Bose-Einstein Condensation of Excitons and Polaritons

Review talk

in honor of John J. Hopfield

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Statistical Mechanics Conference

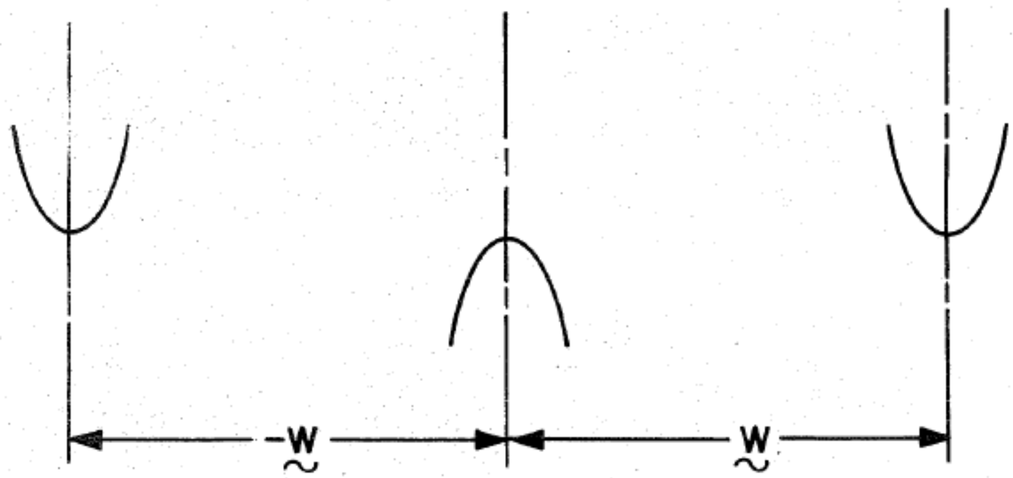
Rutgers, May 11, 2014

Outline

- What are excitons and polaritons?
- Why JJH might be interested in the subject.
- Equilibrium and non-equilibrium condensate states
- Theoretical history: Excitonic Insulators
- Experimental realizations (2D):
  - Bilayer Quantum Hall System in GaAs
  - Cavity-Polariton Condensate in CdTe multilayer

What is an exciton?

- An exciton is a bound state of an electron and a hole in a semiconductor or insulator.
- The exciton has an energy $\varepsilon(\mathbf{k})$ that depends on its total momentum $\mathbf{k}$.



Indirect excitons. If the conduction band minimum and valence band maximum occur at different points in the Brillouin zone, the lowest energy exciton has $\mathbf{k}\neq 0$, cannot couple directly to photons.

What is an exciton?

- **Direct excitons**: If the conduction band minimum and valence maximum occur at the same point in the zone, then exciton minimum occurs at k=0.
- Low energy excitons can mix strongly with photons of the same wave vector. Resulting bosons are called exciton polaritons. (Optical phonons can also combine with photons, to form phonon polaritons)

Hopfield 1958

PHYSICAL REVIEW VOLUME 112, NUMBER 5 DECEMBER 1, 1958

Theory of the Contribution of Excitons to the Complex Dielectric Constant of Crystals*†

J. J. HOPFIELD‡
Physics Department, Cornell University, Ithaca, New York
(Received July 16, 1958)

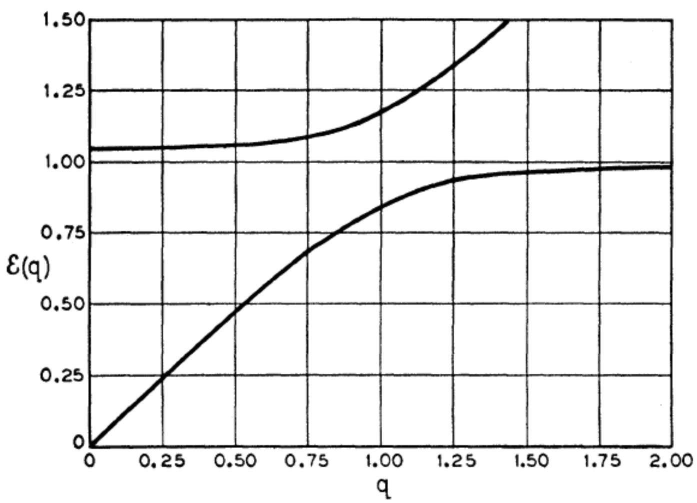


FIG. 1. $E(k)$ for $4\pi\beta=0.1$. Units of $\hbar=c=1$, and $\mathcal{E}=E/\omega_0$, $q=k/\omega_0$.

