Bose-Einstein Condensation of Photons and Periodic Potentials for Light

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BEC of rubidium atoms @ 180nK
Ground State of Bosonic Ensembles (3D-Regime)

Bose-Einstein condensate

atoms

photons?
Earlier Work related towards a Photon BEC

- Proposal for a photon BEC in Compton scattering off a thermal electron gas

Zel'dovich and Levich, 1969

Photons

scattered photons:
shock wave structure

electrons in thermal equilibrium (within plasma)
... Earlier Work

- Exciton-polariton condensates
  strong coupling ('half matter, half light'); in equilibrium for condensed part

- Proposal for photon fluid in nonlinear resonator

Yamamoto, Deveaud-Pledran, Littlewood, Snoke, …

atom

photon-photon scattering
(four-wave mixing)

R. Chiao
Outline of Talk

- thermodynamics of a two-dimensional photon gas in a dye-filled optical microcavity
- Bose-Einstein condensation of photons
- condensate intensity correlations, grand canonical BEC
- periodic potentials for light
Bonn 2D-Photon Gas Experimental Scheme

- use curved-mirror microresonator to modify photon dispersion

\[ d = n \cdot \lambda / 2 \]

(for n=1)

- thermal equilibrium of photon gas by absorption re-emission processes on dye molecules…

Energy vs. wavevector

min. (‘cutoff’) energy of light in resonator

Photon in free space

(transversal) wavevector

Dye molecule
Spectrum of Perylene-Dimide Molecule (PDI)

Kennard-Stepanov theory:

$$\frac{f(\omega)}{\alpha(\omega)} \propto \exp\left(-\frac{\hbar \omega}{k_B T}\right)$$

$$\eta_{\text{quantum}} \approx 0.97$$
Photon Gas Thermalization: Background

Collisionally induced thermalization in dye medium

\[ \frac{f(\omega)}{\alpha(\omega)} \propto \exp\left(-\frac{\hbar \omega}{k_B T}\right) \]

T: (internal rovibrational) temperature of dye solution

Kennard 1912, Stepanov 1956
Model for Photon Thermalization

multiple absorption and emission processes by dye molecules in resonator
Photon Number Variation during Thermalization?

Planck Blackbody Radiation

- Thermal excitation
- Photon emission
- $\Delta E \sim k_B T = 1/40 \text{ eV}$

New Scheme

- Photon absorption
- Photon emission
- $\Delta E \sim \hbar \omega_{\text{cutoff}} = 2.1 \text{ eV}$

- Thermal excitation suppressed by
  \[ e^{-\frac{\hbar \omega_{\text{cutoff}}}{k_B T}} \approx 10^{-36} \]
- Photons average number conserved
  - 'white-wall box' for photons
Photon Trapping versus Atom Trapping

- quadratic photon dispersion

In paraxial approximation ($k_z \gg k_r$):

$$E = \hbar c \sqrt{k_z^2 + k_r^2} \approx \hbar c \left( k_z + \frac{k_r^2}{2k_z} \right)$$

$$= m_{\text{eff}} c^2 + \frac{(\hbar k_r)^2}{2m_{\text{eff}}}$$

with $m_{\text{eff}} = \hbar k_z / c = \hbar \omega_{\text{cutoff}} / c^2$
..Photon versus Atom trapping

- trapping potential from mirror curvature

System formally equivalent to 2D-gas of massive bosons with $m_{\text{eff}} = \hbar \omega_{\text{cutoff}} / c^2$

$$E = m_{\text{eff}} c^2 + \frac{(\hbar k_r)^2}{2m_{\text{eff}}} + \frac{1}{2} m_{\text{eff}} \Omega^2 r^2$$

→ BEC expected for $N > N_c = \frac{\pi^2}{3} \left( \frac{k_B T}{\hbar \Omega} \right)^2 \approx 77000$  
(T=300K, $\Omega=2\pi\cdot4\cdot10^{10}$Hz,  
$m_{\text{eff}} \approx 6.7 \cdot 10^{-36}$kg $\approx 10^{-10} \cdot m_{\text{Rb}}$)
Two-Dimensional Photon Gas in Dye-Filled Optical Resonator

Perylene-diimide (PDI)
Experimental Setup: 2D Photon Gas

pumping laser (532 nm)

dye-filled microcavity

$s d \approx 7 \cdot \lambda / 2$
Spectrum of Thermal Photon Gas in Cavity

→ evidence for thermalized two-dimensional photon gas with $\mu \neq 0$!

