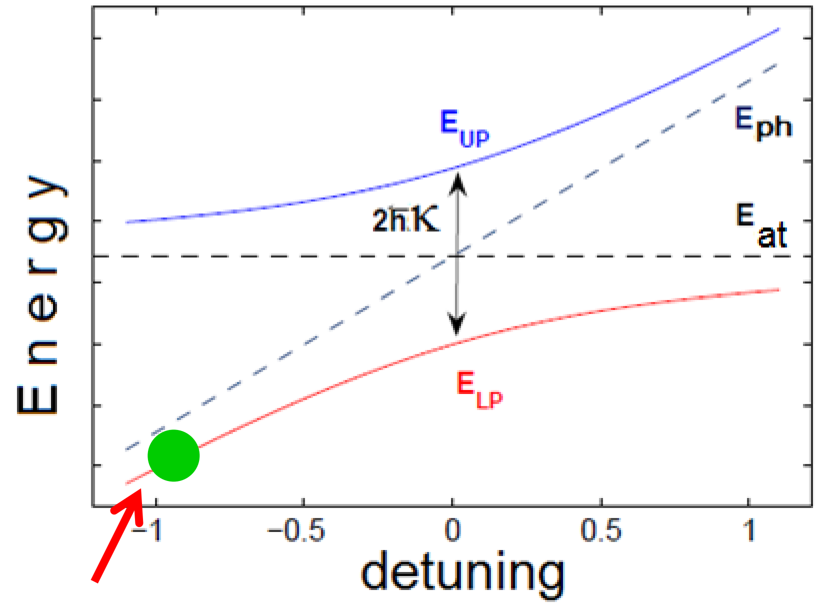
Atomic system without inversion

$$\left[\Phi_{UP}, \Phi_{UP}^{+}\right] = 1 \qquad \left[\Phi_{LP}, \Phi_{LP}^{+}\right] = 1$$

Polaritonic Model of Atom-Field Interaction

Polariton Energy versus atom-light detuning

$$E_{LP,UP} = \frac{1}{2}\left[E_{at} + E_{ph} \pm \sqrt{4\hbar^2\kappa^2 + \delta^2}\,\right]$$



Polariton model valid if

negative atom-field detuning $\delta < 0$

"low temperature" limit $\hbar \mid \delta \mid >> k_B T$

$$\sigma_{bb} << \sigma_{aa} \simeq 1$$

1. **For negative detuning δ under the "low temperature" limit the LB polaritons are photon-like, i.e.** $\Phi_{LP} \simeq f$
2. **No inversion in the atomic system!**

Atom-field Excitations: Mean-Field Theory

Definition 1. Total atom-field excitation density taken from OC model

$$\rho^{(1)} = \frac{1}{2} + \langle N_{ex} \rangle = \lambda^2 + \sigma_{bb}$$

where $\lambda^2 = \langle f^\dagger f \rangle / N_{at}$ **is normalized average photon number (order parameter),**

Definition 2. Total atom-field excitation density

$$\rho^{(2)} = \langle \Phi_1^\dagger \Phi_1 + \Phi_2^\dagger \Phi_2 \rangle / N_{at}$$

It is important that

$$\rho^{(1)} = \rho^{(2)} \equiv \rho$$

Excitation density at equilibrium

$$\rho = \lambda^2 + \frac{1}{2}\left[1 + S_z^{(eq)}\right]$$

where

$$S_z^{(eq)} = -\frac{\tilde{\omega}_{at} \tanh\left(\frac{\hbar}{2k_B T}\left(\tilde{\omega}_{at}^2 + 4\kappa^2\lambda^2\right)^{1/2}\right)}{\left(\tilde{\omega}_{at}^2 + 4\kappa^2\lambda^2\right)^{1/2}}$$

is equilibrium atomic population imbalance,

$$\tilde{\omega}_{at} = \omega_{at} - \mu, \quad \tilde{\omega}_L = \omega_L - \mu$$

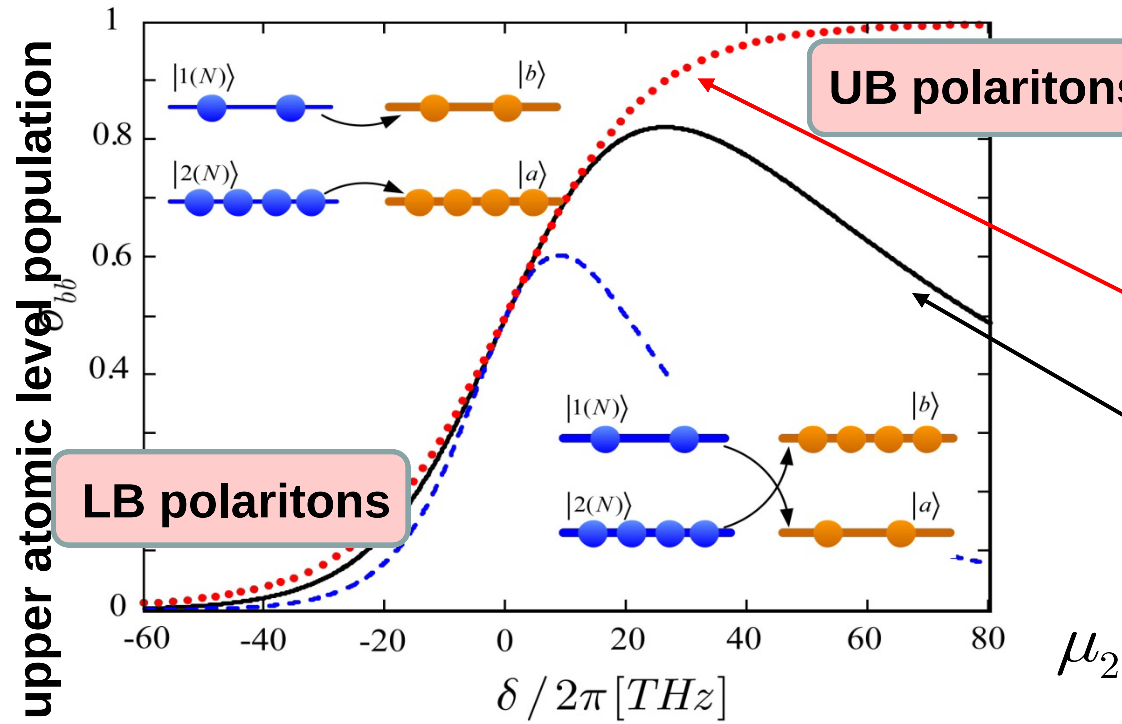
Superradiant Solutions, $\lambda \neq 0$

Solutions for chemical potential

$\mu_1 = \frac{1}{2}(\omega_{\text{at}} + \omega_L + \Omega_{R,\text{eff}})$, **corresponds to upper branch polaritons**

$\mu_2 = \frac{1}{2}(\omega_{\text{at}} + \omega_L - \Omega_{R,\text{eff}})$, **corresponds to lower branch polaritons**

We should consider limit of photon-like polaritons $\mu \simeq \omega_L$



Population imbalance is

$$S_z^{(eq)} \simeq -\frac{\delta}{|\delta|} \tanh\left[\hbar|\delta|/2k_B T\right]$$