Paper based on Hopfield's PhD thesis at Cornell

Contains first use of word "polariton"

(1400 + citations)

Calculation of an exciton-polariton spectrum.

Hopfield and Thomas

PHYSICAL REVIEW VOLUME 116, NUMBER 3 NOVEMBER 1, 1959

Exciton Spectrum of Cadmium Sulfide

D. G. THOMAS AND J. J. HOPFIELD
Bell Telephone Laboratories, Murray Hill, New Jersey

(Received June 10, 1959)

PHYSICAL REVIEW VOLUME 132, NUMBER 2 15 OCTOBER 1963

Theoretical and Experimental Effects of Spatial Dispersion on the Optical Properties of Crystals

J. J. HOPFIELD*†
Department of Physics, University of California, Berkeley, California

AND

D. G. THOMAS
Bell Telephone Laboratories, Murray Hill, New Jersey

(Received 14 June 1963)

Finite exciton mass can have a major effect on the optical reflectivity close to the exciton resonant frequency.

Buckley Prize 1969

- Awarded to J. J. Hopfield and D. G. Thomas

- “for their joint work combining theory and experiment, which has advanced the understanding of the interaction of light with solids.”

Bose-Einstein Condensates of Excitons or Polaritons?

- Since excitons or polaritons are bosons, can they form a Bose Einstein condensate?
- Excitons and polaritons have finite lifetimes, generally short. But if can find system with long-enough life times, they might have time to thermalize before they decay. If density is high and temperature is low, could form Bose-Einstein condensate.
- Alternatively, if energy gap of a semiconductor is small and binding energy is large, isolated excitons could have negative energy. Parent state would be unstable to formation of finite density of excitons.
- Ground state would contain an **equilibrium** BEC of excitons.
- Similarly, for a semimetal with very small band overlap, strong binding between electrons and holes could lead to an insulating ground state, the "excitonic insulator", with a BEC of excitons.

Excitonic Insulator - History

- Ideas introduced by Mott (1961), Knox (1963), Keldysh and Kopaev (1964), des Cloizeaux (1965)

- Theoretical properties explored in a review article by B. I. Halperin and T. M. Rice, “The Excitonic State at the Semiconductor-Semimetal Transition,” in Solid State Physics series, edited by Seitz, Turnbull and Ehrenreich, 1968.

- But no experimental realization until 1987, in a very different context.

Bilayer Quantized Hall System with total Landau-level-filling ν=1.

- Example of equilibrium BEC of excitons.
- Experimental realization in GaAs bilayers with small separation d.
- Strong magnetic field B perpendicular to layers. **Total number** of electrons per flux quantum is ν =1.
- Regime where Coulomb interaction between electrons in different layers is smaller but comparable to interaction between electrons in the same layer. Ignore tunneling between layers.

Simple model

- Assume electrons are completely spin-polarized.
- Introduce pseudospin index $\tau = \pm 1$ to distinguish top and bottom layer.
- For $\nu=1$, put all electrons in the lowest Landau level. Kinetic energy is fixed, must minimize the Coulomb energy. Hartree energy favors uniform density, one electron in each orbital state. But there is freedom to choose the pseudospin orientation for each electron.
- Exchange energy => pseudospin orientation should be the same for every electron.

Finite layer separation

- If $d \neq 0$, Coulomb interaction favors equal occupation of layers. => $< \tau_Z >= 0$.
- If d is not too large, ground state is a Hartree-Fock state with one electron in each orbital state and the same $< \boldsymbol{\tau} >$ for every electron.
- $< \tau_Z >= 0$ => $< \boldsymbol{\tau} >$ must lie in the x-y plane.
- Energy is independent of orientation in the x-y plane, since the Hamiltonian is invariant under U(1) rotations, if one can ignore tunneling between the layers. Ground state has broken U(1) symmetry.
- State is termed a "quantum Hall (pseudo)ferromagnet".

