Title: TBA

Date: Jun 20, 2016 11:00 AM

URL: http://pirsa.org/16060035

Abstract:

JOURNAL OF MODERN OPTICS, 2002,
VOL. 49, NO. 14/15, 2297–2307

Taylor & Francis
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Sharpening accepted thermodynamic wisdom via quantum control: or cooling to an internal temperature of zero by external coherent control fields without spontaneous emission

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(*Received 15 February 2002; revision received 10 May 2002*)

Abstract. Cooling of internal atomic and molecular states via optical pumping and laser cooling of the atomic velocity distribution, rely on spontaneous emission. The outstanding success of such examples, taken together with general arguments, has led to the widely held notion that radiative cooling requires spontaneous emission. We here show by specific examples and direct calculation, based primarily on breaking emission–absorption symmetry as in lasing without inversion, that cooling of internal states by external coherent control fields is possible. We also show that such coherent schemes allow us to practically reach absolute zero in a finite number of steps, in contrast to some statements of the third law of thermodynamics.

"About your cat, Mr. Schrödinger—I have good news and bad news."

Quantum Coherence Can Improve Quantum Heat Engine (QHE) Efficiency

I. Quantum Thermodynamics

II. Photo-Carnot QHE

III. The Laser as a QHE

1. $$\frac{\hbar\nu_{laser}}{\hbar\nu_{pump}} = 1 - \frac{T_c}{T_h}$$ From Detailed Balance

2. Quantum Coherence Can Improve Laser QHE Quantum Efficiency by Breaking Detailed Balance

IV. The Photocell as a QHE

1. $$\frac{eV}{\hbar\nu_{pump}} = 1 - \frac{T_c}{T_h}$$ From Detailed Balance

2. Quantum Coherence Can Improve Photocell QHE Quantum Efficiency by Breaking Detailed Balance

V. Noise Induced Quantum Coherence Can Enhance:

1). Laser QHE Power

2). Photocell QHE Power

3). Efficiency of Photosynthesis

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Heat Engines

- Classical Heat Engines produce useful work by extracting energy from a high temperature energy source and rejecting entropy to a low temperature entropy sink.
- A Photo-Carnot Engine is a Carnot cycle engine in which photons are the working fluid and the piston is driven by radiation pressure. Quantum coherence allows us to achieve thermodynamic efficiency beyond the Carnot limit without violating the second law.
- Laser and Photocell Quantum Heat Engines are driven by thermal radiation and governed by the laws of quantum thermodynamics.

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Quantum Thermo I

Planck studies Entropy of Light to Arrive at the Quantum*

Wein Entropy

$$\frac{\partial^2 S}{\partial \bar{\varepsilon}^2} = -\frac{1}{b\omega\bar{\varepsilon}}$$

where $\bar{\varepsilon}$ = average energy of oscillator with frequency ω

Planck Entropy 1900

$$\frac{\partial^2 S}{\partial \bar{\varepsilon}^2} = -\frac{k_B}{\bar{\varepsilon}(\hbar\omega - \bar{\varepsilon})} \Rightarrow \bar{\varepsilon} = \frac{\hbar\omega}{e^{\hbar\omega/k_BT} - 1}$$

*Planck Photon Statistics and Bose Einstein condensation, Progress in Optics 2007

Quantum Thermo II

Einstein studies Entropy of Light to Arrive at the Photon*

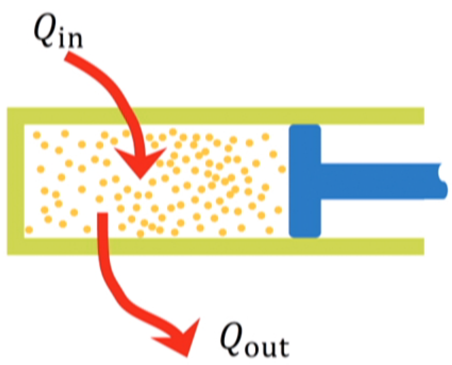
Fluctuations

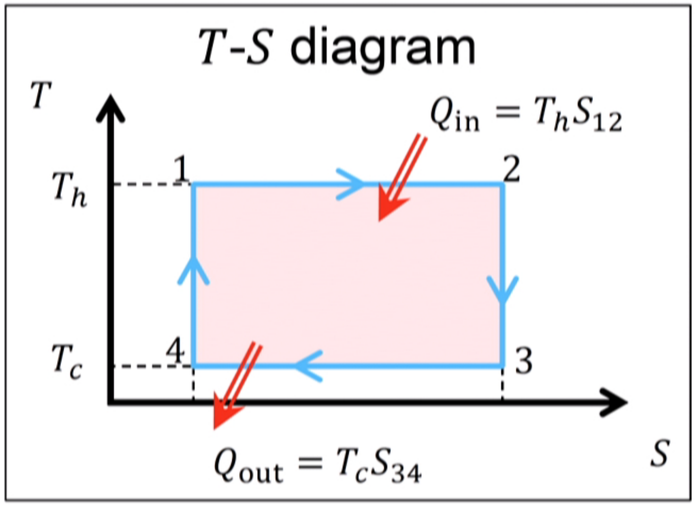
$$\frac{\langle (\Delta E)^2 \rangle}{(\hbar \omega)^2} = \underbrace{\overline{n}^{\,2}}_{\text{wave}} + \underbrace{\overline{n}}_{\text{particle}}$$

Wave Particle Duality 1905

*Progress in Optics 2007

Carnot Efficiency

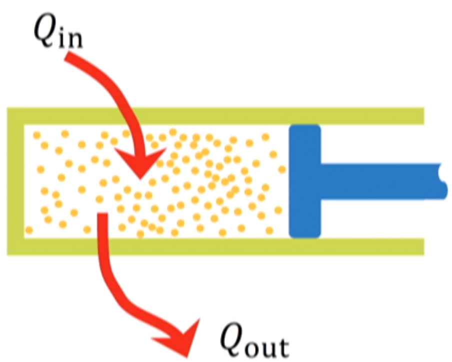




thermal efficiency

$$\eta = \frac{Q_{\text{in}} - Q_{\text{out}}}{Q_{\text{in}}} = \frac{T_h S_{12} - T_c S_{34}}{T_h S_{12}} = 1 - \frac{T_c}{T_h}$$

Carnot Efficiency



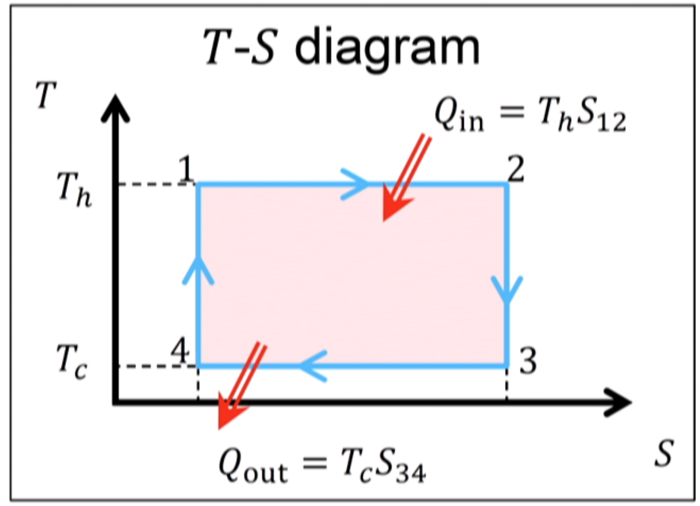


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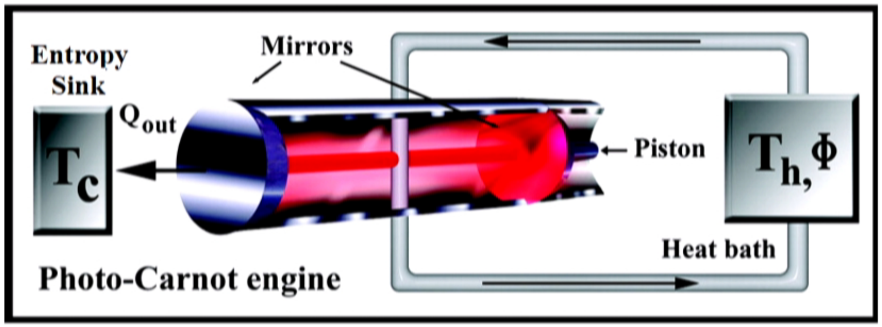
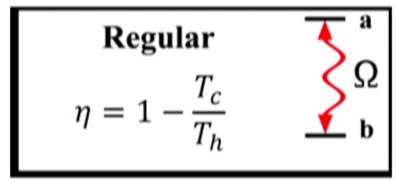
Photo-Carnot Engine

- Working Fluid(radiation) heated by two-level atoms

$$PV = \hbar\Omega\bar{n}$$





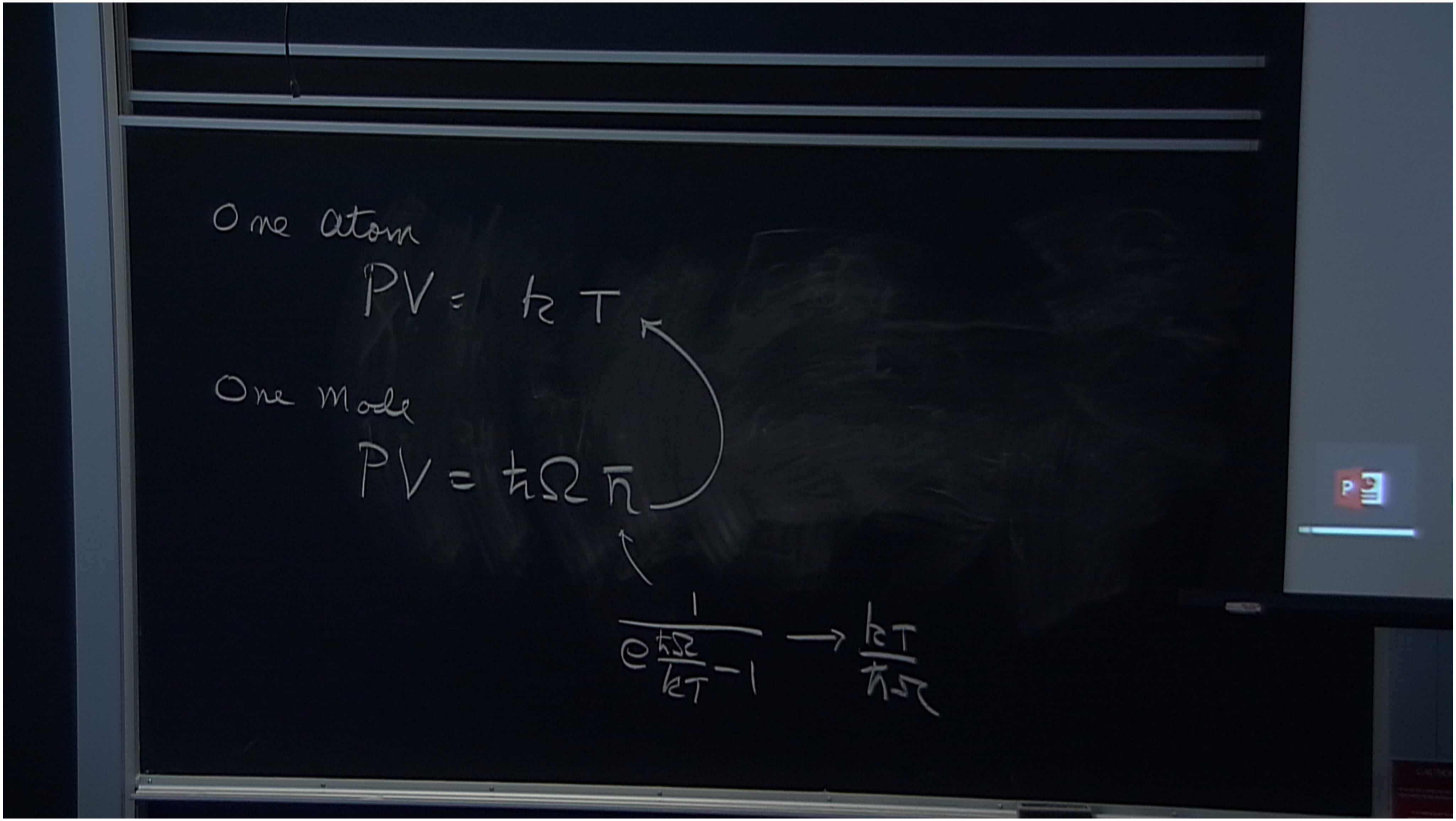
Science AAAS

Extracting Work from a Single Heat Bath via Vanishing Quantum Coherence

M. Scully, M. Zubairy, G. Agarwal, and H. Walther

Science **299**, 862 (2003);