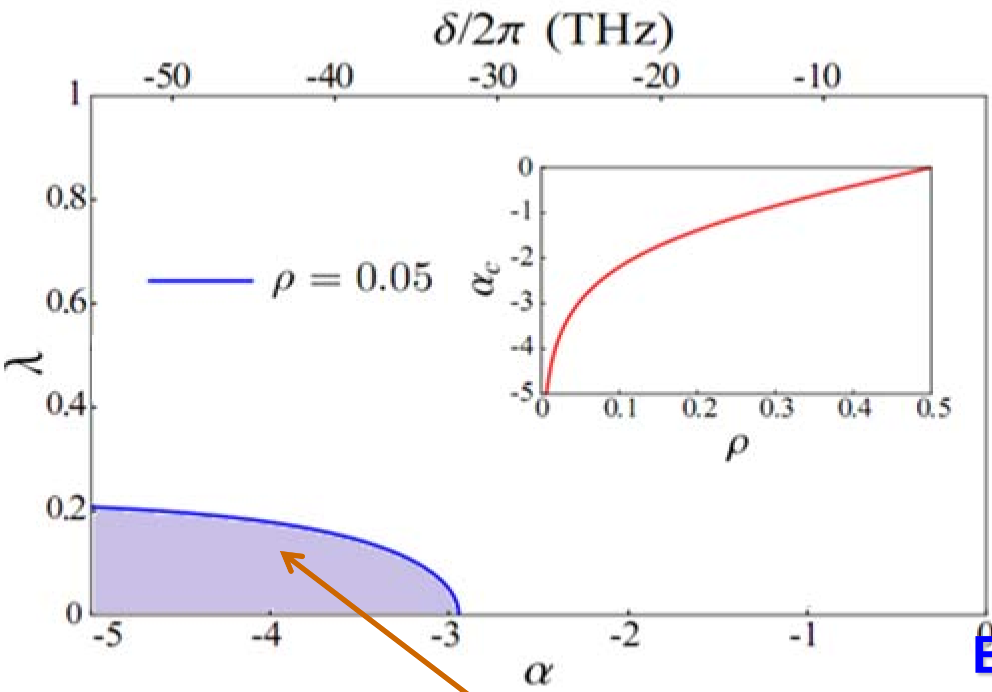
Full thermodynamic equilibrium

$$\sigma_{bb} = \frac{1}{1+e^{-\hbar\delta/k_b T}}$$

Quasi-equilibrium state

Photon-like Phase Transition for LB Polaritons

Order parameter behavior can be approximated as



$$\lambda(\alpha) \simeq \lambda_\infty \left[1 - \rho^{\alpha/\alpha_C - 1}\right]^{1/2}$$

$\lambda_\infty \equiv \lambda(\alpha)\big|_{|\delta| \to \infty}$ **is order parameter at zero temperature limit**

$\alpha = \hbar\delta / k_B T$ **is normalized atom-field detuning**

$$k_B T << \hbar |\delta|$$

The "low temperature" domain corresponds to superfluid photon-like LB polaritons

Experimentally it is easier to manipulate by atom-field detuning instead of temperature

The critical value of vital parameter

$$\alpha_C \simeq -\ln\left[(1-\rho)/\rho\right]$$

Prerequisites for Polariton BEC Observation

Temporal window for polariton BEC observation

For polariton thermalization we should have *(I.Yu. Chestnov, A. P.Alodjants, S.M. Arakelian, Phys. Rev. A, 83, 053802 (2011))*

$$T_{therm} << \tau_{pol} \leq \tau_{spont}$$

where τ_{pol} is a polariton lifetime.

For current experiments with rubidium atoms under OC's we can have

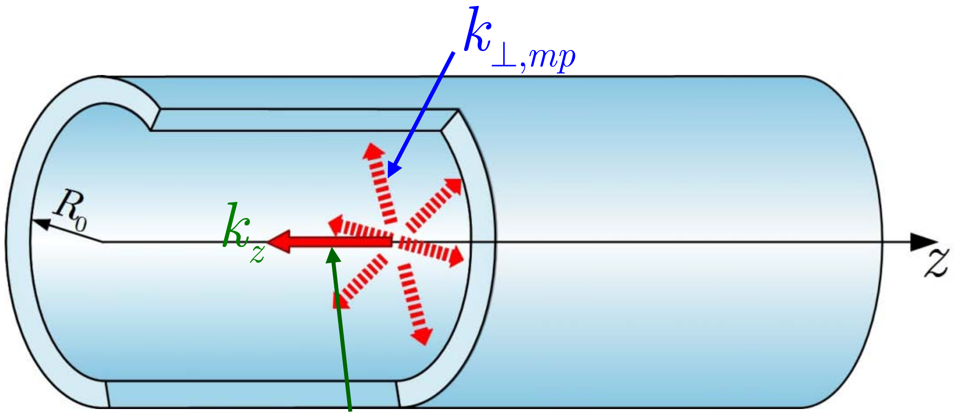
$$3ns < \tau_{pol} \leq 27ns$$

Conditions for polariton BEC observation

We should have:
(i) photon confinement to create finite photon mass;
(ii) cavity to increase time of atom-field interaction.

Photonic field inside metallic tube

Orthogonal wave vector component is quantized



Longitudinal wave vector forms a continuum

Helmholtz equation

$$\frac{1}{\rho}\frac{\partial}{\partial\rho}\left(\rho\frac{\partial \mathrm{E}}{\partial\rho}\right)+\frac{\partial^2\mathrm{E}}{\partial z^2}+\frac{1}{\rho^2}\frac{\partial^2\mathrm{E}}{\partial\varphi^2}+k^2\mathrm{E}=0$$

defines allowed modes

$$\mathrm{E}\sim J_m(k_\perp\rho)$$

J_m - функция Бесселя

Photon energy is $E_{ph}=\hbar c\sqrt{k_\perp^2+k_z^2}\simeq\hbar c k_\perp+\dfrac{\hbar c k_z^2}{2k_\perp}$