Spectra for Different Cavity Cutoff Frequencies

optically dense regime,
thermalization of photon gas
Reabsorption: Required for Photon Thermalization

![Diagram of dye molecule](image)
Snapshot: Thermalization of Photon Gas in Dye Microcavity
Thermalization – Photon Diffusion towards Center

Experimental data

| $|x_{max}|$ ($\mu$m) |
|---------------------|
| 150                 |
| 100                 |
| 50                  |
| 0                   |

trap center

pump beam position $x_{exc}$ ($\mu$m)

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Thermalized photon gas

pumping
nature physics

GALAXY CLUSTERS
Vestigial region models

FLUID DYNAMICS
Diffusive transport\,\,\textsuperscript{1\textsuperscript{st}DITION}

COMMUNITY
Testing journal (observatories)

Thermalized photons
Photon Gas at Criticality

\[ \text{BEC!} \]

\[ N \ll N_c \quad \text{versus} \quad N > N_c \]

Rh6G, duty cycle 1:16000, 0.5\( \mu \text{s} \) pulses
Bose-Einstein condensate of Light

below threshold

Bose-Einstein condensate

Cooling
(or increase of $n\lambda_{db}^2$)

Light Bulb

ground state: filament off
Spectra for Densities around Photonic BEC Threshold

\[ \Omega = \frac{\pi}{3} \left( \frac{k_B T}{\hbar \Omega} \right)^2 \approx 7.7 \cdot 10^4 \]

\[ P_{c,\text{exp}} \approx 1.55(60) \text{ W} \]
\[ \rightarrow N_{c,\text{exp}} \approx (6.3\pm2.4) \cdot 10^4 \]

see also recent Imperial College experiment: J. Marelic and R. Nyman, PRA 91, 033813 (2015)
Spatial intensity distribution around BEC threshold for atoms: \(g_{\text{eff,2D}} \approx 7 \cdot 10^{-4}\) (too small for Kosterlitz-Thouless physics) \(\rightarrow\) BEC expected

for atoms: \(g_{\text{eff,2D}} \approx 10^{-1} - 10^{-2}\) (Dalibard, Phillips)
Michelson Interference Pattern above Photon BEC Threshold

optical path length difference: 15 mm
Bose-Einstein Condensation versus Lasing

**equilibrium**

ideal photon box (with number-conserving thermalization & low-frequency cutoff) $\rightarrow$ BEC

**out of equilibrium**

pumping and losses dominate $\rightarrow$ laser, requires inverted active medium

see also: lasing a nonequilibrium phase transition (Haken,...), polariton BEC $\leftrightarrow$ polariton lasing.

Experimental Data: Laser to BEC Crossover

Low thermal contact

Thermalization of photons

mode-locked laser state

Bose-Einstein condensate

Grand Canonical BEC and Condensate Fluctuations

usual BEC
(e.g. cold atoms, polaritons..)
microcanonical ensemble

\[ N \]
particle number fixed

\[ g^{(2)}(0)=1 \]
quite condensate

Grand canonical BEC
particle exchange with reservoir

\[ N \leftrightarrow M \]
reservoir: dye electronic excitations

system: photons

\[ + \leftrightarrow \]
flickering condensate, \( \Delta N \approx N \)

\[ g^{(2)}(0)=2 \]
particles in BEC

time

J. Klaers et al., PRL 108, 160403 (2012), see also: D. Sobyanin, PRE 85, 061120 (2012)
Photon Intensity Correlation in BEC Mode vs. Delay Time

condensate fraction: 56%

system size
large: $N > \sqrt{M}/2$

$\approx$ (usual) canonical BEC regime
with Poissonian fluctuations

condensate fraction: 4%

system size
small: $N < \sqrt{M}/2$

evidence for grand canonical BEC regime!

