January 2010, Maynooth

Photons

Myungshik Kim

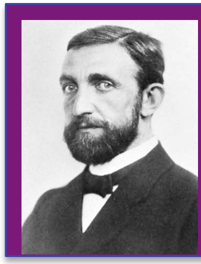
http://www.qteq.info

Contents

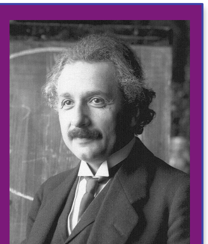
- Einstein 1905
- Einstein 1917
- Hanbury Brown and Twiss

Light quanta

- In 1900, Max Planck was working on black-body radiation and suggested that the energy in electromagnetic waves could only be released in "packets" of energy, he called these *quanta.*
- Later, in 1905 Albert Einstein went further by suggesting that EM waves could only exist in these discrete wave-packets. He called such a wave-packet the light quantum *(German: das Lichtquant).*



Photoelectric effect
Observed by von Lenard in 1902
Explained by Einstein in 1905



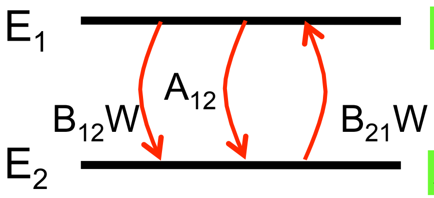
Einstein 1917

- **Einstein turned to the question of how the kinetic energy of a gas of atoms maintains thermal equilibrium with a radiation field.**
- **Einstein suggested three processes for the interaction of atoms and light quanta: spontaneous emission, absorption and stimulated emission.**

In equilibrium

$$\frac{dN_2}{dt} = N_1 A_{12} + N_1 B_{12} W - N_2 B_{21} W = 0$$

$$\Rightarrow W = \frac{A_{12}}{(N_2/N_1)B_{21} - B_{12}} = \frac{A_{12}}{e^{(E_1-E_2)/kT} B_{21} - B_{12}} \Rightarrow \frac{\alpha\omega^3}{e^{\hbar\omega/kT} - 1}$$



$N_1 \propto e^{-E_1/kT}$

$N_2 \propto e^{-E_2/kT}$

canonical distribution

Planck's blackbody radiation

Bohr's stationary state theory

Einstein 1917

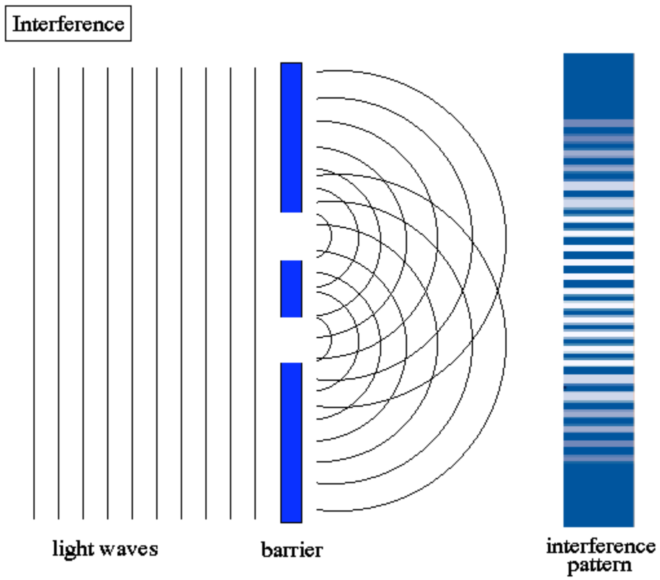
- **Momentum transfer in each step of radiation is central to Einstein's analysis. That the light quantum carries momentum as well as energy is an innovation of the 1917 paper. In the 1905 paper on the photoelectric effect, momentum played no role.**
- **Einstein assumed that atoms react to the radiation differently when they move from at stationary – Doppler shift.**
- **Maxwell-Boltzmann velocity distribution together with the definition of spontaneous and stimulated processes result in the radiation field to bear the Blackbody radiation statistics as it gives the relation**

$$\frac{Wh\nu}{2kT} = \left(W - \frac{1}{3}\nu\frac{\partial W}{\partial \nu}\right)\left(1 - e^{-h\nu/kT}\right)$$