kinetic energy

$$E_{ph}\simeq m_{ph}c^2+\hbar^2k_z^2/2m_{ph}$$

Cutoff energy $\hbar\omega_{\mathrm{cutoff}}=m_{ph}c^2$

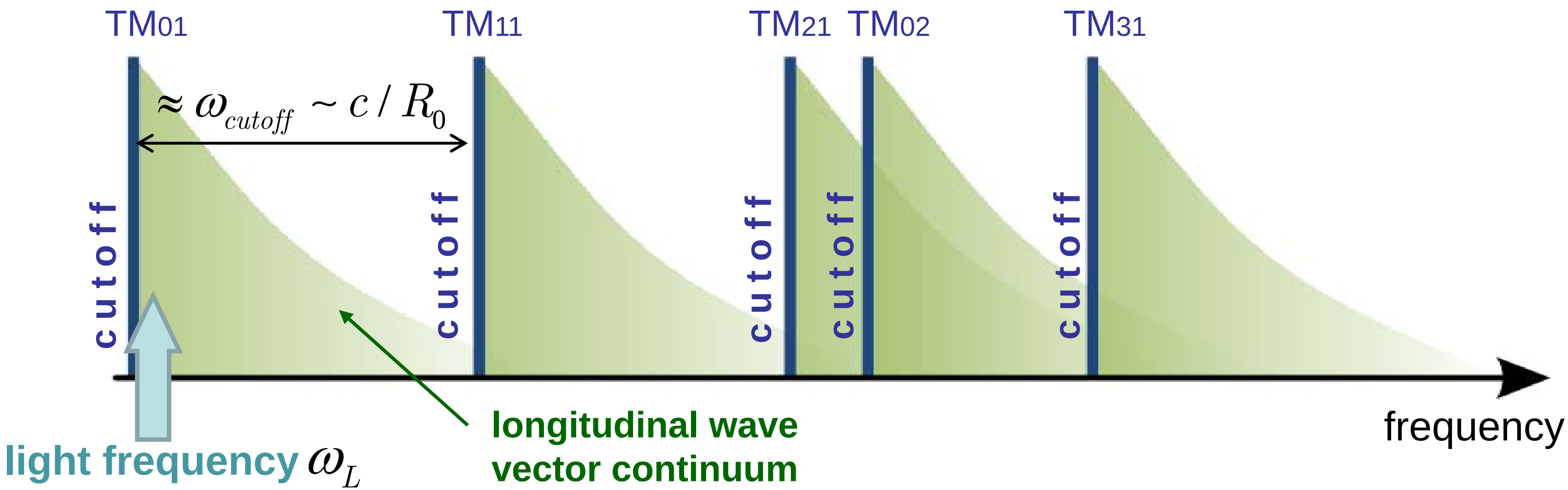
where

$m_{ph}=\hbar k_{\perp,mp}/c$ **is photonic mass**

m, p **are integer quantum numbers**

Photonic field inside metallic tube

TM-modes pattern of cylindrical waveguide:



For fulfilement a single transverse mode regime $\omega_{cutoff} \sim c / R_0 >> k_B T$

And we can guarantee the transverse quantum number is frozen.

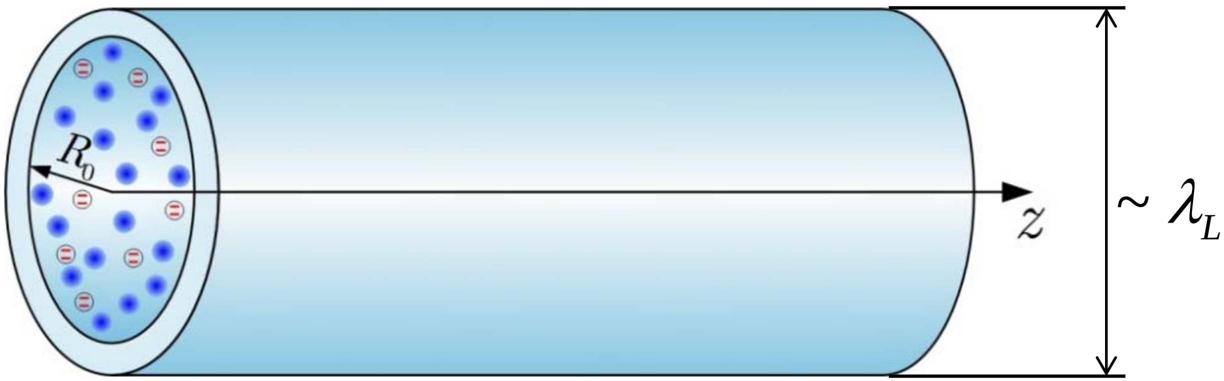
We take TM01 mode and

$$R_0 \sim 2.405c / \omega_L \approx 300 \text{ nm}$$

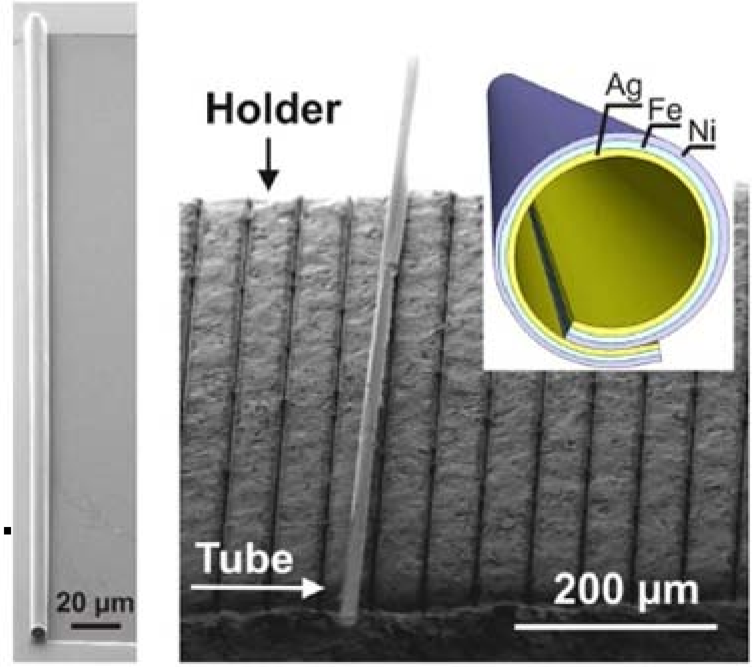
The system is effectively (kinematically) one dimensional

Photon and Atom Confining System

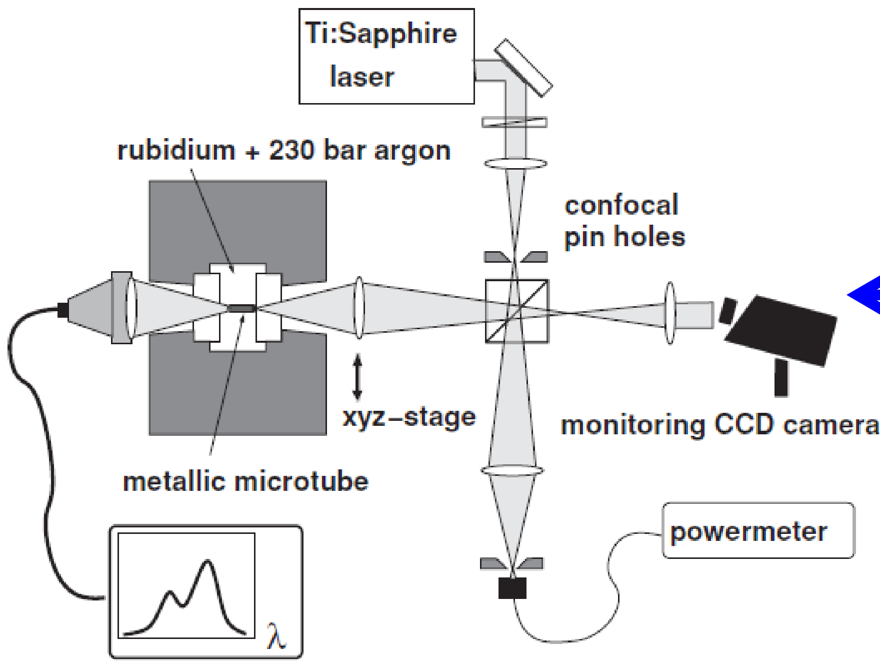
Metallic waveguides for confinement



Two level rubidium atoms, Buffer gas atoms.



O.G. Schmidt and K. Eberl, Nature 410, 168 (2001).