DOI: 10.1126/science.1078955


One atom
PV = kT
One mode
PV = ħΩ n̄
1/(e^(ħΩ/kT) − 1) → kT/ħΩ

Single Mode = Single Atom

$$PV = kT \qquad \text{(One atom)}$$

$$PV = \hbar\Omega\bar{n} \qquad \bar{n} = \frac{kT}{\hbar\Omega}$$

$$= kT \qquad \text{(One mode)}$$

$$\eta_c = 1 - \frac{T_c}{T_h}$$

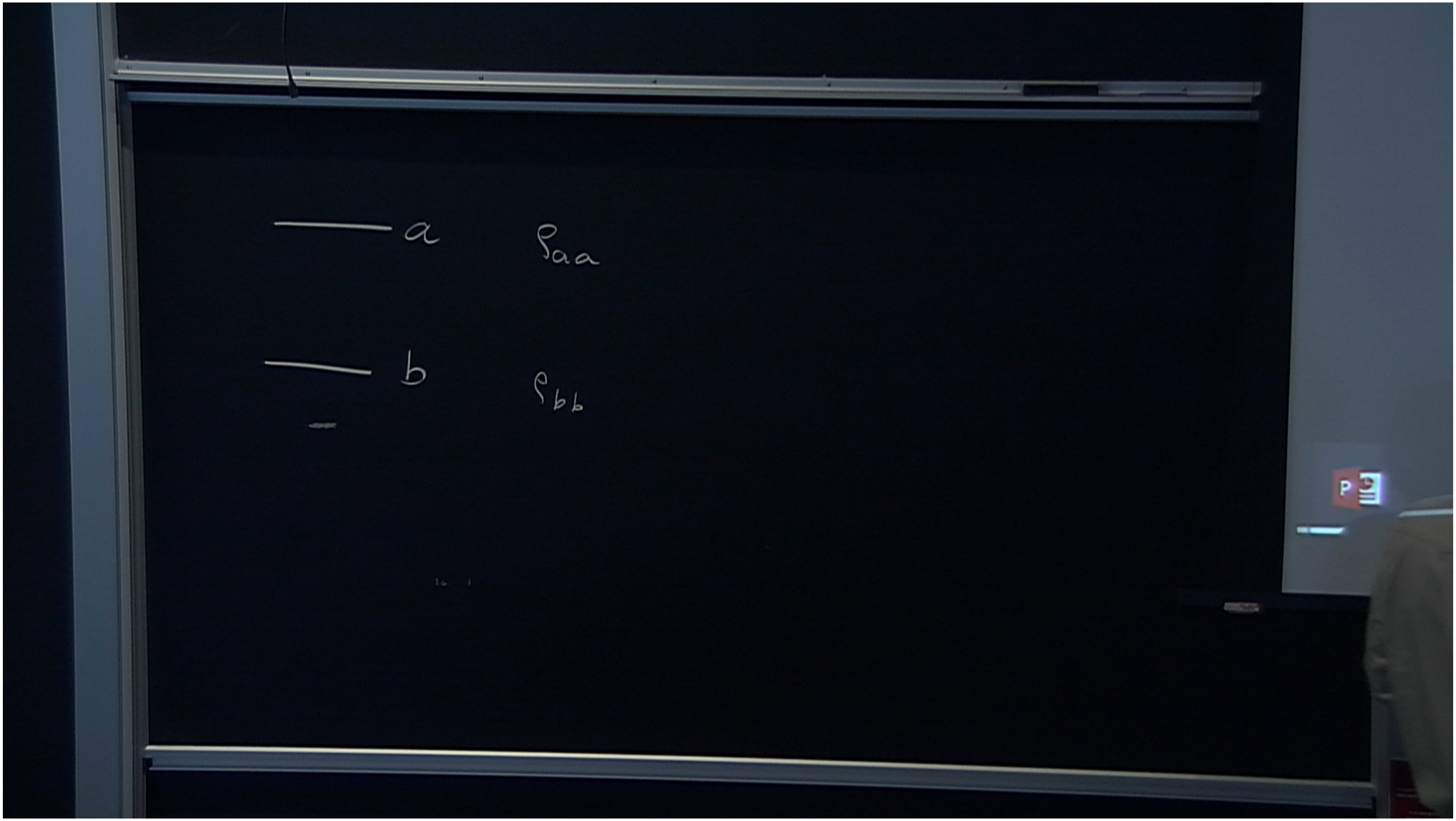
Rate equation for photon number (I)

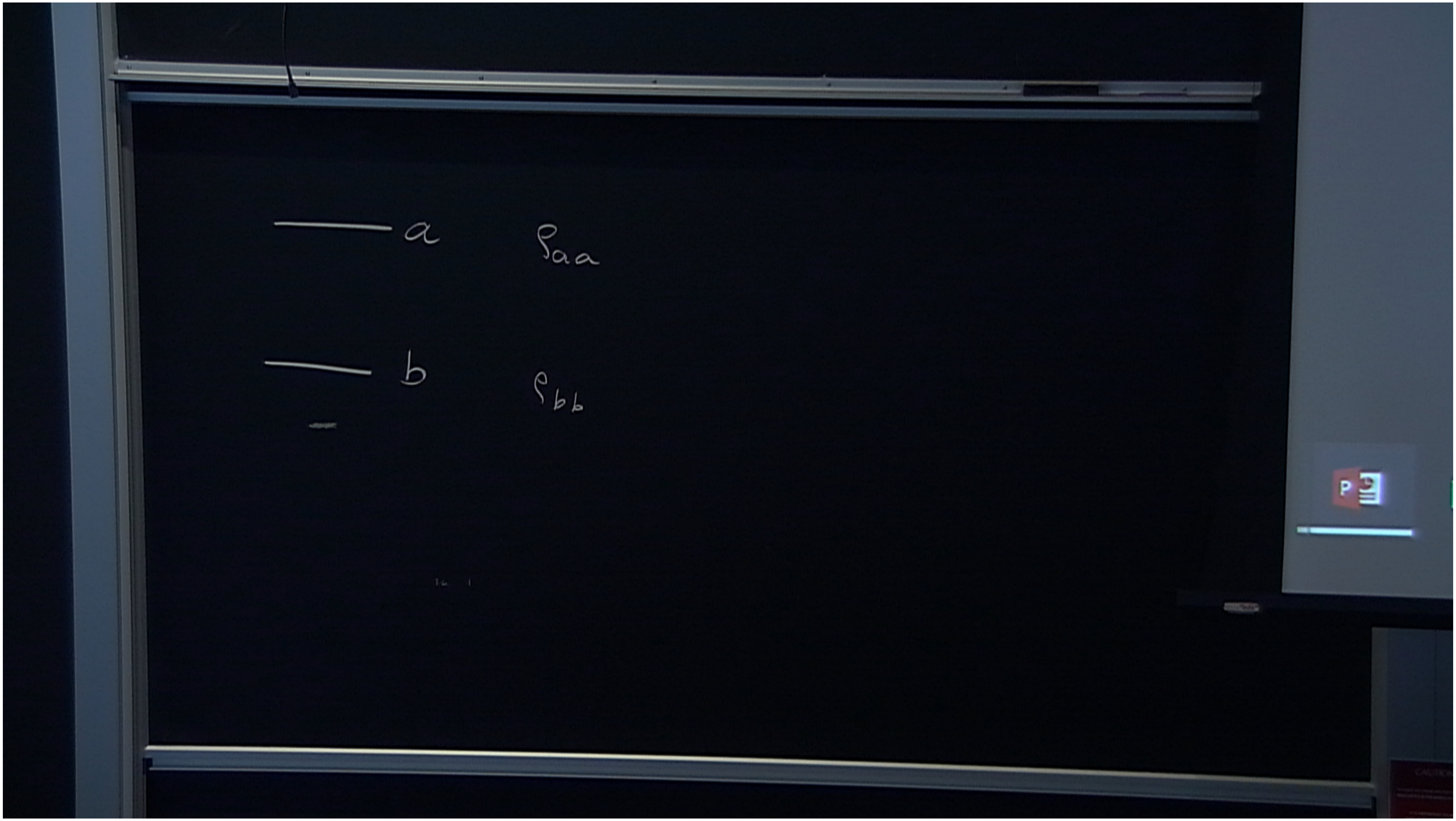
- With two-level atoms field,

$$\dot{\bar{n}} = \alpha[\rho_{aa}(\bar{n}+1) - \rho_{bb}\bar{n}]$$

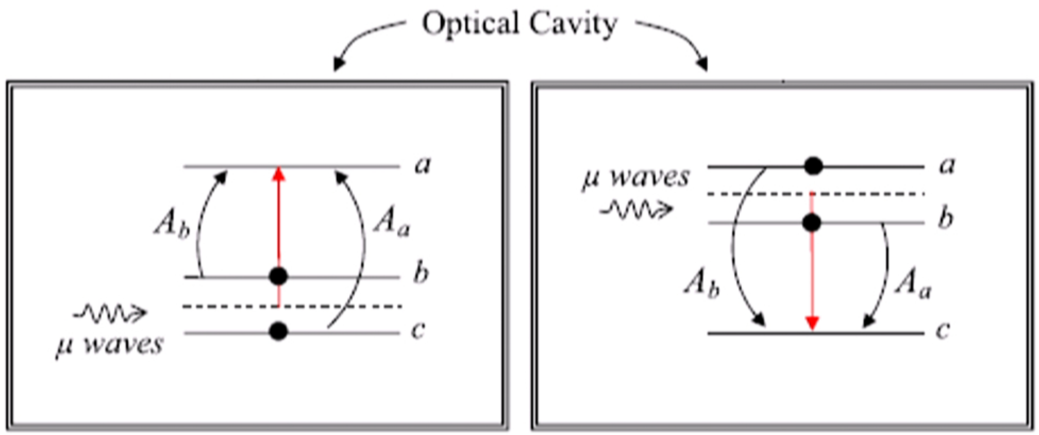
- The steady-state solution is

$$\bar{n} = \frac{1}{\frac{\rho_{bb}}{\rho_{aa}} - 1} = \frac{1}{\exp(\hbar\Omega/kT_h) - 1} \xrightarrow[\hbar\Omega/kT_h \ll 1]{\text{high tempearture}} \frac{kT_h}{\hbar\Omega}$$


a
ρaa
b
ρbb


a
ρaa
b
ρbb

Lasing Without Inversion



(a) Canceling absorption (b) Canceling emission

(a) Use of quantum coherence in ground state b,c to cancel absorption
(b) the use quantum coherence in the excited state a,b to cancel emission

$$\dot{\bar{n}}_{laser} = \alpha(\bar{n}+1)\left(|A_a|^2 + |B_b|^2\right) - \alpha\bar{n}|A_a + B_b|^2$$