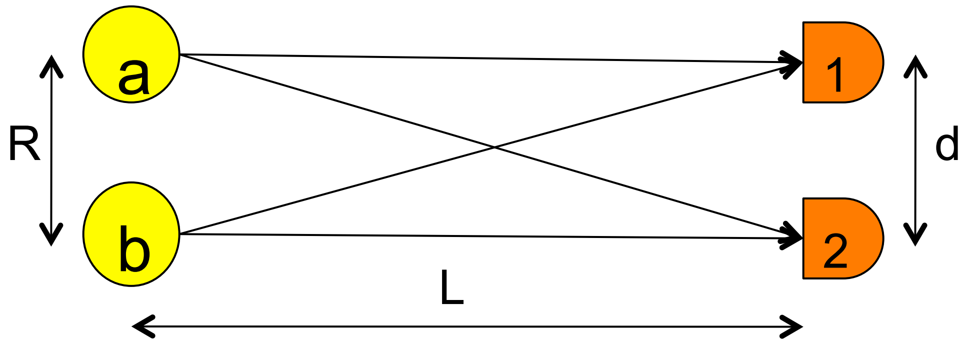
Bose-Einstein statistics

- Maxwell-Boltzmann statistics: for distinguishable classical particles in thermal equilibrium
- In 1924, Bose's elegant, first-principle derivation of the Planck formula for black body radiation was based on the indistinguishability of light particles and the fact that any number of particles can be in one state.
- In the same year, Einstein extended the method to give the quantum theory of an ideal gas.

Interference



Hanbury Brown & Twiss interferometer



- HBT suggested an intensity interferometer to measure the diameter of a star
- Assume two independent light sources a and b

The total amplitude at detector 1 is

$$A_1 = \alpha e^{ikr_{1a}+i\phi_a} + \beta e^{ikr_{1b}+i\phi_b}$$

The total intensity in 1 is

$$I_1 = |\alpha|^2 + |\beta|^2 + \alpha^* \beta e^{i(k(r_{1b}-r_{1a})+\phi_b-\phi_a)} + \alpha\beta^* e^{-i(k(r_{1b}-r_{1a})+\phi_b-\phi_a)}$$

On averaging over the random phases, the intensities at the two detectors

$$\langle I_1 \rangle = \langle I_2 \rangle = \langle |\alpha|^2 + |\beta|^2 \rangle$$

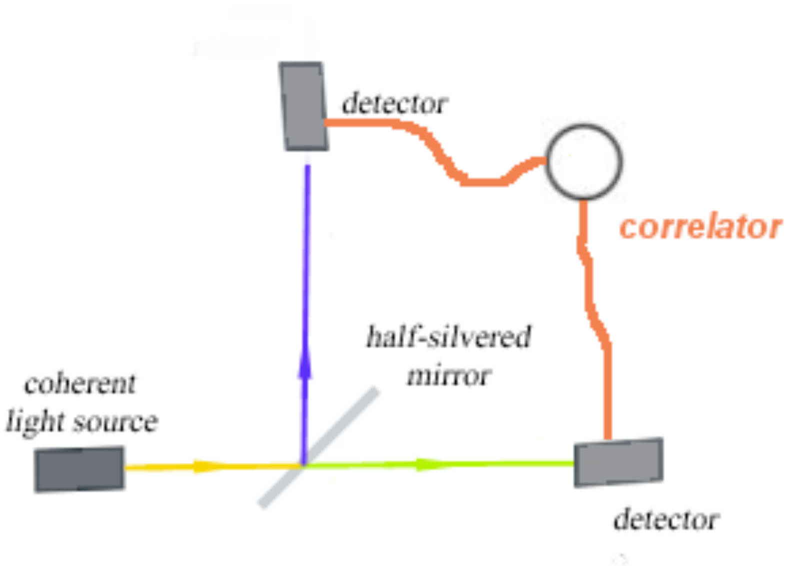
The intensity correlation on the other hand is

$$\langle I_1 I_2 \rangle = \langle I_1 \rangle \langle I_2 \rangle + |\alpha|^2 |\beta|^2 \cos(k(r_{1a} - r_{1b} + r_{2b} - r_{2a}))$$

The intensity correlation shows periodic behaviour wrt the path differences.