← **Experimental Set-up (Bonn Uni.)**

U. Vogl et al, *Phys. Rev. A 83, 053403 (2011)*

Некоторые особенности БЭК

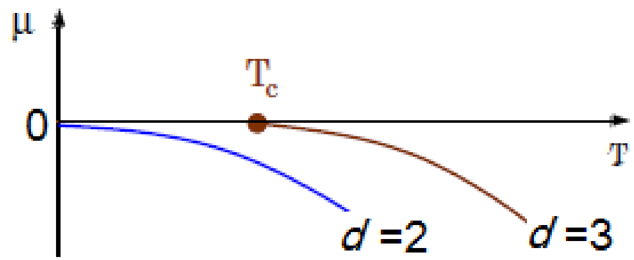
Равновесное распределение числа частиц (для идеального газа без ловушки)

$$N=\sum_{\vec{k}} N_{\vec{k}}=\int \frac{V^{(d)}}{(2\pi)^d}\frac{d^{(d)}k}{\exp\left[\left(E_{\vec{k}}-\mu\right)/k_BT\right]-1}$$

$d=1,2,3$ размерность системы (размерность газа), $V^{(d)}$ размерный объем, $E_{\vec{k}}=\dfrac{\hbar^2k^2}{2m}$

Ищем критическую температуру T_C БЭК полагая $\mu=0$

Зависимость химического потенциала μ от температуры



БЭК невозможна при

$T_C\neq 0$

Плотность состояний

$$\rho(\varepsilon)\propto\varepsilon^{(d/2-1)}$$

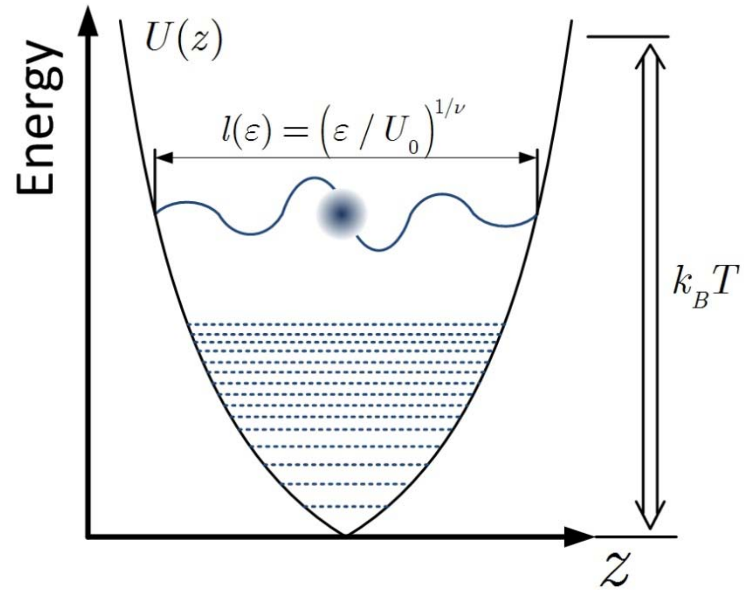
Убывает вместе с ε при $d=3$

При $d=1,2$ нужна ловушка для достижения необходимой плотности состояний

BEC in One Dimension in power-law potential

Non-interacting 1D Bose-gas in power law potential is

$$U(z) = U_0 |z|^\nu$$



Density of states is

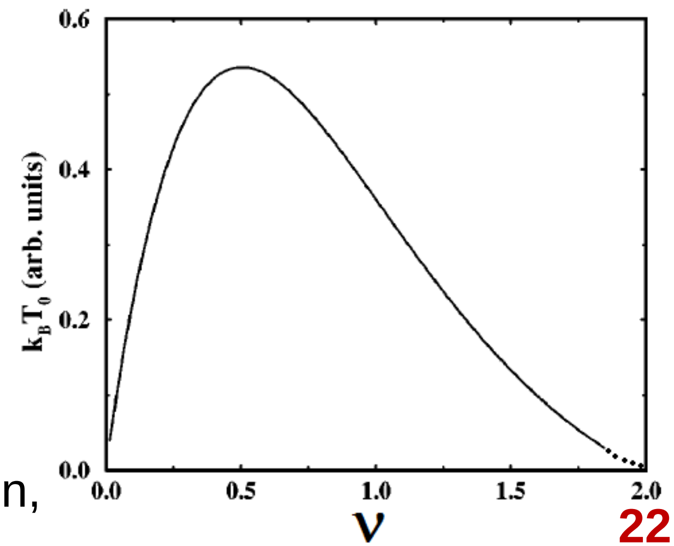
$$\rho(\varepsilon) = \frac{\sqrt{2}}{\pi\hbar} \int_0^{l(\varepsilon)} \left(\frac{m}{\varepsilon - U(z)} \right)^{1/2} dz.$$

where $l(\varepsilon) = (\varepsilon / U_0)^{1/\nu}$

BEC condition $\mu = 0, \quad T = T_C$

For $\nu = 2, T_C \to 0$!

In quasi-classical approximation the 1D system can support true BEC if trapping potential is more confining than parabolic .

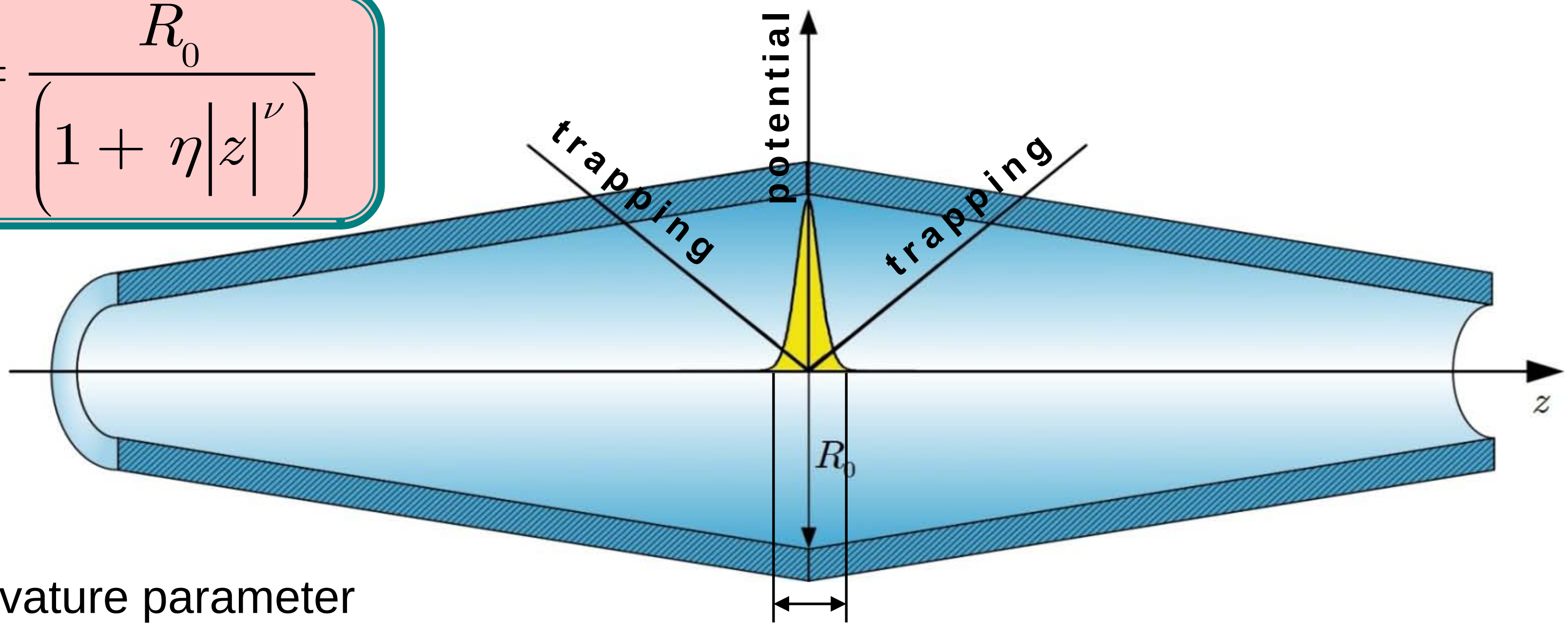


For $\nu = 2$ we are not able to use quasi-classical approximation, see D. S. Petrov, et al , *J. Phys. IV France* **116, 7 (2004).**