Description as an **exciton condensate**.

- Add an electric field **E** perpendicular to the layers, which favors an imbalance between layers. Fix total filling at $\nu=1$.
- If **E** is sufficiently large, ground state will have all electrons in one layer, say $<\tau_Z> = 1$. State has **no** broken U(1) symmetry. ("Reference state")
- Lowest energy neutral excitation is an exciton, consisting of a hole in the top layer, bound to an electron in the lower layer, with the same orbital state.

Description as an exciton condensate.

- If **E** is reduced below a critical value, exciton energy becomes negative, reference state is unstable with respect to the spontaneous formation of excitons. New ground state will have finite density of excitons => finite fraction of electrons in each layer.
- Excitons form a Bose-Einstein condensate.

Then $< \tau_Z > \neq 1$, and $< \boldsymbol{\tau} >$ will have a component in the x-y plane. Broken U(1) symmetry.

- Balanced state (**E**=0), has one exciton per two flux quanta.
- Note: Coherent state requires separation d less than 1.7 l_B.

Properties of the BEC state

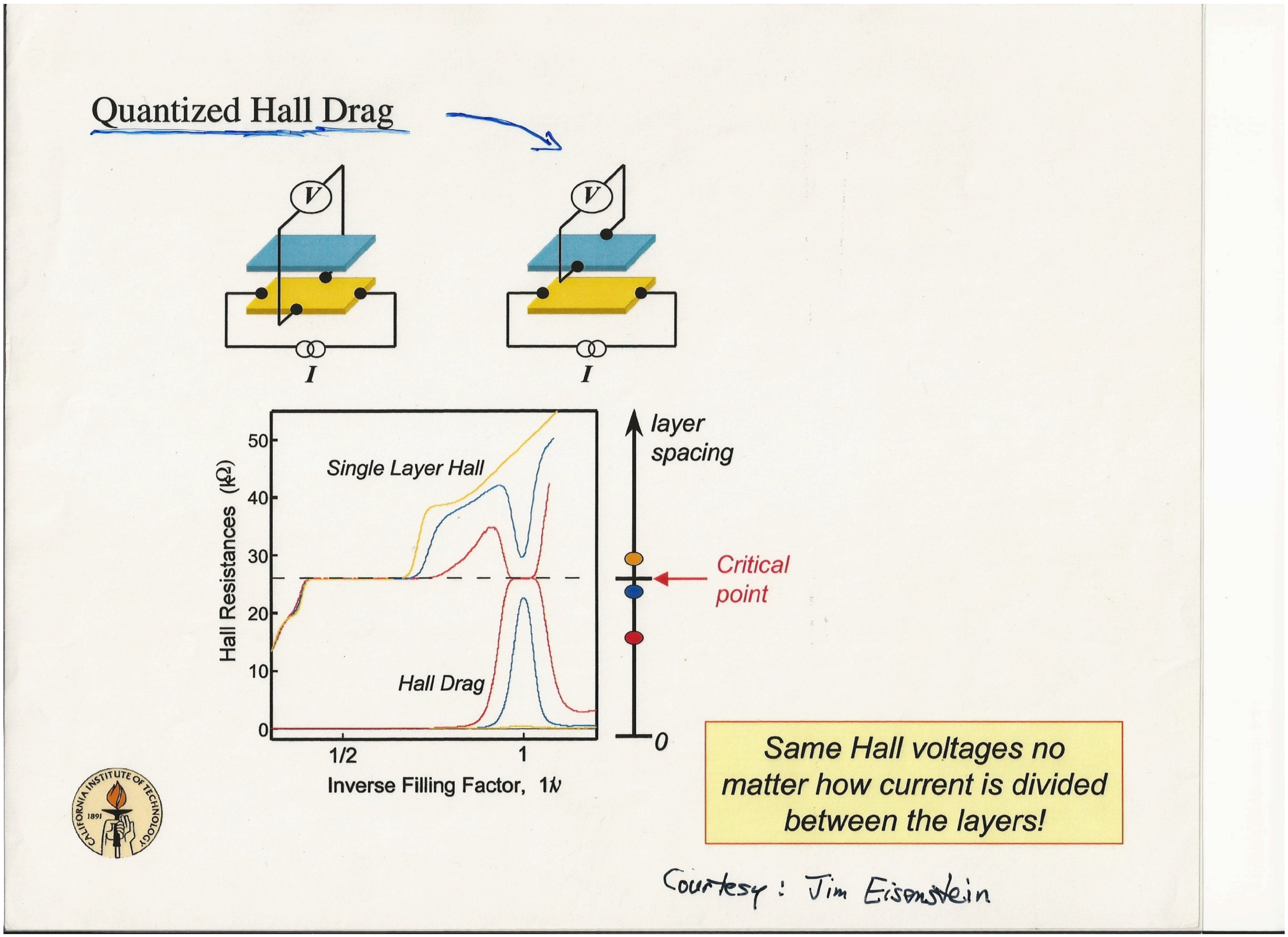
- System shows quantized Hall conductance for summed electric current flowing in two layers ($\varrho_{xy} = h/e^2$, $\varrho_{xx} = 0$.)