Using the relation, $d = \lambda/\theta$ and $\theta = R/L$, we find the diameter.

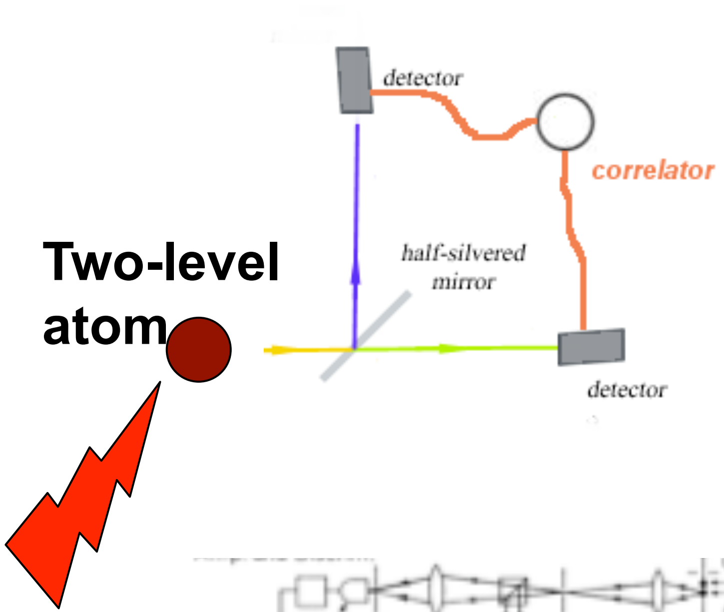
Hanbury Brown and Twiss interferometer



Interferometer that would observe no correlation, if the light source is a coherent laser beam, and positive correlations if the light source is a filtered one-mode thermal radiation.

Looking for bunching
to show indistinguishability and arbitrary number of photons in one state

Bunching vs Antibunching



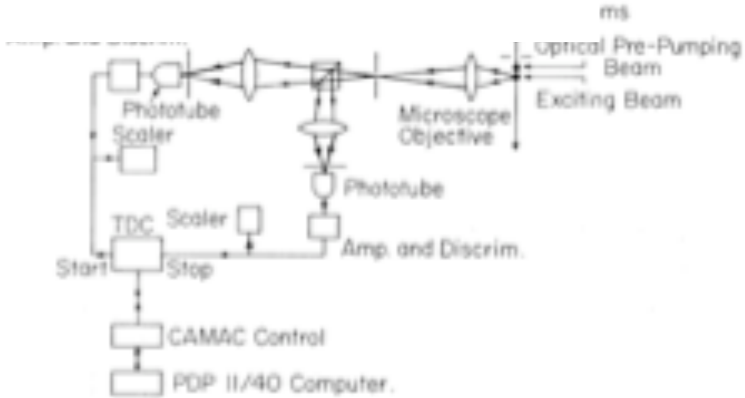


FIG. 1. Outline of the principal elements of the experiment.