Biconical Waveguide Cavity For Photon Trapping

Waveguide for photon (LB polariton) trapping

$$R(z) = \frac{R_0}{\left(1 + \eta \left|z\right|^{\nu}\right)}$$



$\sim 2d_{ph}$ characteristic scale of photon localization

η is curvature parameter

Photon energy is

kinetic energy

$$E_{ph} \simeq m_{ph}c^2 + \hbar^2 k_z^2 / 2m_{ph} + U_{ph}\left|z\right|^{\nu}$$

cutoff ground energy

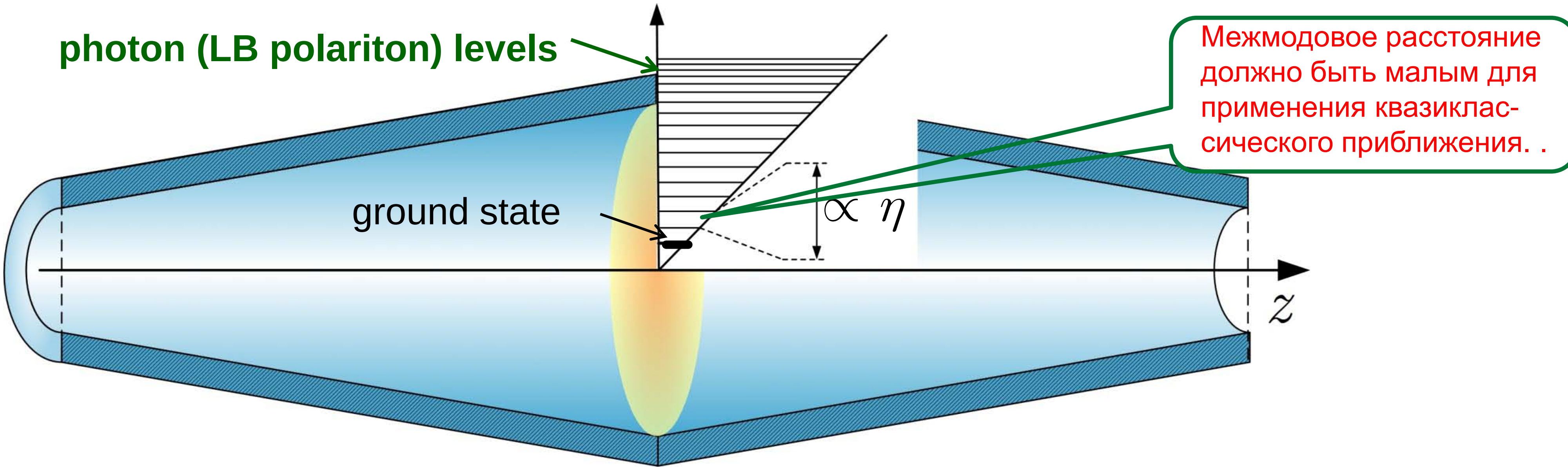
trapping energy

$$U_{ph} = m_{ph}c^2\eta$$

photonic potential

Photon (LB polariton) is confined inside the potential

Biconical Waveguide Cavity For Photon Trapping



Photon energy spectrum $E_n = \hbar\omega_{tr}(n + 1/2)^{2\nu/(\nu+2)}$ Bohr-Sommerfeld quantization rule

where $\omega_{tr} \propto \eta$

Waveguide parameters:

Maximal radius is $R_0 \sim 2.405c/\omega_L \approx 300\ \mathrm{nm}$

Fundamental TM_{01} **mode volume** $V_{\mathrm{mode}} \sim \mu\mathrm{m}^3$ → Single transverse mode regime

Waveguide radius variation should be slow, i.e. η **small** → Quasiclassical BEC description

Main Approximations

Energy spacing between polariton energy levels		Thermal energy		Energy spacing between polariton branches
ΔE_n	$<<$	$k_B T$	$<<$	$\hbar\sqrt{\delta^2 + 4\kappa^2}$

quasiclassical approximation ($\Delta E_n << k_B T$)

upper polariton branch neglecting condition ($k_B T << \hbar\sqrt{\delta^2 + 4\kappa^2}$)

Is a polariton gas really ideal?

Atom-light Hamiltonian with saturation nonlinearity

$$H=\hbar\sum_{\vec{k}}\left(\omega_{ph}\hat{f}_{\vec{k}}^{\dagger}\hat{f}_{\vec{k}}+\omega_{at}\hat{p}_{\vec{k}}^{\dagger}\hat{p}_{\vec{k}}+\kappa\left(\hat{f}_{\vec{k}}^{\dagger}\hat{p}_{\vec{k}}+\hat{p}_{\vec{k}}^{\dagger}\hat{f}_{\vec{k}}\right)-\frac{\hbar\kappa}{2N_{at}}\sum_{kk'q}\left(\hat{f}_{k+q}^{\dagger}\hat{p}_{k'-q}^{\dagger}\hat{p}_{k}\hat{p}_{k'}+\hat{p}_{k}^{\dagger}\hat{p}_{k'}^{\dagger}\hat{p}_{k'-q}\hat{f}_{k+q}\right)\right)$$

κ is a collective atom-light coupling parameter

In a polariton basis, neglecting upper branch polaritons

$$H_{LB}=\hbar\sum_{\vec{k}}\left(\frac{\hbar k_z^2}{2m_{pol}}+U_{\mathrm{pol}}\left|z\right|^{\nu}\right)\hat{\Xi}_{2,\vec{k}}^{\dagger}\hat{\Xi}_{2,\vec{k}}+\sum_{kk'q}U_{\vec{k}\vec{k}'\vec{q}}\hat{\Xi}_{2,k+q}^{\dagger}\hat{\Xi}_{2,k'-q}^{\dagger}\hat{\Xi}_{2,k}\hat{\Xi}_{2,k'}$$

$$m_{pol}\approx m_{ph}\frac{2\left(\Delta^2+4\kappa^2\right)^{1/2}}{\left(\Delta^2+4\kappa^2\right)^{1/2}+\left|\Delta\right|}$$ is polaritonic mass; $$U_{\mathrm{pol}}=U_{ph}\frac{\left(\Delta^2+4\kappa^2\right)^{1/2}+\left|\Delta\right|}{2\left(\Delta^2+4\kappa^2\right)^{1/2}}$$