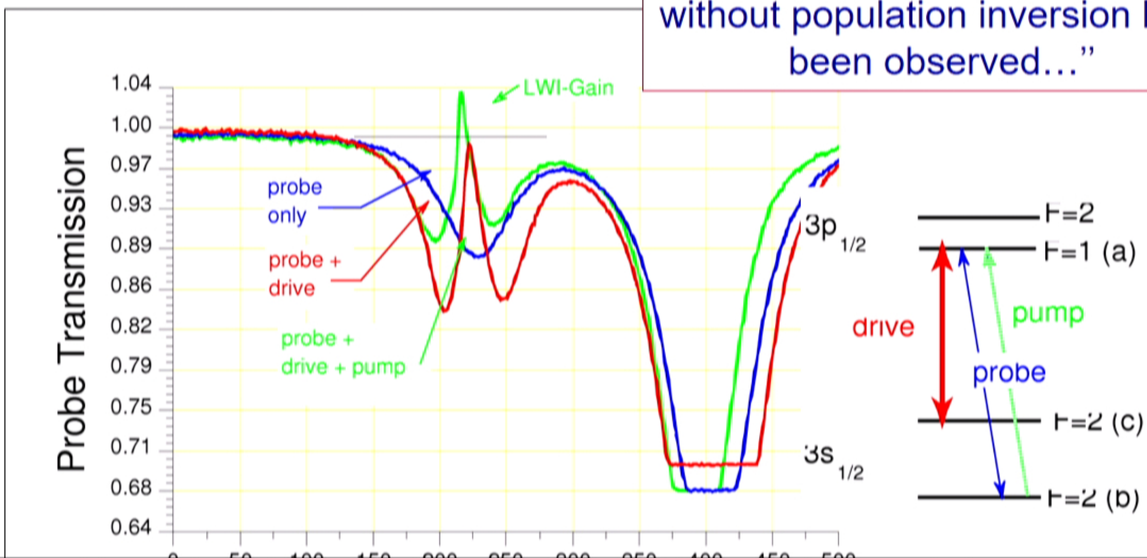
VOLUME 76, NUMBER 12 PHYSICAL REVIEW LETTERS 18 MARCH 1996

Laser Oscillation without Population Inversion in a Sodium Atomic Beam

G. G. Padmabandu,[1,2,*] George R. Welch,[1,2] Ivan N. Shubin,[1] Edward S. Fry,[1,2,†] Dmitri E. Nikonov,[1,2,‡] Mikhail D. Lukin,[1,2] and Marlan O. Scully[1,2,3]
[1]*Texas Laser Laboratory, Houston Advanced Research Center, The Woodlands, Texas 77381*
[2]*Department of Physics, Texas A&M University, College Station, Texas 77843-4242*
[3]*Max-Planck-Institut für Quantenoptik, D-85748 Garching, Germany*
(Received 29 August 1995)

Continuous wave (cw) amplification and laser oscillation without population inversion have been observed for the first time in a Λ scheme within the sodium D_1 line. This is also the first demonstration in which the lasing medium was an atomic beam; this is
the physics, lays a foundation for extensions into the ult
structure were critical to the choice of experimental appr
matrix calculations and clearly show there was no populat

"Continuous wave (cw) amplification and laser oscillation without population inversion have been observed…"



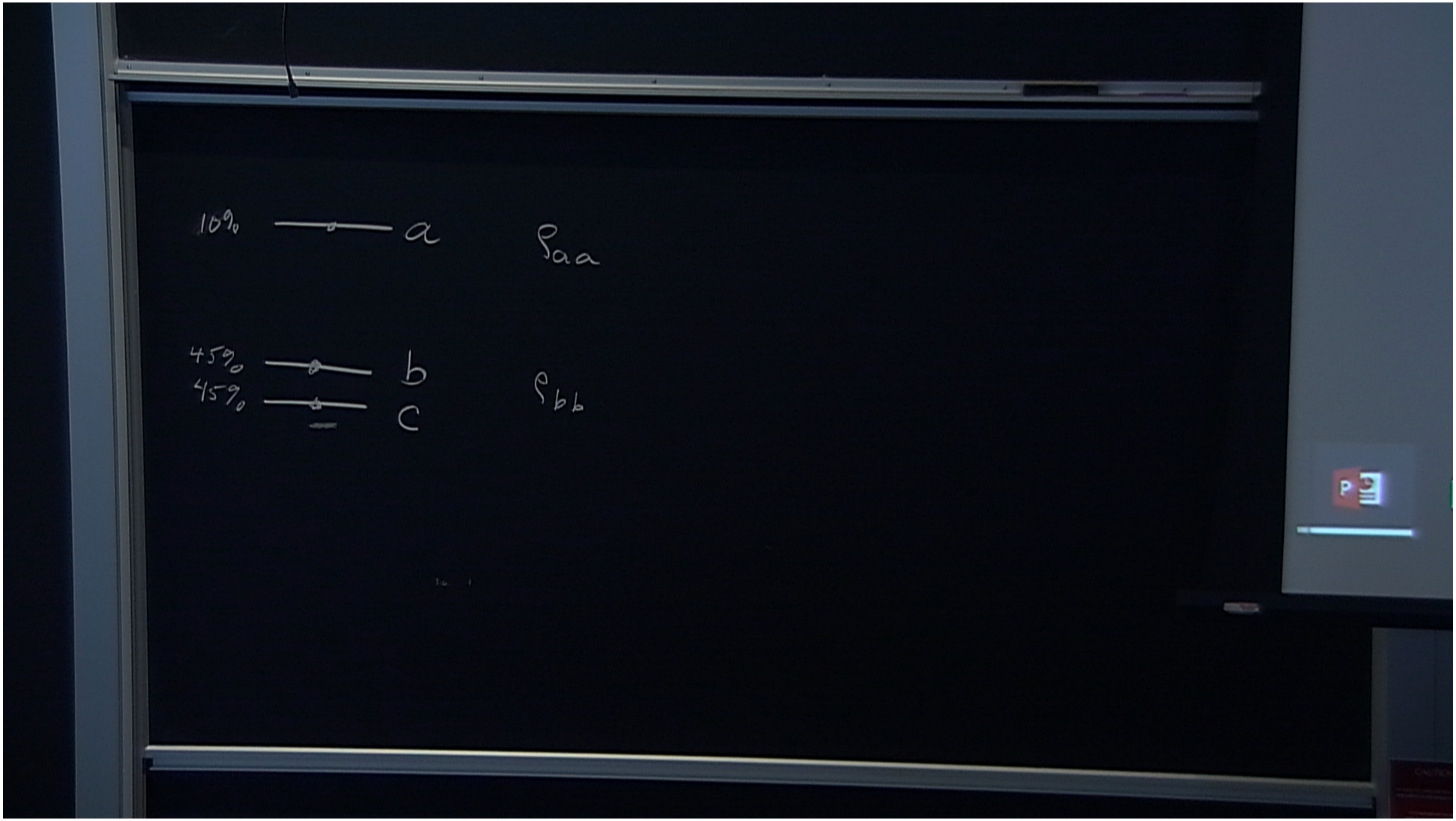
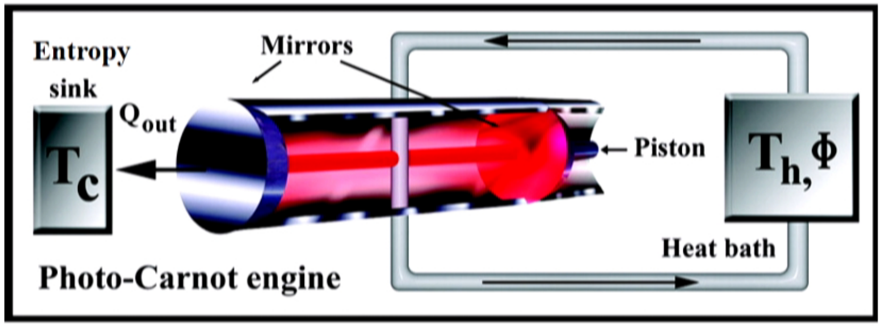
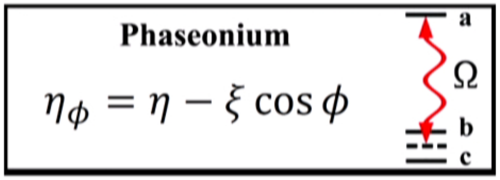

10%
a
ρ_{aa}
45%
b
45%
c
ρ_{bb}

Photo-Carnot Engine

- Working Fluid heated by phaseonium





Rate equation for photon number (II)

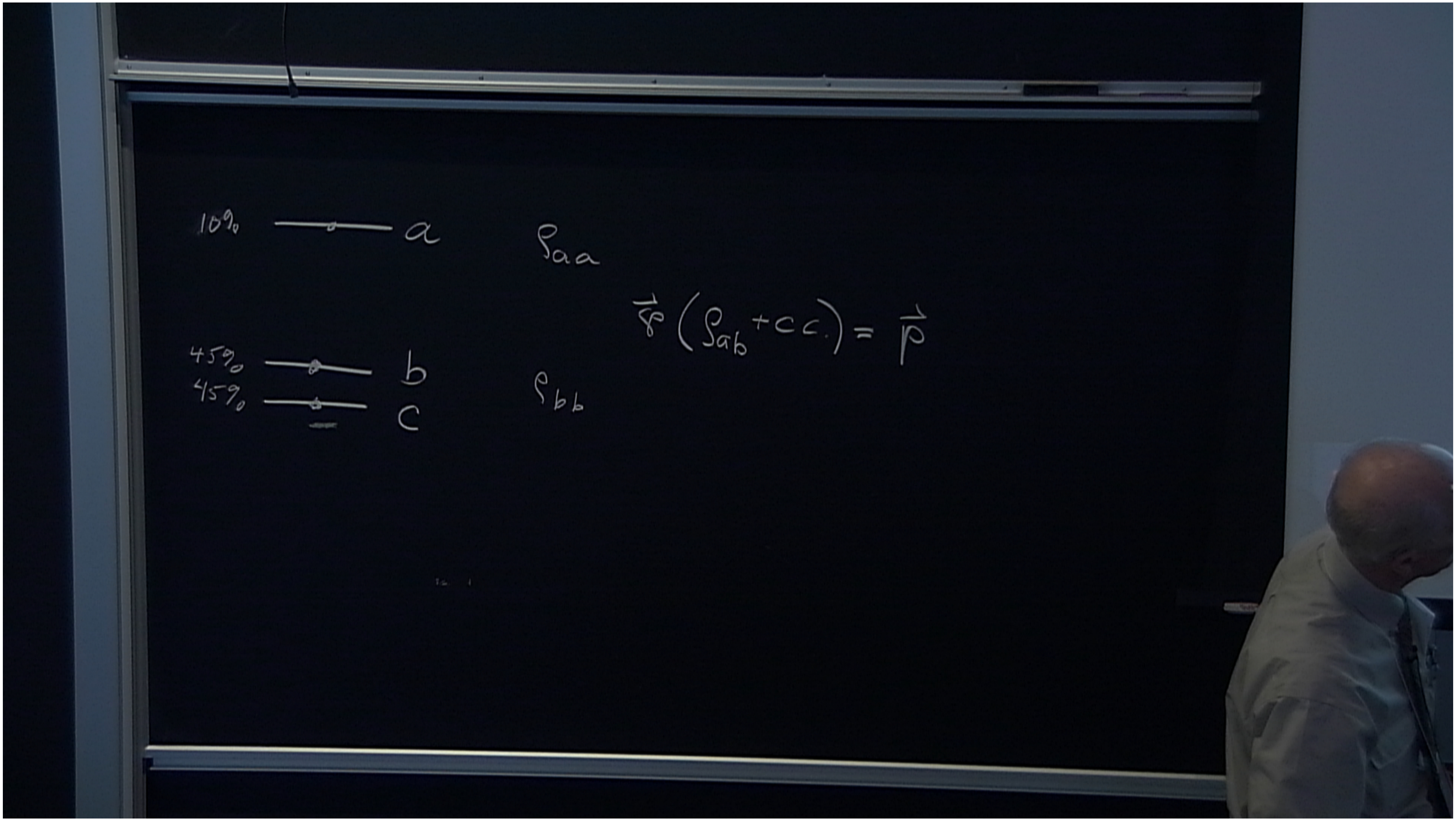
- With phased three level atoms(phaseonium) field,

$$\dot{\bar{n}}_\phi = \alpha\left[2\rho_{aa}\left(\bar{n}_\phi + 1\right) - \left(\rho_{bb} + \rho_{cc} + \rho_{bc} + \rho_{cb}\right)\bar{n}_\phi\right]$$

- The steady-state solution is

$$\bar{n}_\phi \xrightarrow[\hbar\Omega/kT_h \ll 1]{\text{high tempearture}} \frac{kT_h}{\hbar\Omega}\left(1 - \bar{n}\frac{|\rho_{bc}|}{\rho_{aa}}\cos\phi\right) \equiv \frac{kT_\phi}{\hbar\Omega}$$