- System behaves like a superfluid for difference currents in two layers: ($\varrho_{xx} = \varrho_{xy} = 0$.) Zero voltage difference between layers.

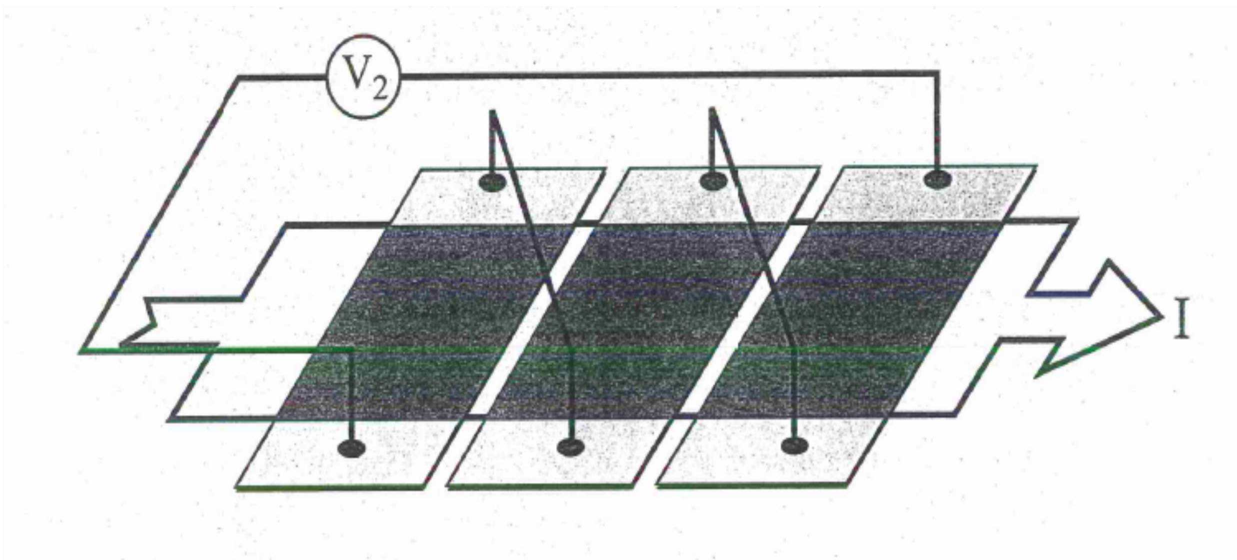
- Counterflowing currents can occur with no voltage drop.

- Leads to phenomenon of **quantized Hall drag**.

Quantized Hall Drag



Proposal: dc step-up transformer



Dark gray areas are in coherent bilayer state. White areas have upper layer depleted, lower layer in ν=1 state.

[Halperin, Stern and Girvin (2003)]

Other properties of ν=1 bilayer

- For non-zero tunnel coupling between layers, apply voltage difference to layers and measure tunneling current. Find sharp conductance peak at zero bias, analogous to Josephson effect. Details, such as height and width of peak are only partially understood.

- BEC state disappears for d larger than $d_c \approx 1.7\ l_B$. Details of transition are poorly understood.