Δ is atom-light detuning

$$U_{NL}\left(\propto CX^3\right)\approx\hbar\kappa^4/(N_{at}\left|\Delta\right|^3)$$ **nonlinear interaction parameter**

For photon-like polaritons $X(\text{atomic part})\rightarrow 0$ **and** $C(\text{photonic part})\rightarrow 1$

$\kappa/\left|\Delta\right|=0.057$
$U_{NL}\sim 20\ \mathrm{kHz}$

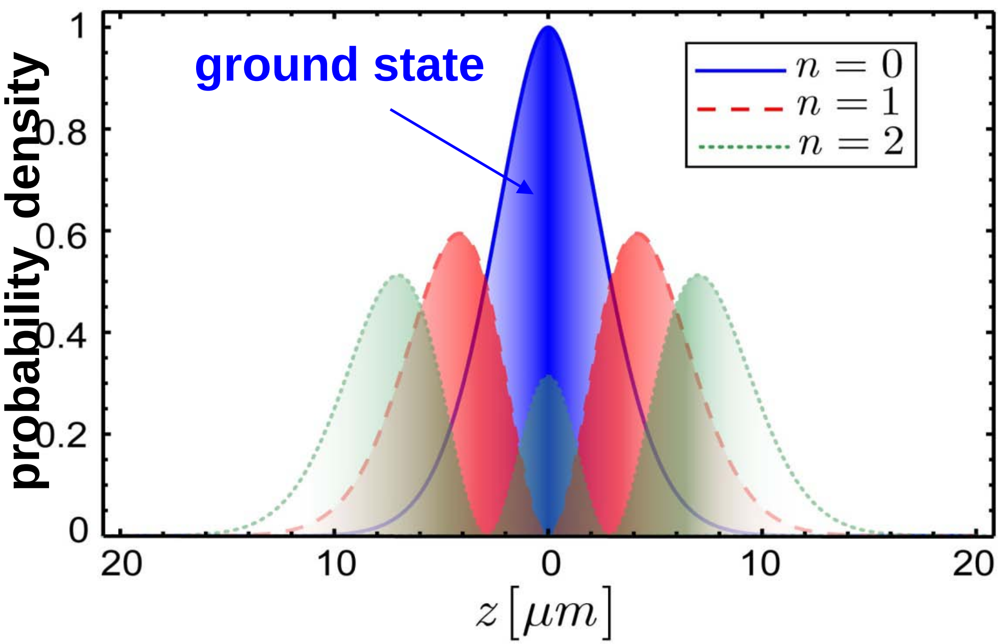
For experimental data

Photon-like LB polaritons in the BWC

Schrödinger equation for LB polaritons trapped in the cavity

$$\frac{\partial^2 \Psi(z)}{\partial z^2} + \frac{2m_{pol}}{\hbar^2}\left(E - U_{pol}\,|z|\right)\Psi(z) = 0$$

$U_{pol} = m_{ph}c^2\eta\left(\Omega_{R0} + |\Delta|\right)/2\Omega_{R0}$ **"force" acting on polariton inside the cavity**



polariton wave functions distribution

The solutions of Schrödinger equation are a set of Airy-shaped wave functions

$$\Psi_n = \frac{1}{\sqrt{d_{ph}}}\frac{1}{\sqrt{2}\sqrt{-a'_{n/2+1}}\mathrm{Ai}\left(a'_{n/2+1}\right)}\mathrm{Ai}\left(\frac{|z|}{d_{ph}} + a'_{n/2+1}\right),$$

$$E_n = -a'_{n/2+1}V_0 d_{ph}, \quad n = \{2k,\ k \in \mathbb{N}\},$$

$$\Psi_n = \frac{1}{\sqrt{d_{ph}}}\frac{\mathrm{sgn(z)}}{\sqrt{2}\mathrm{Ai}'\left(a_{(n+1)/2}\right)}\mathrm{Ai}\left(\frac{|z|}{d_{ph}} + a_{(n+1)/2}\right),$$

$$E_n = -a_{(n+1)/2}V_0 d_{ph}, \quad n = \{2k+1,\ k \in \mathbb{N}\}.$$

Waveguide parameters

$$\eta = 0.0005 \quad \mu\mathrm{m}^{-1}$$
$$R_0 \approx 0.3\ \mu\mathrm{m}$$

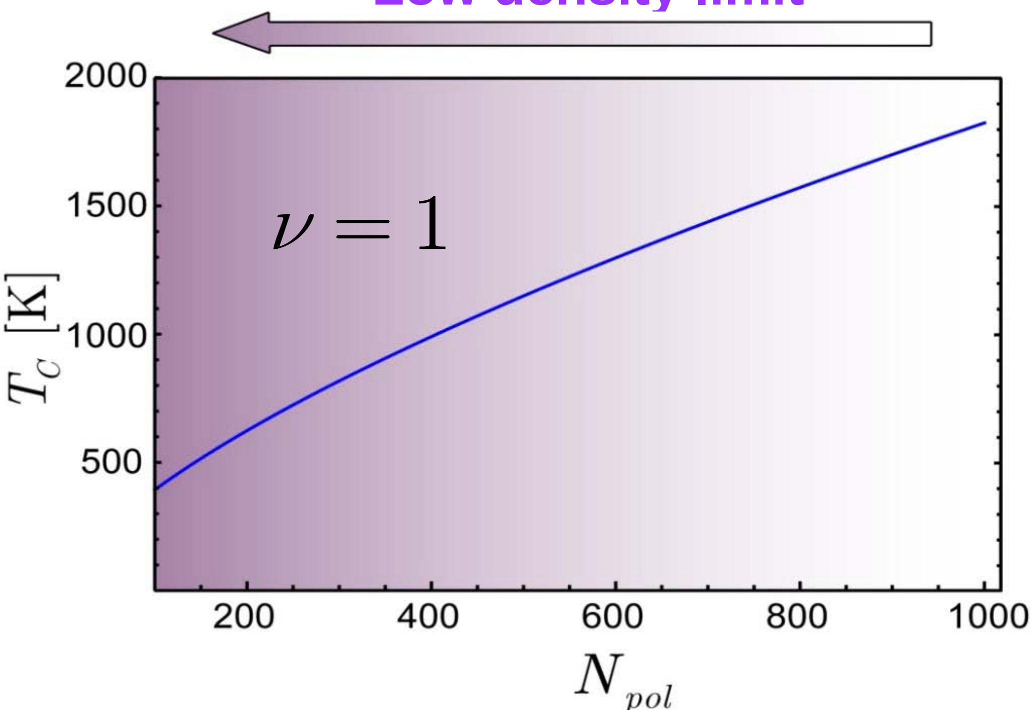
Polariton BEC in the BWC

Critical temperature for photon-like polariton BEC in a semiclassical limit

$$k_B T_C = \left[\frac{\pi \hbar N_{pol} \nu U_0^{1/\nu}}{\sqrt{2 m_{pol}} F(\nu) \Gamma(x) \zeta(x)} \right]^{2\nu/(2+\nu)}$$

$N_{pol} \approx N_{ph}$ **number of polaritons under the low density limit ($N_{ph} << N_{at}$)**

Low density limit



$$F(\nu) = \int_0^1 \frac{t^{1/\nu - 1} dt}{\sqrt{1-t}}$$

$\Gamma(x)$ gamma functions

$\zeta(x)$ Riemann functions

$x = 1/\nu + 1/2$

De Broglie wavelength at T=530K

$$\Lambda_T = [2\pi\hbar^2/(m_{\rm pol} k_B T)]^{1/2} = 1.89\ \mu{\rm m}$$

Возможна ли Бозе-Эйнштейновская конденсация фотонов?