T_ϕ : effective radiation temperature


10%
a
ρ_{aa}
$\vec{\gamma}(\rho_{ab} + c.c.) = \vec{p}$
45%
b
45%
c
ρ_{bb}

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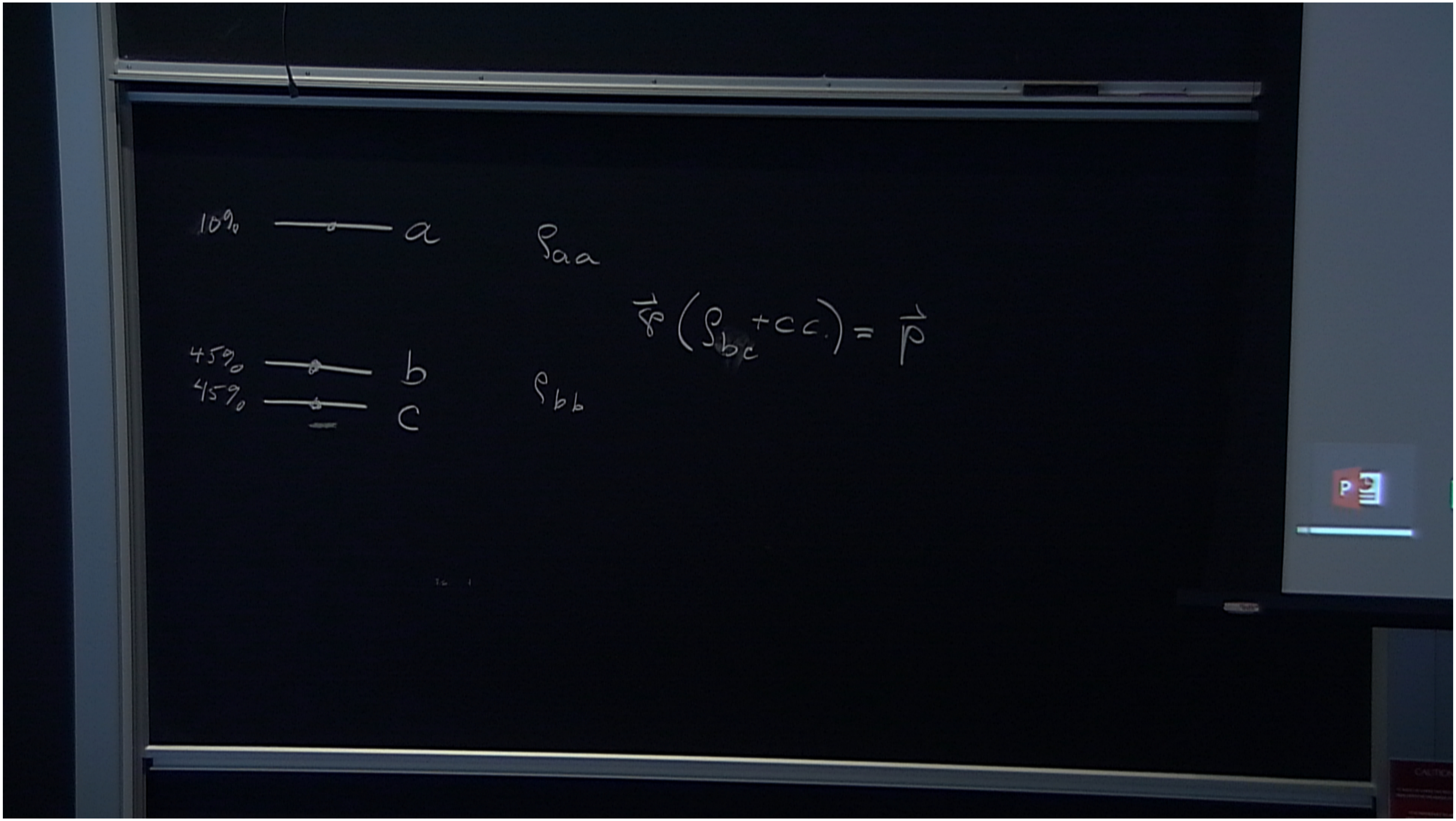
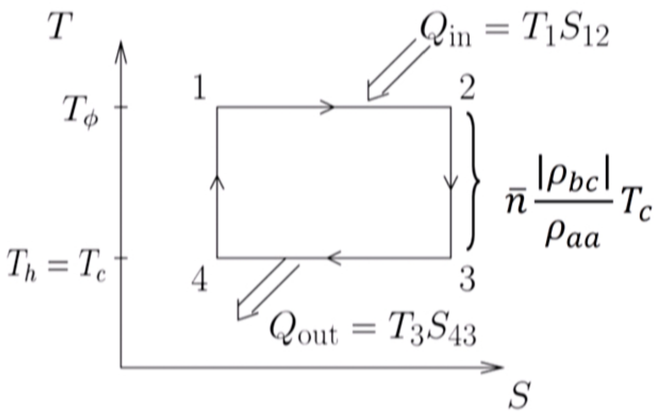

10%
a
ρ_{aa}
$\vec{\wp}(\rho_{bc} + c.c.) = \vec{P}$
45%
b
45%
c
ρ_{bb}

Efficiency of a Quantum Carnot Engine



$$\eta = \frac{Q_{in} - Q_{out}}{Q_{in}}$$

Temperature-entropy diagram for Carnot cycle engine.

In the present QHE, Q_{in} is provided by the hot atoms.

When $T_h = T_c$, the photo-Carnot engine can still produce useful work if the coherent three-level heat bath atoms are "phased" such that $\phi =$

$$\eta_\phi = \frac{T_\phi S_{12} + T_c S_{43}}{T_\phi S_{12}} = \eta - \frac{T_c}{T_h}\bar{n}\frac{|\rho_{bc}|}{\rho_{aa}}\cos\phi$$

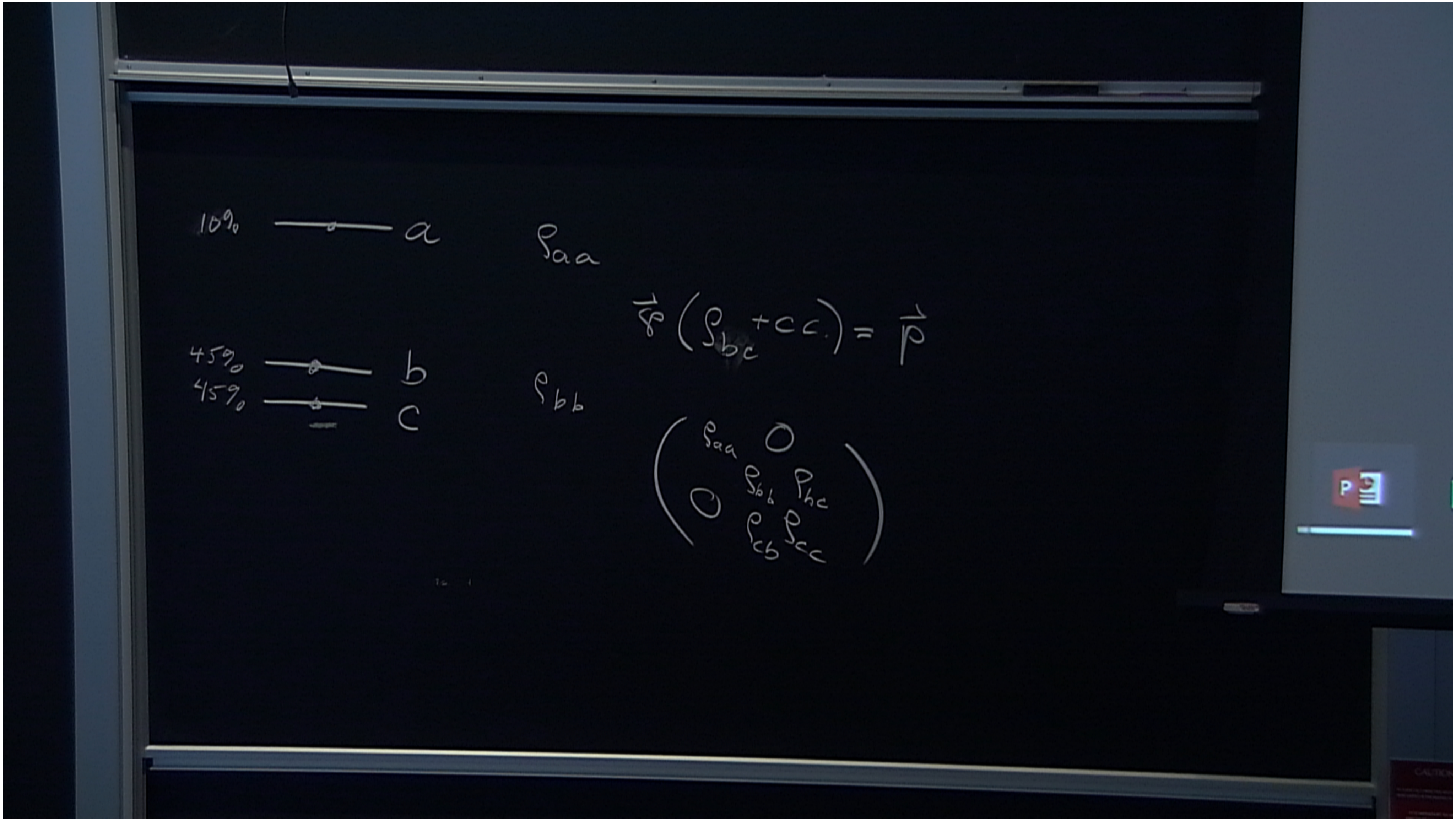
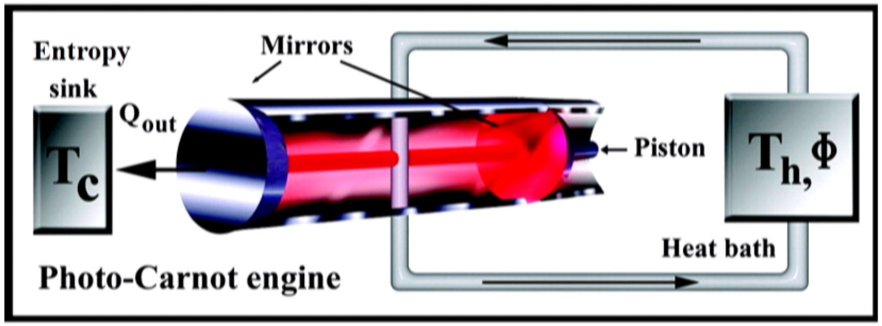
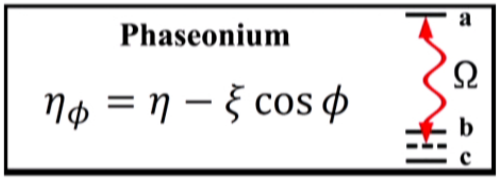

10%
a
45%
b
45%
c
ρaa
ρbb
(ρbc + c.c.) = P
ρaa 0
ρbb ρbc
0 ρcb ρcc

Photo-Carnot Engine

- Working Fluid heated by phaseonium





Quantum Coherence Can Improve Quantum Heat Engine (QHE) Efficiency

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III. The Laser as a QHE

1. $$\frac{\hbar\nu_{laser}}{\hbar\nu_{pump}} = 1 - \frac{T_c}{T_h}$$ From Detailed Balance

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V. Noise Induced Quantum Coherence Can Enhance:

1). Laser QHE Power

2). Photocell QHE Power

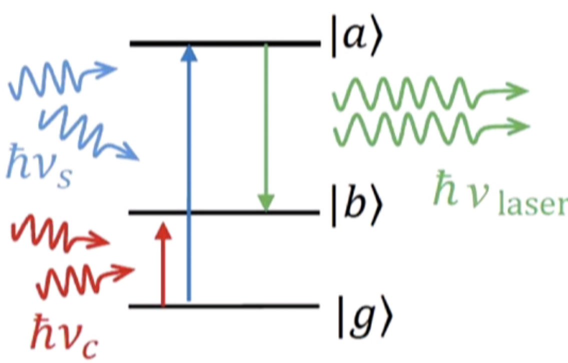
3). Efficien[illegible] of P[illegible]synt[illegible]sis

Laser Quantum Heat Engine (QHE)