Bose–Einstein condensation of exciton polaritons

J. Kasprzak[1], M. Richard[2], S. Kundermann[2], A. Baas[2], P. Jeambrun[2], J. M. J. Keeling[3], F. M. Marchetti[4], M. H. Szymańska[5], R. André[1], J. L. Staehli[2], V. Savona[2], P. B. Littlewood[4], B. Deveaud[2] & Le Si Dang[1]

Nature 443, 410 (2006) (Experiments at EPFL and Grenoble)

BEC of Polaritons in CdTe/CdMgTe quantum well structure.

Sample contains 16 parallel wells in an optical cavity

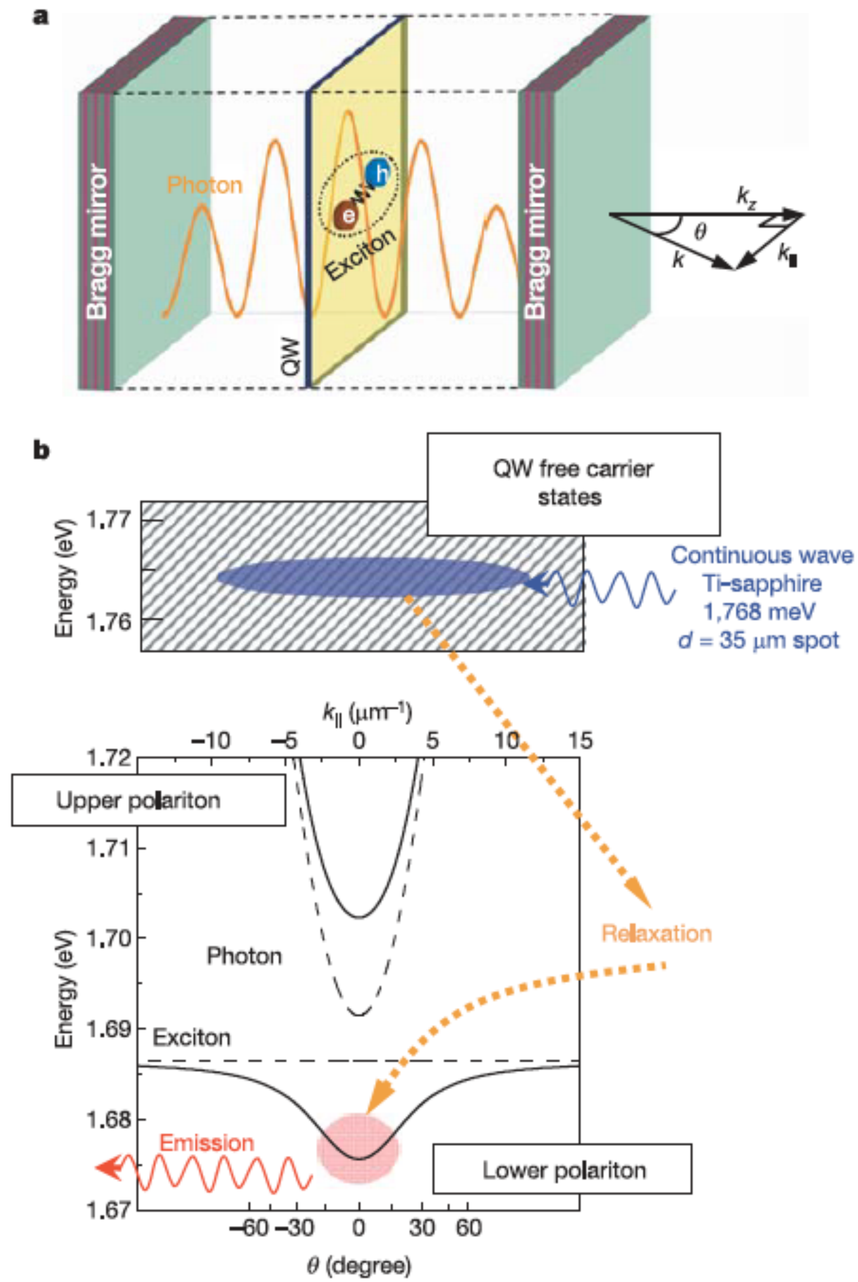
Microcavity diagram and energy dispersion

Polariton mass = 10^{-4} m_e .