Р. Кубо ***Статистическая Механика*** **, Мир: 1966г.**

имеет решение при $\mu < 0$. В этом случае величина $N_0 = O(1)$ и ею можно пренебречь по сравнению с N' $[= O(N)]$. При уменьшении T до T_c величина μ стремится к нулю, а при $T < T_c$ имеем $\mu = 0$ и $N_0 = O(N)$ (см. [4]) [1]).

6. Показать, что химический потенциал газа фотонов равен нулю.

РЕШЕНИЕ

Число фотонов в сосуде не является постоянным, так что объем сосуда V и температура T определяют лишь его среднее значение. Это связано с тем, что фотоны (свет) могут испускаться и поглощаться внутри сосуда и его стенками. Поэтому теперь мы должны отказаться от условия постоянства числа частиц ($N = \text{const}$), использованного при выводе распределения Бозе (см. гл. 1, задача 31). Соответственно химический потенциал, который был введен в качестве множителя Лагранжа, не входит в распределение Бозе. Это эквивалентно условию $\mu = 0$ в (4.14).

Ранние схемы получения БЭК фотонов

SOVIET PHYSICS JETP VOLUME 28, NUMBER 6 JUNE, 1969

BOSE CONDENSATION AND SHOCK WAVES IN PHOTON SPECTRA

Ya. B. ZEL'DOVICH and E. V. LEVICH

Institute for Applied Mathematics, USSR Academy of Sciences

Submitted July 12, 1968

Zh. Eksp. Teor. Fiz. 55, 2423–2429 (December, 1968)

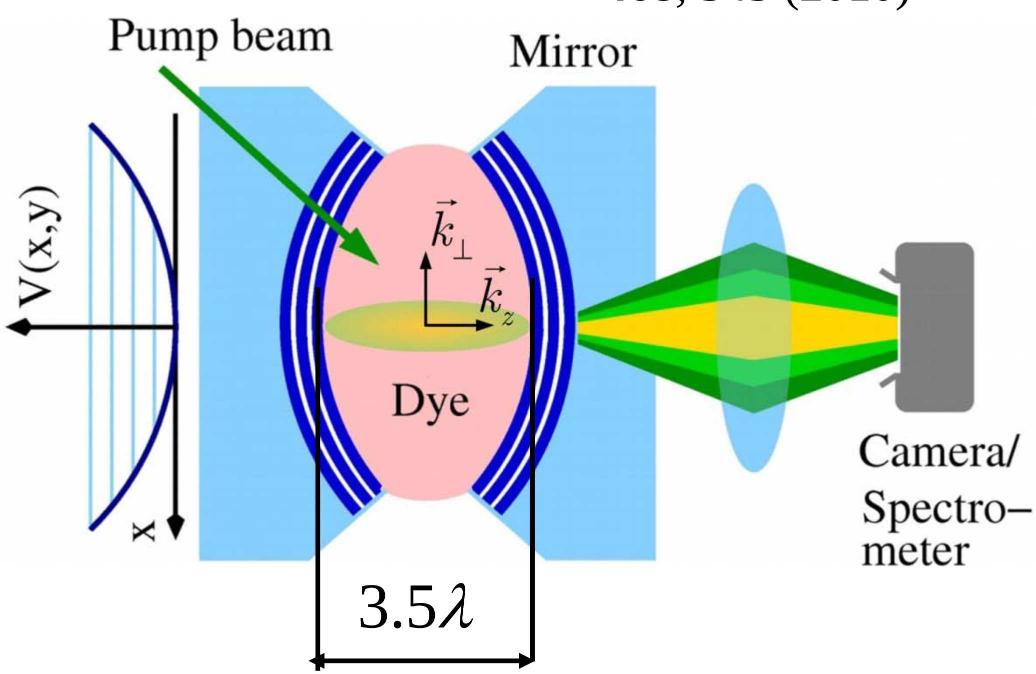
The process of establishment of equilibrium in a system consisting of radiation and totally ionized plasma is investigated. By solving the kinetic equation it is shown that in the absence of absorption the photons undergo Bose condensation. The process depends essentially on the form of the initial distribution. For a certain form of the initial spectrum a shock wave occurs in the spectrum in the course of its temporal evolution. The process is substantially affected by absorption, in the presence of which Bose condensation is replaced by an accumulation with time of the photons in the region of low frequencies.

«The statistical equilibrium between the photons and the plasma will establish itself as a result of both scattering processes, which do not involve a change of the number of photons, and processes involving the emission and absorption of photons».

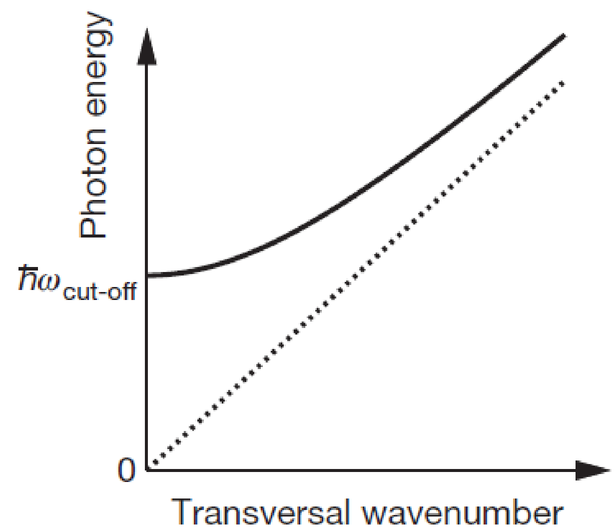
BEC of photons achieved by Compton scattering off a thermal electron gas

Photon 2D BEC in dye-filled microcavity

Experimental scheme J. Klaers, J.Schmitt, F. Vewinger & Martin Weitz, **Nature, 468**, 545 (2010)



Photon dispersion in the cavity



Confocal cavity forms transversal harmonic trapping

transversal kinetic energy

$$E_{ph} \simeq m_{ph}c^2 + \hbar^2 k_\perp^2 / 2m_{ph} + \frac{1}{2} m_{ph}\omega_{harm}^2 r^2$$

cutoff ground energy **harmonic trapping**

where $r = \sqrt{x^2 + y^2}$

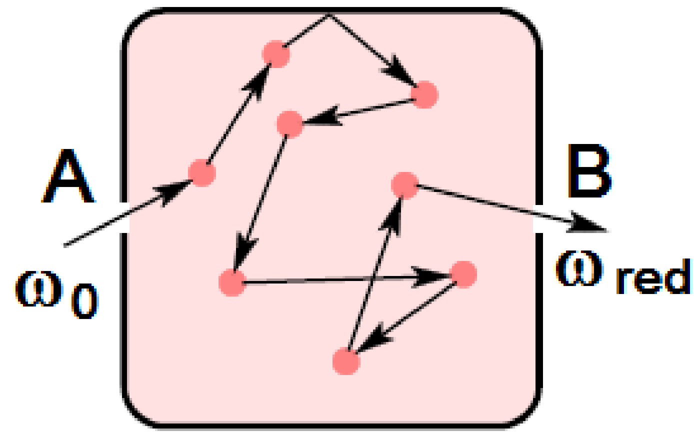
$$m_{ph} = \hbar k_z / c \simeq 6,7 \times 10^{-36} kg$$

is photonic mass

Photon gas forms kinematically two dimensional system

Photon Gas Thermalization

Multiple absorption-fluorescence cycles in a macroscopic dye-filled photon box.



$$\omega_0 > \omega_{red}$$

i) Spectrum at point B is red shifted with respect to that obtained for a single fluorescence event due to partial thermalization.