Photon Intensity Correlation vs. Condensate Fraction

![Graph showing intensity correlation $g^{(2)}(0)$ vs. condensate fraction (%)]

- **T/T_c**
  - 0.95, 0.89, 0.84, 0.77, 0.71, 0.63

- **intensity correlation $g^{(2)}(0)$**
  - Values range from 2.0 to 1.0

- **condensate fraction (%)**
  - Values range from 0 to 60

Legend:
- R1: $\Delta = -7.8 k_B T$, $\rho = 10^{-4}$ mol/l
- R2: $\Delta = -7.4 k_B T$, $\rho = 10^{-3}$ mol/l
- R3: $\Delta = -5.3 k_B T$, $\rho = 10^{-3}$ mol/l
- R4: $\Delta = -1.8 k_B T$, $\rho = 10^{-4}$ mol/l
- R5: $\Delta = -2.3 k_B T$, $\rho = 10^{-3}$ mol/l
Periodic Potentials for Light: Motivation

Possible experiments:
- strongly correlated quantum gases: Mott-insulator transition for photons
- artificial magnetic fields, quantum Hall states, ..

Proposals: Plenio, Greentree, Angelakis, Türeci, Carusotto, Hafezi, Hartmann, Stoof ..
See also experimental lattice work in polaritons: Yamamoto, Bloch
One Approach: Use Mirror Structuring to Create Variable Potentials for Light

- **Single trap**
- **double well**

![Diagram of single trap and double well](image)

- Photon trapping potential from mirror curvature
- Potential

$x$
Thermo-Optic Imprinting:
Variable Potentials for Trapped Photon Gas

plane mirrors

manipulate optical length locally by heating

\[ \text{optical length} = \wedge \]

hot

optical length
Thermo-Sensitive Polymer (PolyNIPAM): Controlled Variation of Refractive Index

Low temperature: polymer chains in water (solvable)

\[ n_{\text{eff}} \approx 1.35 \]

High temperature: collapsed polymer chains

\[ n_{\text{eff}} \approx 1.46 \]
Setup for Generation of Lattice Potentials

- Two-dimensional galvo scanner
- Heating beam
- Absorbing silicon layer
- Dye polymer microcavity
- Pump beam
- Microcavity emission
Dye Microcavity Emission for Photonic Lattice Potentials

D. Dung et al, to be published
..A Nonperiodic Potential Pattern in Microcavity
Spectral Analysis of the Emission of One Site: Investigating Effective Photon Interactions

thermo-optic interactions occur temporally delayed
→ frequency chirp of the emission
Coupling Two Sites in a Double-Well System

Potential well 1
\[ N_{\text{PHOTONS}}(t=0) >> 1 \]

Potential well 2
\[ N_{\text{PHOTONS}}(t=0) = 0 \]

Detuning
\[ \delta(t) = \omega_1 - \omega_2 \]

Coupling
\[ j(d) \]

Distance \( d = (8...14) \mu m \)

Photons
Pump beam
\[ \omega_1 \]
\[ \omega_2 \]
we observe tunneling when the sites are tuned into resonance. From the resonance width, the tunnel coupling can be extracted.
Tunnel Coupling Versus Distance Between Sites

D. Dung et al, to be published
Conclusions

- thermalization of 2D-photon gas with nonvanishing chemical potential and Bose-Einstein condensation of photons

- observation of a grandcanonical BEC regime with enhanced intensity fluctuations

- variable potentials for photonic quantum gas. We see tunneling and effective photon interactions in double well system
Outlook

- photon thermalization: concentration of diffuse sunlight

- photon BEC: new states of light
  (some) future directions:
  • grand canonical BEC regime: $g^{(1)}(\tau)$, superfluidity (?), …
  • Josephson physics for photons
  • study of quantum manybody states in periodic potentials

photon gas
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