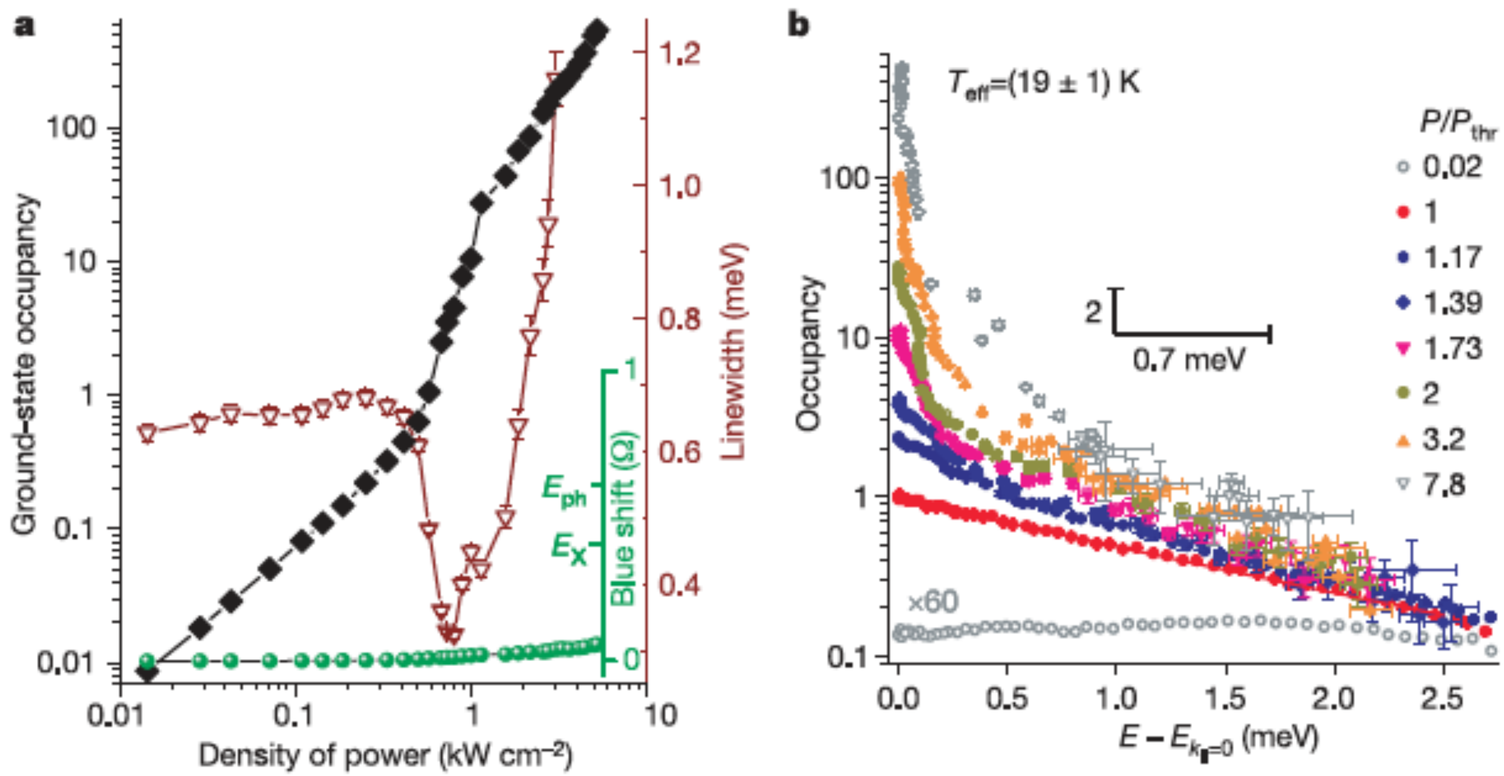
System is continuously pumped (at high energies) to counteract losses.