PRL **2**, 262 (1959) PHYSICAL REVIEW LETTERS March 15, 1959

THREE-LEVEL MASERS AS HEAT ENGINES*

H. E. D. Scovil and E. O. Schulz-DuBois
Bell Telephone Laboratories,
Murray Hill, New Jersey
(Received January 16, 1959)

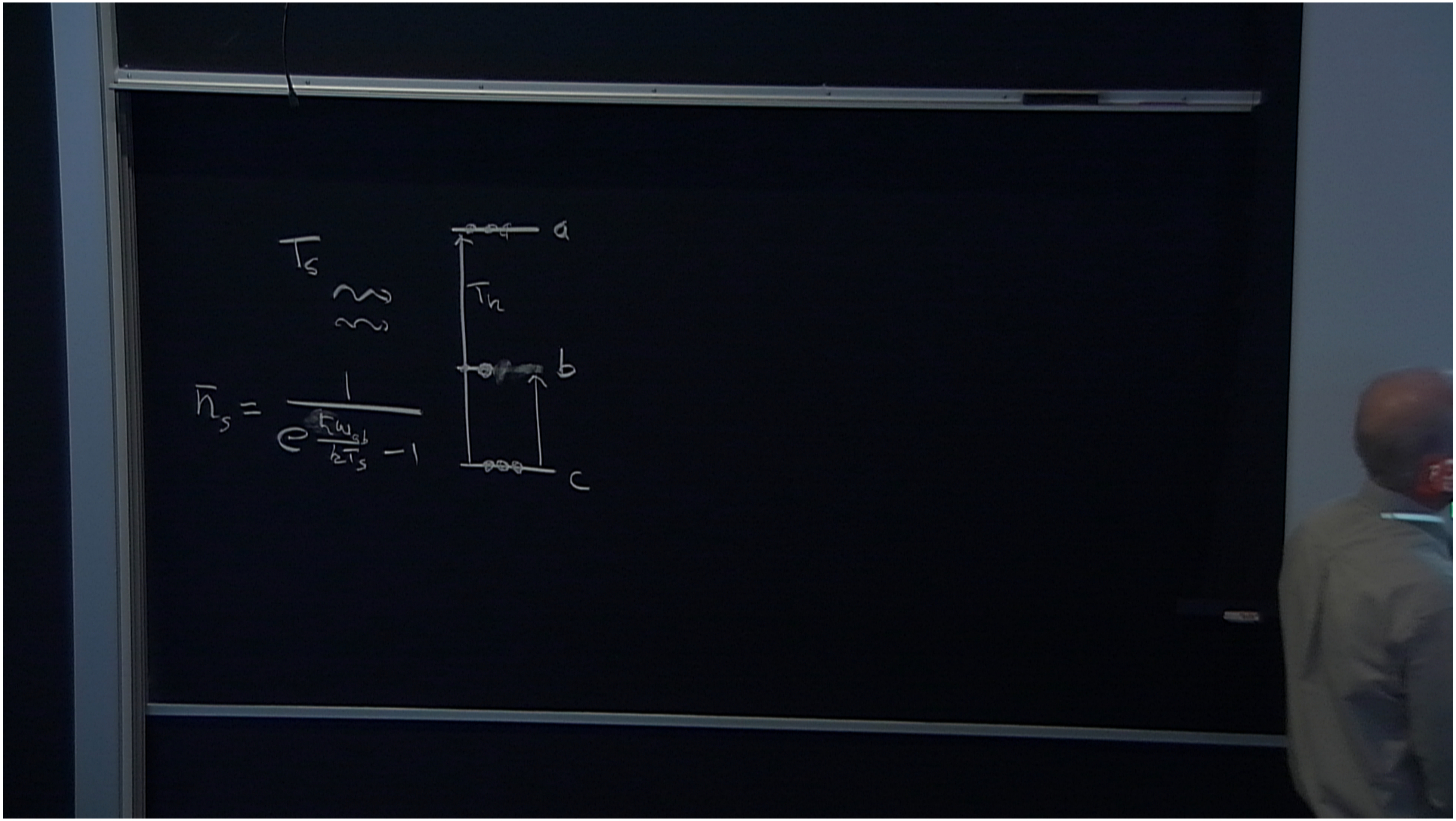


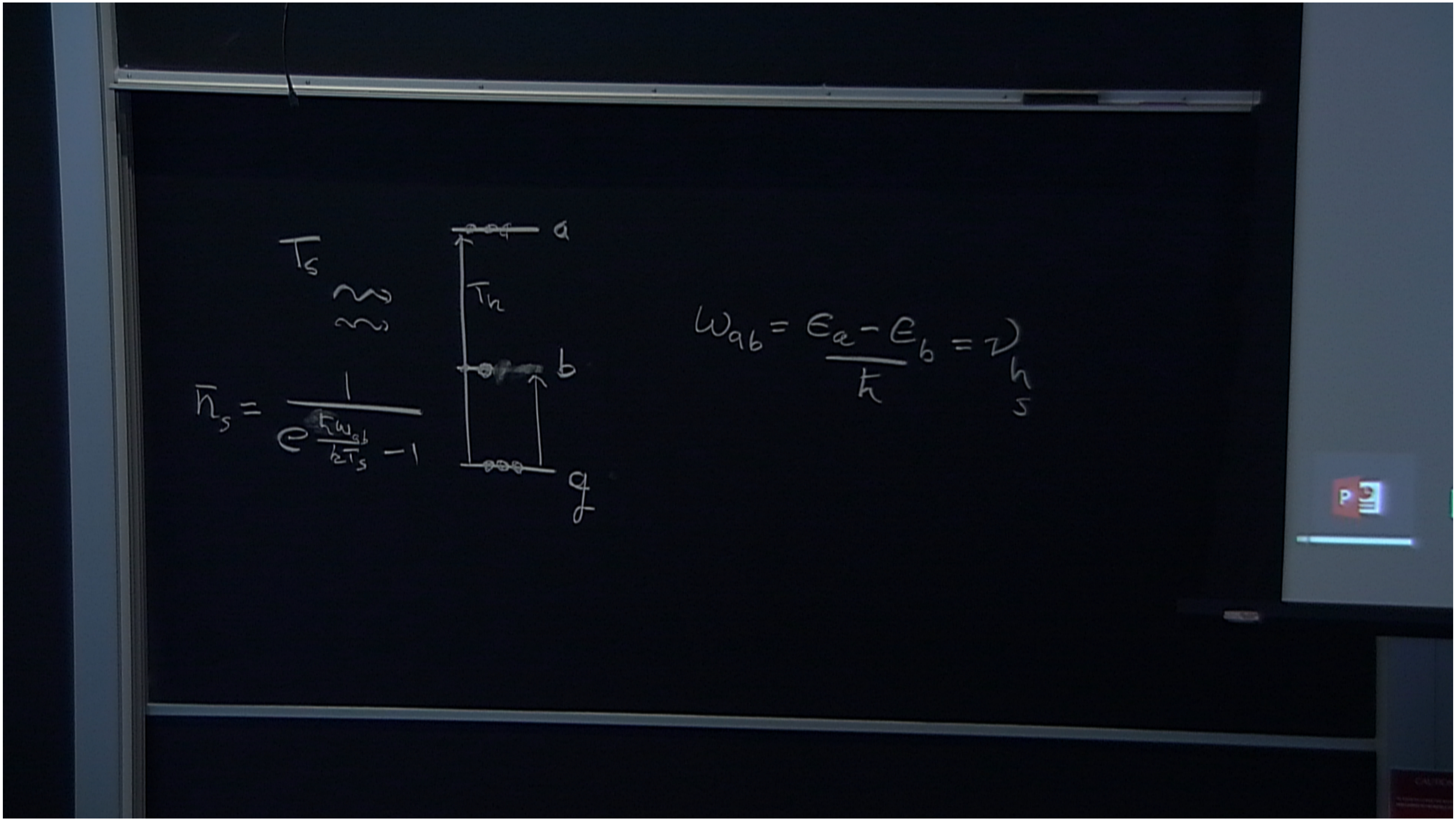
Boltzmann distribution

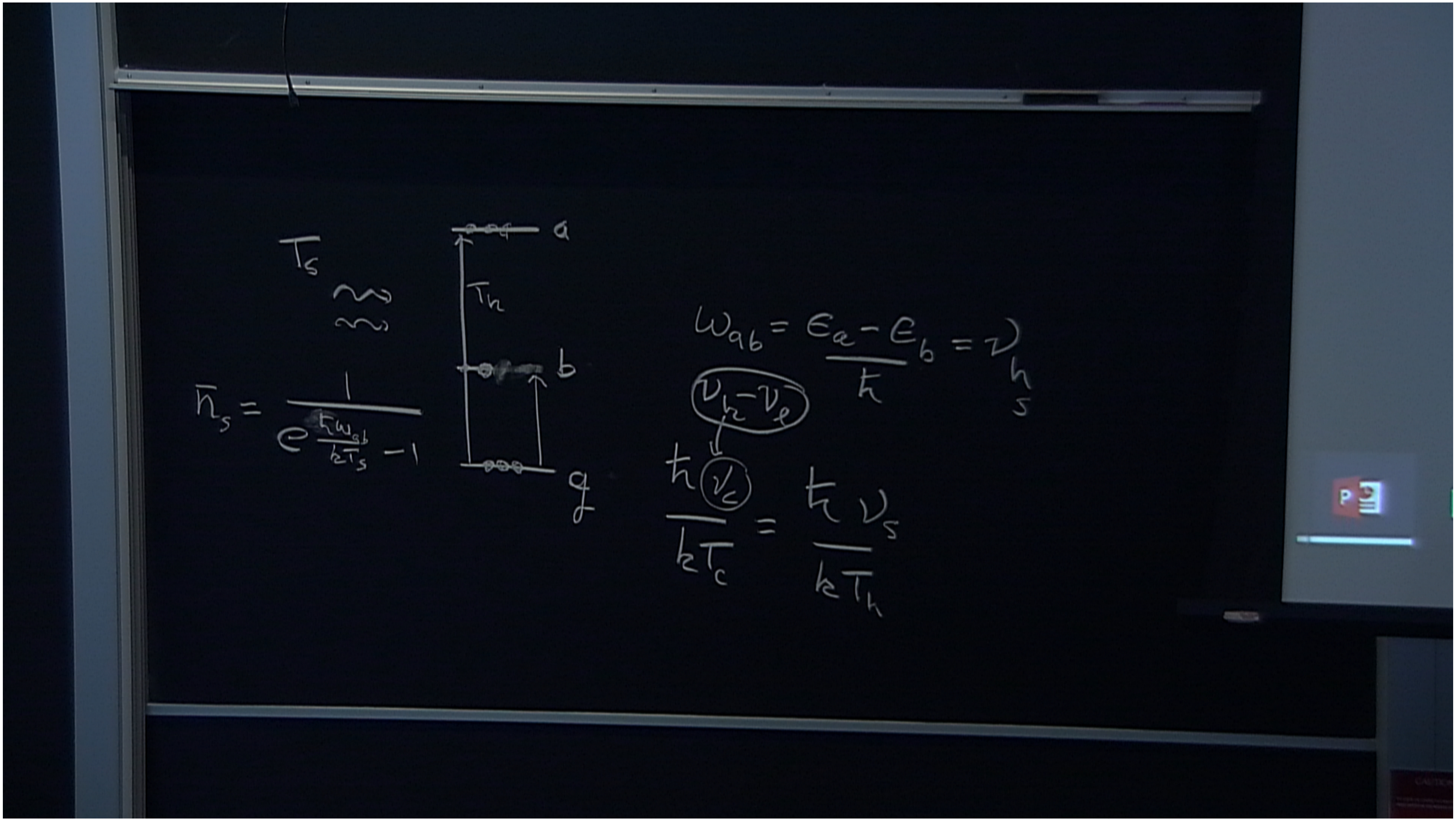
$$\frac{n_b}{n_a} = \frac{n_b}{n_g} \cdot \frac{n_g}{n_a} = e^{-\hbar\nu_c/kT_c} \cdot e^{\hbar\nu_s/kT_h}$$