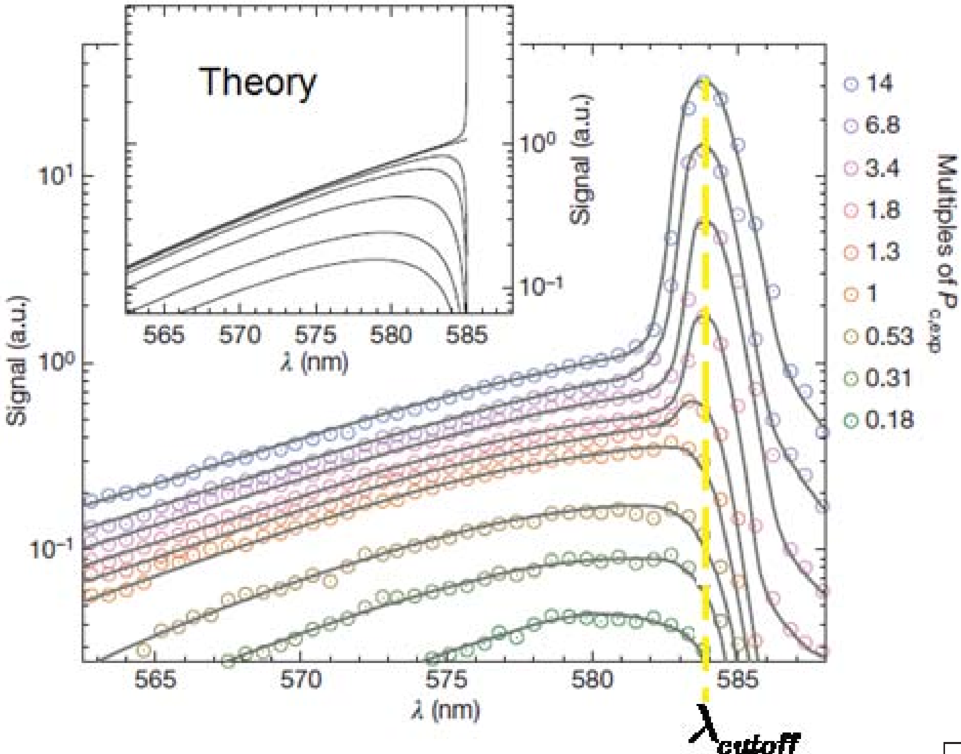
(i) Photon thermalization is reached due to multiply absorption and reemission processes in a dye solution;

iii) The process of thermalization in the box is incomplete due to limited spectral bandwith of the dye solution

iV) The low-frequency cutoff ω_{cutoff} , imposed by the resonator, prevents a succesive red-shift of the photon gas.

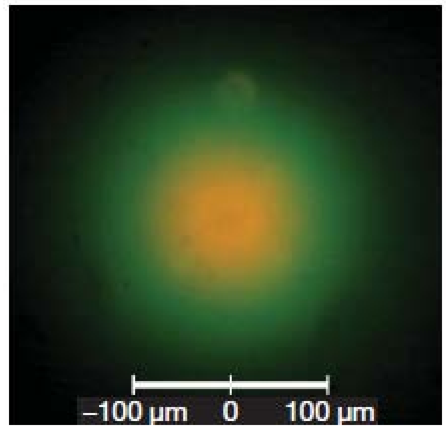
Photon BEC Observation

Spectral intensity distributions for



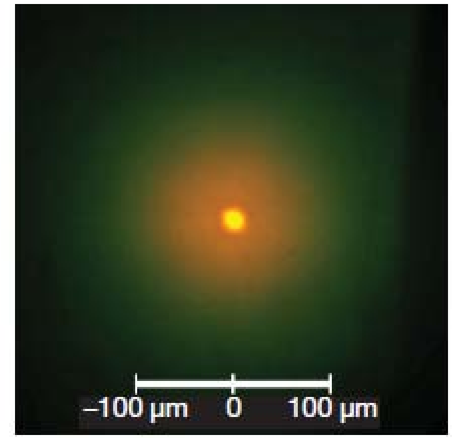
Images of the spatial radiation distribution

NO BEC



$$N < N_c$$

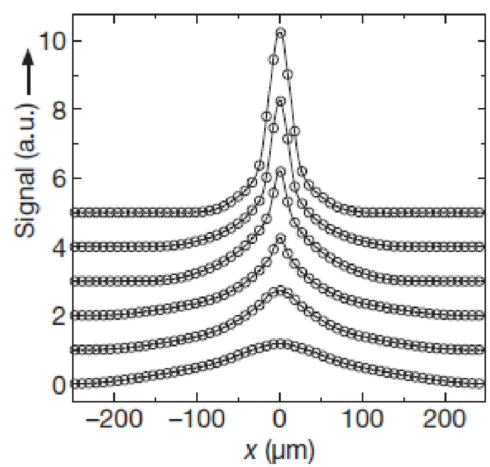
BEC !



$$N > N_c$$

Critical photon number **Practically more easier to vary photon number density instead of temperature**

$$N_c = \frac{\pi^2}{3}\left(\frac{k_B T}{\hbar\omega_{harm}}\right)^2$$



Normalized spatial intensity profiles along one axis for increasing pumping power near the critical value.

Outlook

БЭК связанных состояний среды и поля возможно для низкоразмерных систем , неотъемлемой частью которых является резонатор, позволяющий придать фотону конечную эффективную массу и увеличить время его жизни, которое должно быть больше времени термализации.

Высокотемпературные фазовые переходы, а также лазерная генерация - две стороны «одной медали». Они являются результатом механизма ОС, приводящего к перераспределению интенсивности и термализации населенностей одетых состояний при различных знаках атомно- оптической отстройки.

БЭК фотонов возможна при достижении термодинамического равновесия для двумерного газа фотонов в резонаторе с определенным хим. потенциалом в условиях слабой связи между молекулами и полем.

Our publications

1. I. Yu. Chestnov, A. P. Alodjants, S. M. Arakelian, J. Klaers, F. Vewinger, M. Weitz, *Bose-Einstein condensation for trapped atomic polaritons in a biconical waveguide cavity*, Phys.Rev. A. 85, 053648 (2012).
2. A. P. Alodjants, I. Yu. Chestnov, and S. M. Arakelian, *High temperature phase transition in the coupled atom-light system in the presence of optical collisions*, Phys. Rev. A 83, 053802 (2011).
3. I. Yu. Chestnov, A. P. Alodjants, S. M. Arakelian, J. Nipper, U. Vogl, F. Vewinger, and M. Weitz, *Thermalization of coupled atom-light states in the presence of optical collisions*, Phys. Rev. A 81, 053843 (2010).