Thermalized polariton gas has T = 19 K. (Lattice T = 5 K)

Condensation into polariton ground state is observed above a critical exciton density

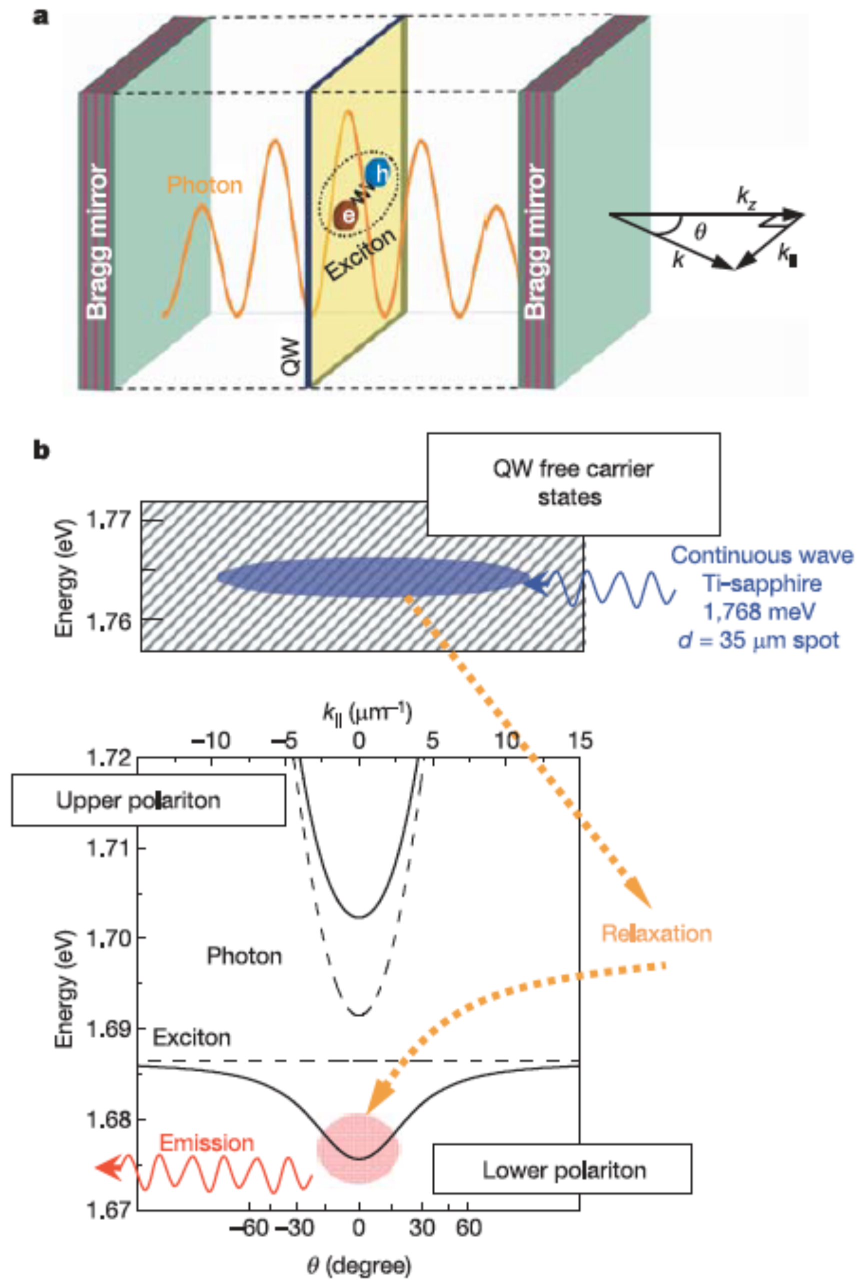


Polariton occupancy measured at lattice T = 5K



Polarization coherence was also observed.

What is the difference between a polariton condensate and an ordinary semiconductor laser?



BEC of excitons or polaritons have also been reported in other systems.

- Cavity polaritons in GaAs quantum wells
- Triplet excitons in 3D Cu_2O (but condensate fraction only 1%.)

Conclusions

- Research involving excitons and polaritons is alive and well.
- Effects related to BEC are a fascinating aspect of this work.
- Much of it rests on foundations to which John Hopfield made some seminal contributions
- Happy Birthday John.