At threshold (n_b=n_a) efficiency of maser QHE

$$\frac{\hbar\nu_\ell}{\hbar\nu_s} = 1 - \frac{T_c}{T_s}$$

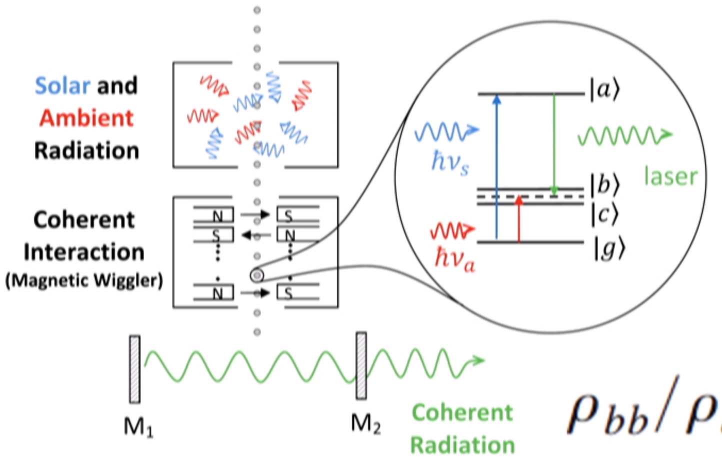

T_s
T_h
a
b
c
$\bar{n}_s = \frac{1}{e^{\frac{\hbar\omega_{ab}}{kT_s}} - 1}$


T_s
T_h
a
b
g
n̄_s = 1 / (e^{ħω_ab / kT_s} − 1)
ω_ab = (ε_a − ε_b) / ħ = ν_hs



T_s
T_h
a
b
g
n̄_s = 1 / (e^(ħω_ab / kT_s) − 1)
ω_ab = (ε_a − ε_b)/ħ = ν_h − ν_s
ν_h − ν_c
ħν_c / kT_c = ħν_s / kT_h

PRL **106,** 049801 (2011) PHYSICAL REVIEW LETTERS week ending 28 JANUARY 2011



Marlan O. Scully
Texas A&M University
College Station
Texas 77843, USA and
Princeton University
Princeton, New Jersey 08544, USA

$$\rho_{bb}/\rho_{aa} = \exp-[\epsilon_b/kT_c - \epsilon_a/kT_h]$$

$$\dot{\mathcal{E}} = \kappa(2\rho_{aa} - \rho_{bb} - \rho_{cc} - \rho_{bc} - \rho_{cb})\mathcal{E}$$

At threshold

$$\frac{\hbar\nu_\ell}{\hbar\nu_s} = \eta_{\text{Carnot}} + \delta\eta \qquad \delta\eta = kT_c|\rho_{bc}|/\hbar\nu_s\rho_{aa}$$

Summary

- Efficiency from QHE can exceed the classical Carnot Efficiency by using phased three-level atoms.
- The Photo-Carnot QHE can produce work from a single thermal bath.
- Efficiency of Laser QHEs can be increased by quantum coherence.

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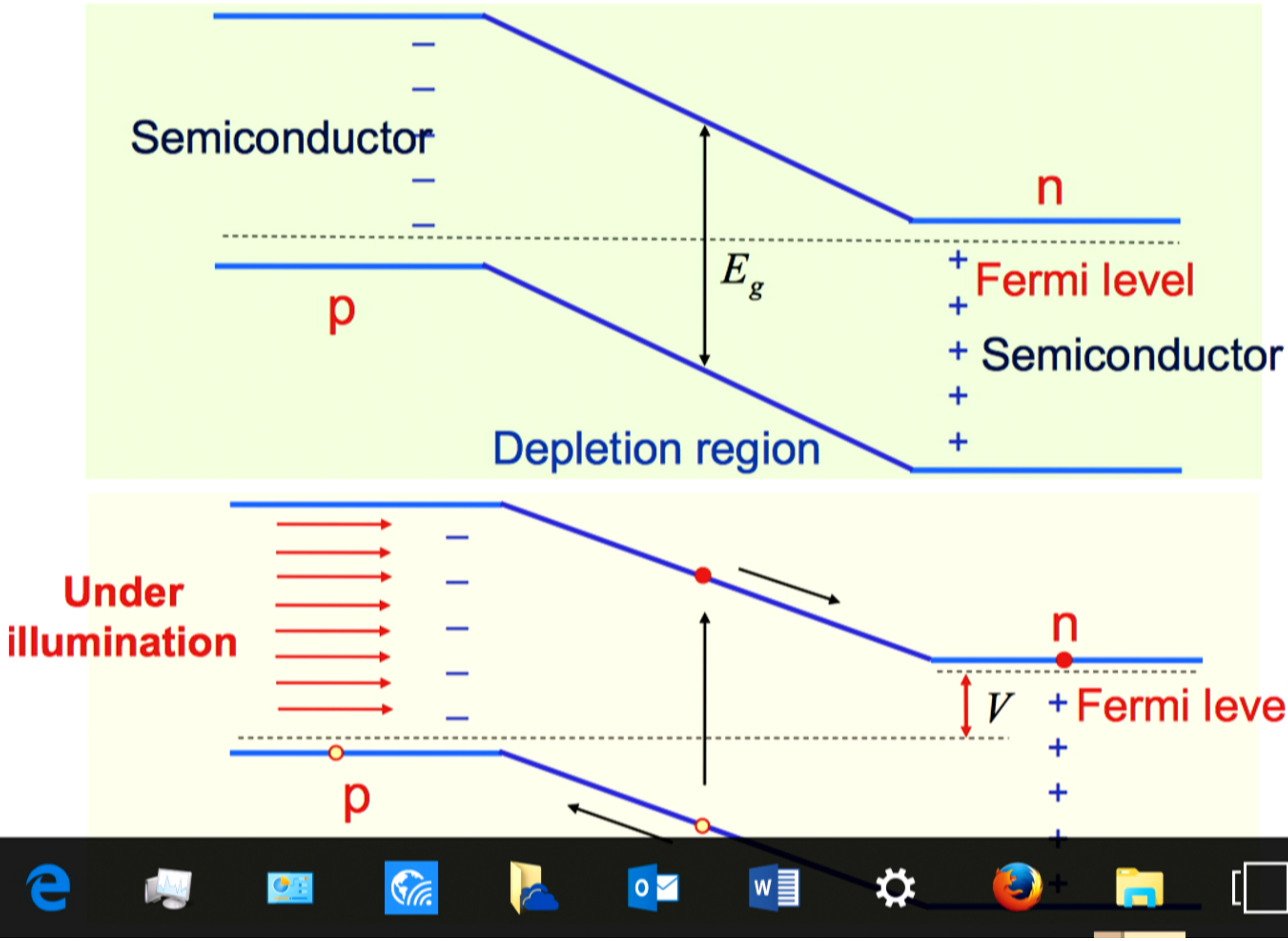
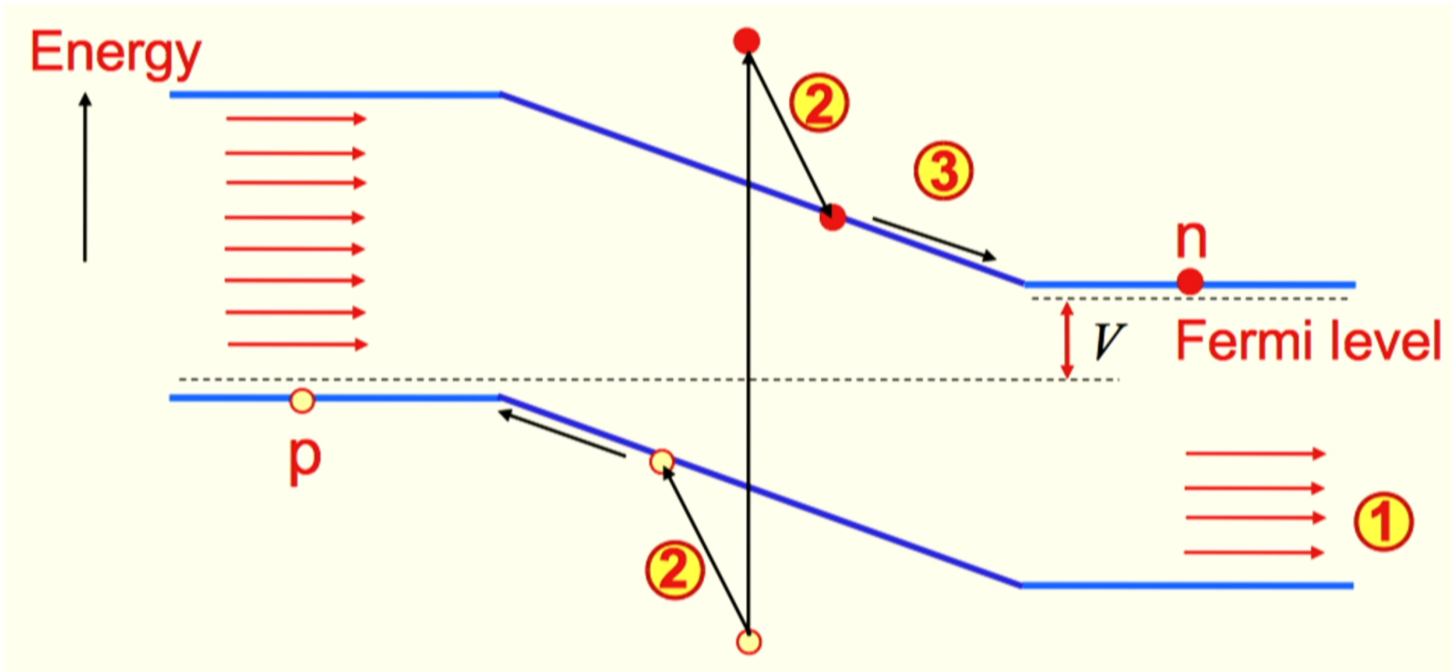
3). Efficien[illegible] of P[illegible]synt[illegible]sis

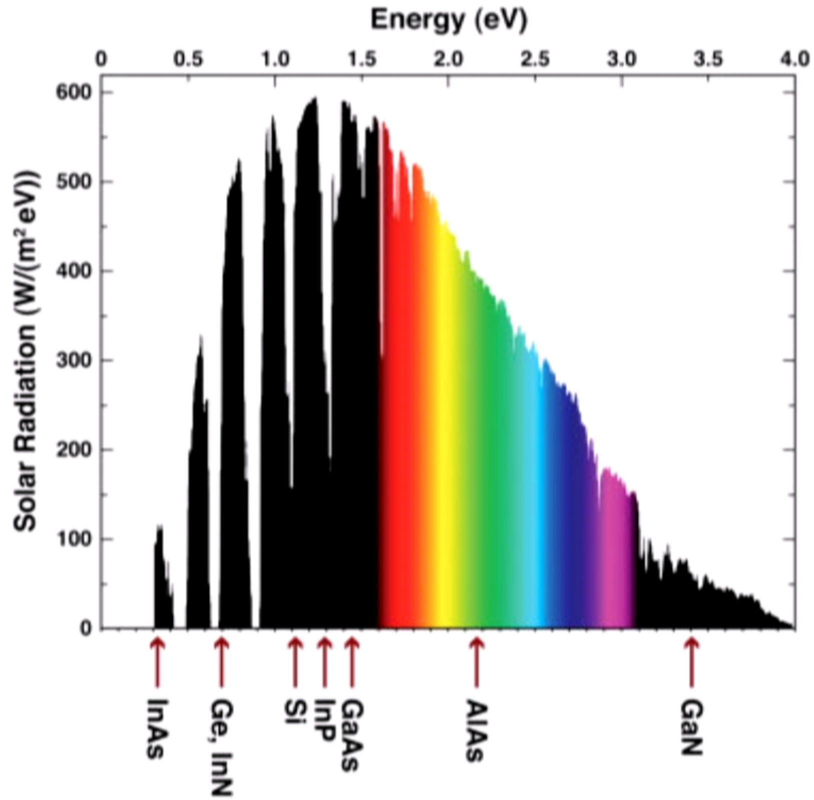
pn-junction solar cell



Solar cell losses



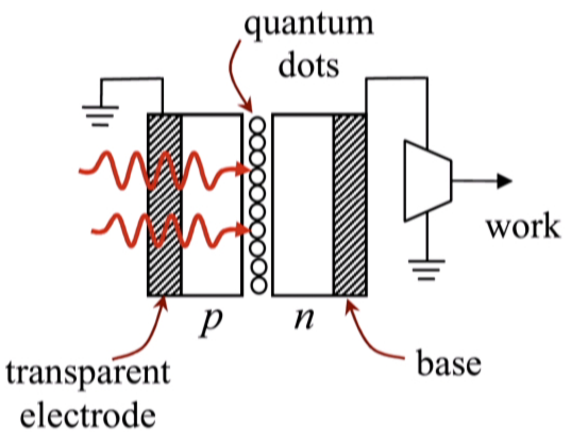
1. Photons with energy less then E_g are not absorbed
2. Thermal relaxation, energy is lost to phonons
3. Losses due to finite temperature of the cell (thermodynamic)



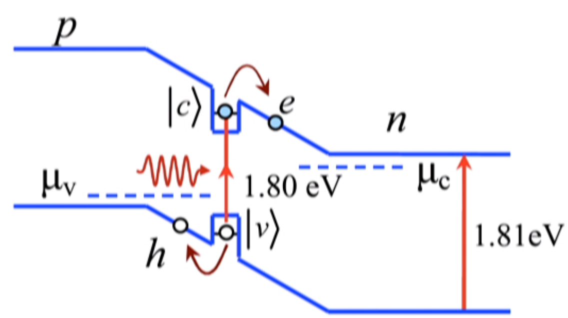
Solar spectrum with the bandgaps of semiconductors

Quantum Dot Photo/Solar Cell

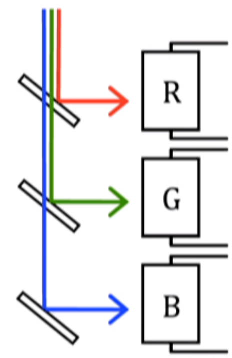
Solar cell with array of quantum dots

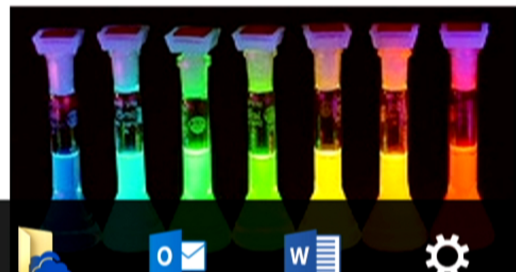


Electron-hole separation



Dividing photon flux onto monochromatic components





Texas A&M University

PRINCETON UNIVERSITY

Solar Cells and Detailed Balance

PRL **104,** 207701 (2010) PHYSICAL REVIEW LETTERS week ending 21 MAY 2010

Quantum Photocell: Using Quantum Coherence to Reduce Radiative Recombination and Increase Efficiency

Marlan O. Scully
Texas A&M University, College Station, Texas 77843, USA
Princeton University, Princeton, New Jersey 08544, USA
(Received 18 November 2009; published 21 May 2010)

The fundamental limit to photovoltaic efficiency is widely thought to be radiative recombination which balances radiative absorption. We here show that it is possible to break detailed balance via quantum coherence, as in the case of lasing without inversion and the photo-Carnot quantum heat engine. This yields, in principle, a quantum limit to photovoltaic operation which can exceed the classical one. The present work is in complete accord with the laws of thermodynamics.

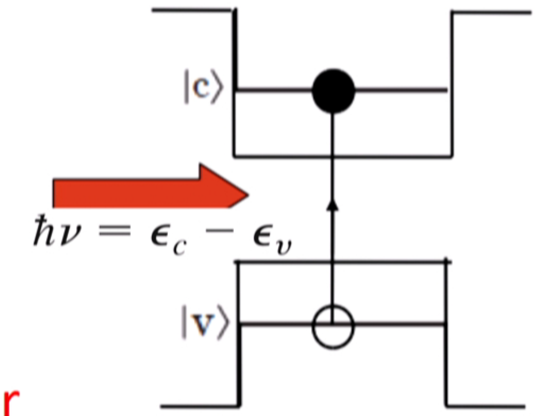
P. Würfel, *Chimia* **61**, 770 (2007)
"That leaves radiative recombination as the major [energy loss] process. Can this be avoided? The answer is no. If a radiative upward transition to generate the excitation is allowed, its reversal, the radiative downward transition must be allowed as well."

Solar cell with detailed balance

Population on levels c and v at temperature T_a

$$\frac{N_v}{N_c} = \exp[\epsilon_c - \epsilon_v - (\mu_c - \mu_v)]/kT_a$$

$eV = \mu_c - \mu_v$ Cell voltage



Average photon number

$$\dot{n} = -R\left[\frac{1}{e^{\hbar\nu/kT_s} - 1} - \frac{1}{e^{(\hbar\nu - eV)/kT_a} - 1}\right],$$

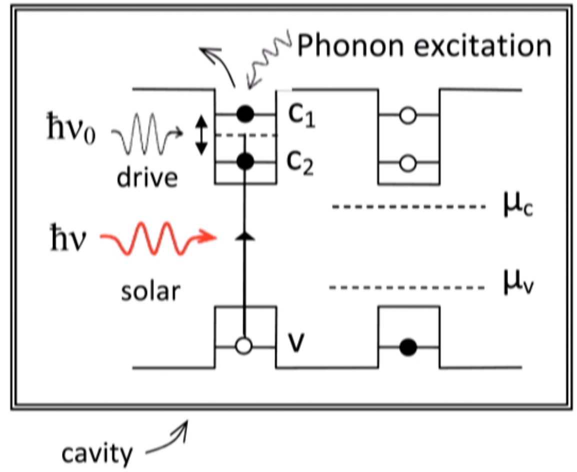
Thermodynamic efficiency

$$eV = \hbar\nu\left(1 - \frac{T_a}{T_s}\right)$$

Solar cell with external coherence

External drive $\hbar\nu_0 = \frac{1}{2}(\epsilon_{c1} - \epsilon_{c2})$

Resonant interaction $\Omega = \omega_1 - \nu$



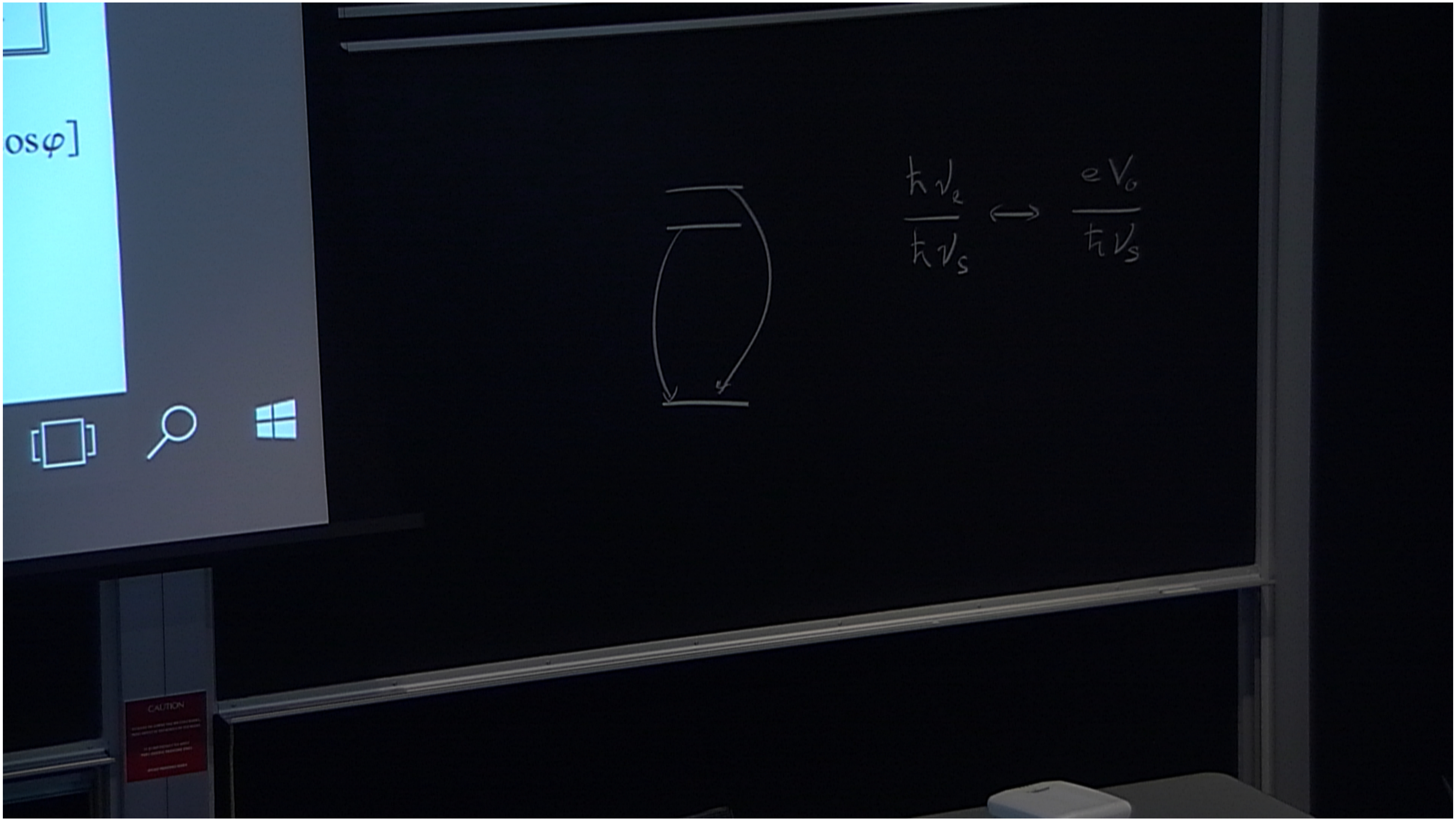
Average photon number

2-level 3-level

$$\frac{1}{e^{(\hbar\nu - eV)/kT_a} - 1} \rightarrow \frac{1}{e^x - 1} \qquad e^x = 2\rho_{v,v}/[\rho_{1,1} + \rho_{2,2} + (\rho_{11} - \rho_{22})\cos\varphi]$$

Thermodynamic efficiency $\varphi = \pi$

$$eV = \hbar\nu\left(1 - \frac{T_a}{T_s}\right) + \hbar\nu_0$$



osφ]
$\frac{\hbar\nu_e}{\hbar\nu_s} \longleftrightarrow \frac{eV_0}{\hbar\nu_s}$
CAUTION

Detailed balance revisited

"That leaves radiative recombination as the major

[energy loss] process. Can this be avoided? The

Yes!

answer is ~~no.~~ If a radiative upward transition to

generate the excitation is allowed, its reversal, the

radiative downward transition ~~must be allowed as well.~~"

can be mitigated by breaking detailed balance
via quantum coherence!

Summary

- Quantum coherence induced by an external microwave field can increase the quantum efficiency (open circuit voltage) of the photocell.

- Furthermore such a coherent driven photocell generates more power. The extra power produced by the device is much larger then that derived from the microwave source which creates the coherence.

- Induced coherence results in more efficient utilization of the pump photons by increasing absorption and/or quenching unwanted emission.

Quantum Coherence Can Improve Quantum Heat Engine (QHE) Efficiency

I. Quantum Thermodynamics

II. Photo-Carnot QHE

III. The Laser as a QHE

1. $$\frac{\hbar\nu_{laser}}{\hbar\nu_{pump}} = 1 - \frac{T_c}{T_h}$$ From Detailed Balance

2. Quantum Coherence Can Improve Laser QHE Quantum Efficiency by Breaking Detailed Balance

IV. The Photocell as a QHE

1. $$\frac{eV}{\hbar\nu_{pump}} = 1 - \frac{T_c}{T_h}$$ From Detailed Balance

2. Quantum Coherence Can Improve Photocell QHE Quantum Efficiency by Breaking Detailed Balance

V. Noise Induced Quantum Coherence Can Enhance:

1). Laser QHE Power

2). Photocell QHE Power

3). Efficie[illegible] of P[illegible]synt[illegible]sis

Noise induced quantum coherence

- External source:
  - ✓ Lasing Without Inversion
  - ✓ Supercharged Quantum Heat Engine
- No external field
  - ✓ Fano interference (quantum noise)
  - ✓ Agarwal (Fano-Harris) lasing without inversion

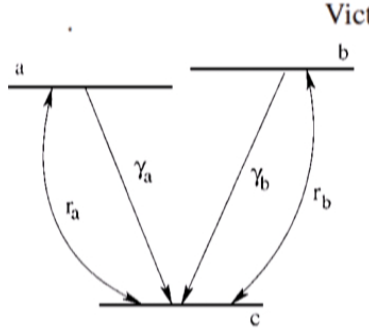
"...The preceding coherent drive model illustrates the role of quantum coherence in a simple way. However, it is possible to generate coherence without the use of an external field. For example, quantum noise induced coherence via Fano coupling..."

Noise induced coherence

PHYSICAL REVIEW A 74, 063829 (2006)

Inducing quantum coherence via decays and incoherent pumping with application to population trapping, lasing without inversion, and quenching of spontaneous emission

Victor V. Kozlov,[1,2] Yuri Rostovtsev,[1] and Marlan O. Scully[1,3,4]



Steady state coherence

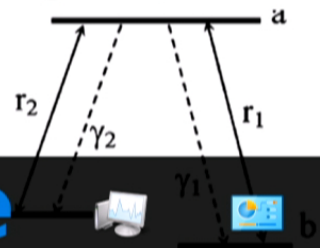
$$\rho_{ab} = \frac{p}{2}\,\frac{\sqrt{r_a r_b} - \sqrt{\gamma_a \gamma_b}}{r_a + r_b + \gamma_a + \gamma_b}$$

$$p \equiv \frac{\mu_{ac}\mu_{bc}}{|\mu_{ac}||\mu_{bc}|}$$

Optics Communications 281 (2008) 4940–4945

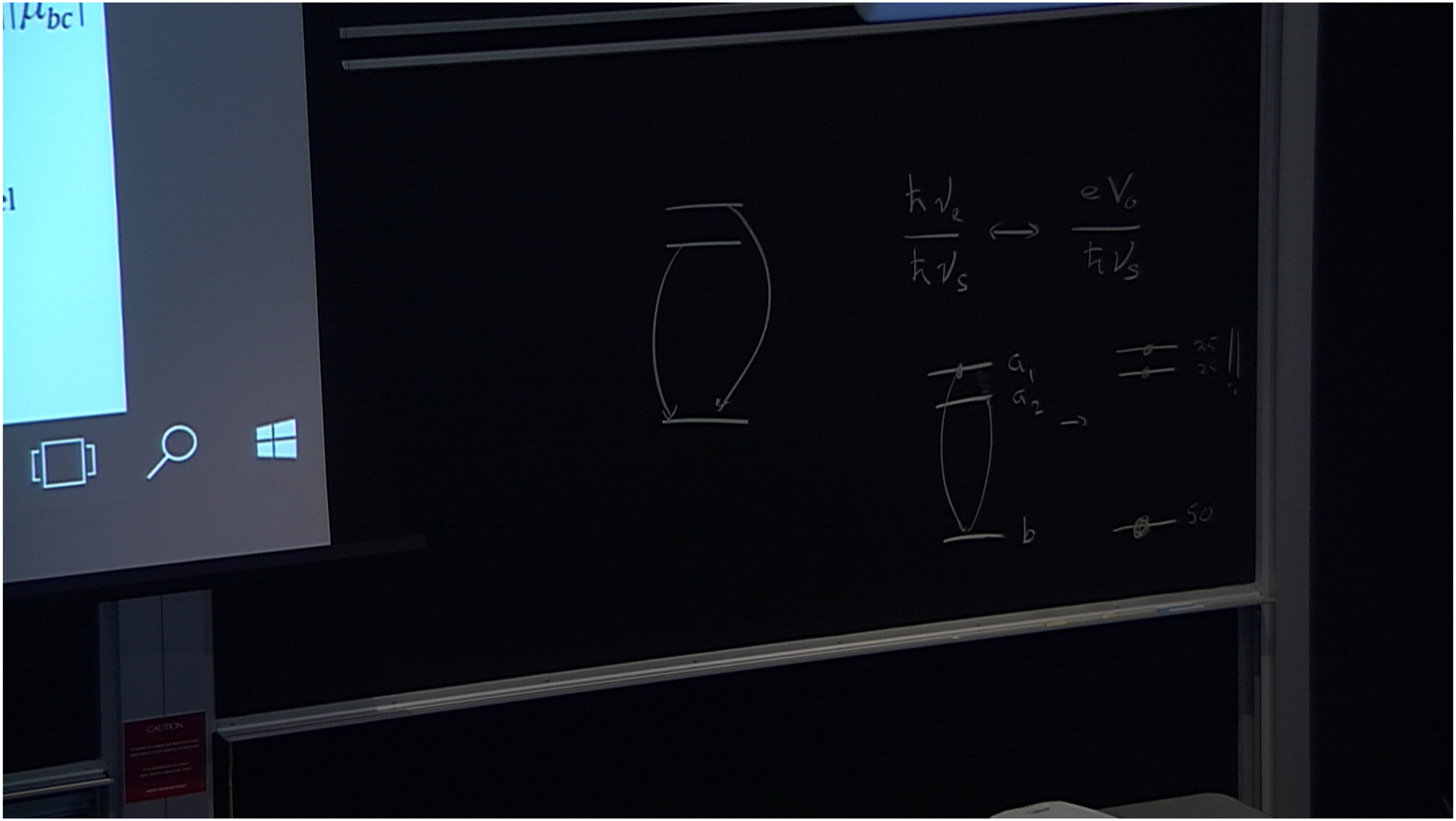
Coherence induced by incoherent pumping field and decay process in three-level Λ type atomic system

Bao-Quan Ou *, Lin-Mei Liang, Cheng-Zu Li

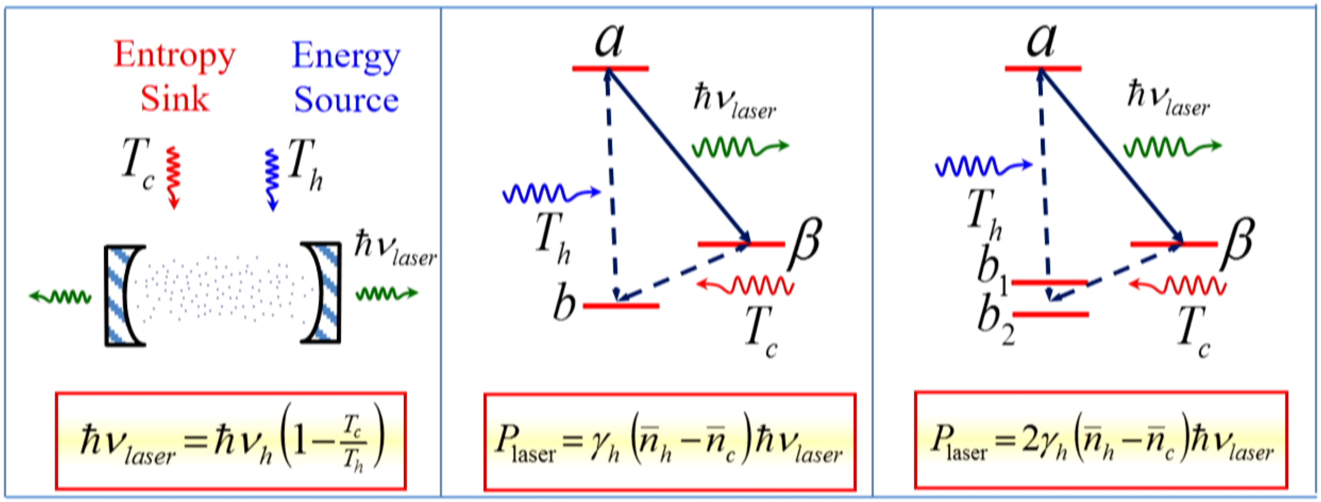


Steady state coherence

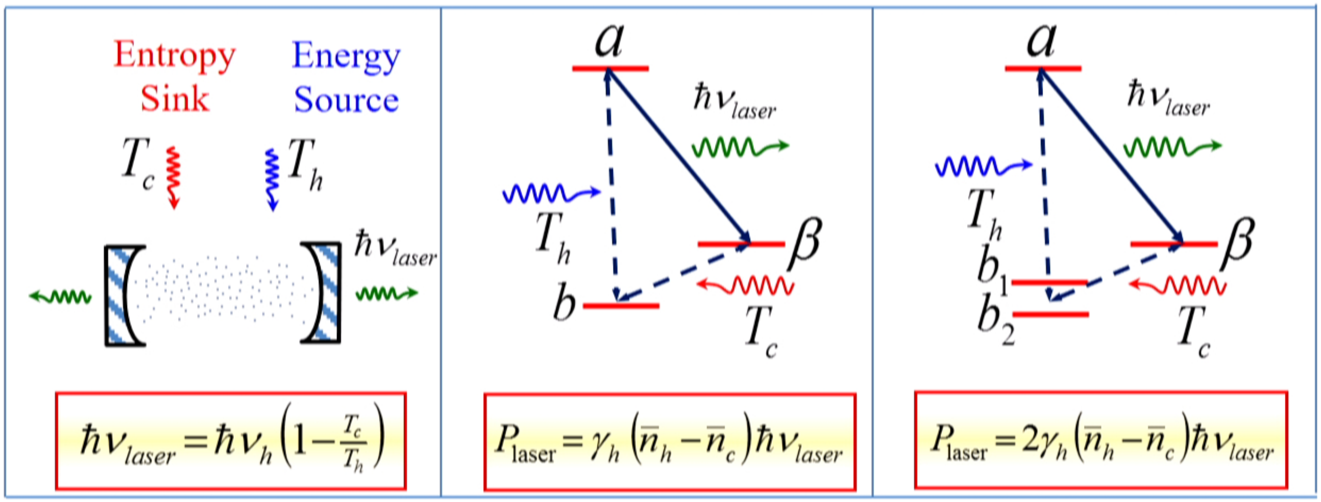
$$\rho_{bc} = -\frac{\sqrt{r_1 r_2}}{r_1 + r_2}$$


μ_{bc}
$\hbar\nu_e$
$\hbar\nu_s$
eV_0
$\hbar\nu_s$
a_1
a_2
b
50
CAUTION

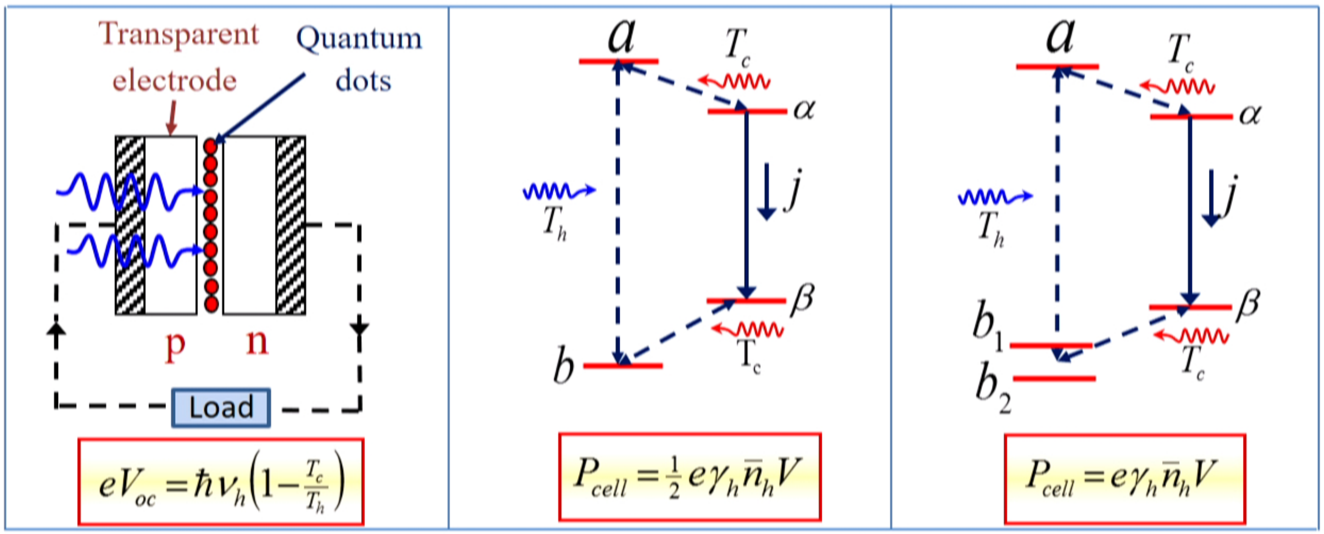
Noise induced quantum coherence can double the laser power at no extra cost!



Noise induced quantum coherence can double the laser power at no extra cost!



Noise induced coherence can **double** photocell power at no extra cost!



Noise induced coherence in photosynthetic systems

Konstantin Dorfman, Dmitri Voronine, Shaul Mukamel, and Marlan Scully

Noise induced coherence in photosynthetic systems

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