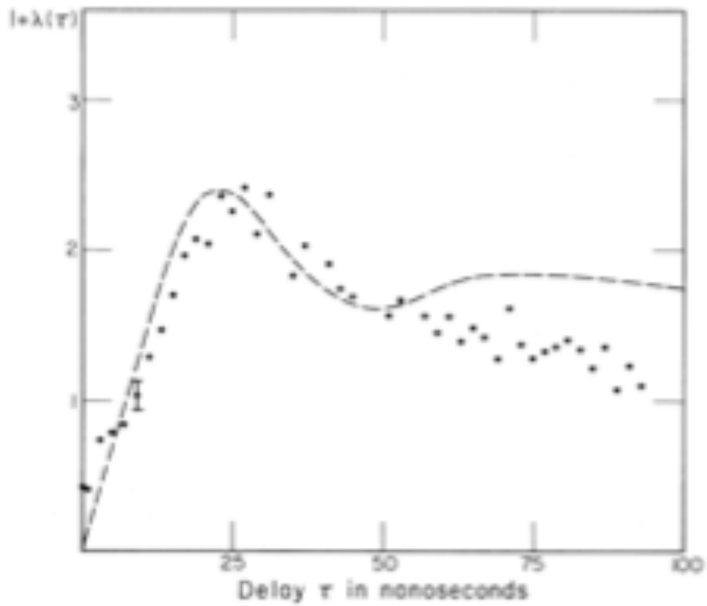
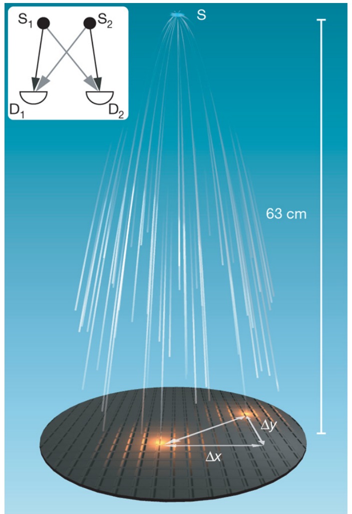
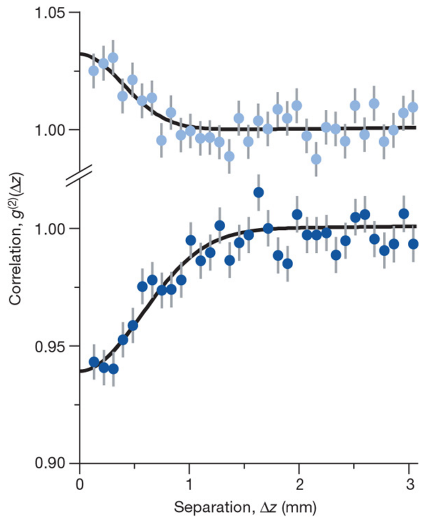


FIG. 3. Values of $1 + \lambda(\tau)$ derived from the data. The broken curve shows the theoretically expected form of $\langle \hat{I}_G(\tau) \rangle$ (with $\Omega/\beta = 4$) for a single atom, arbitrarily normalized to the same peak.

Kimble et al, PRL (1997)

HBT effect for bosons & fermions



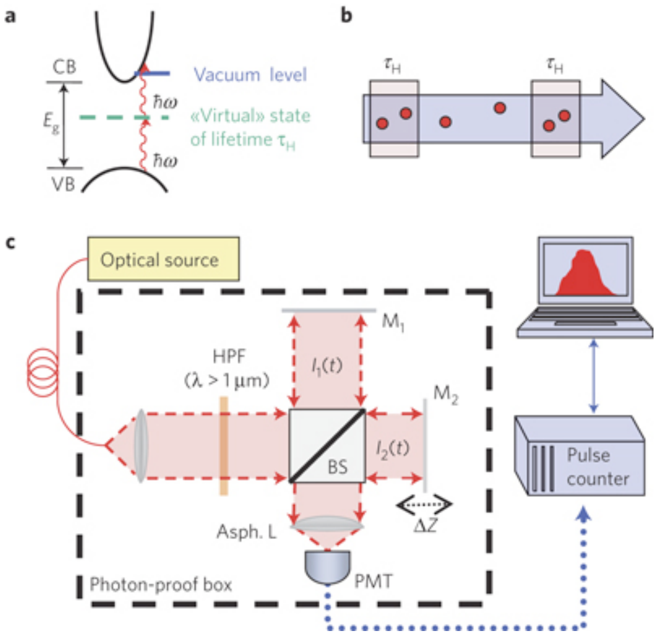


Normalized correlation functions for $^4He^*$(bosons) in the upper plot, and $^3He^*$(fermions) in the lower plot.

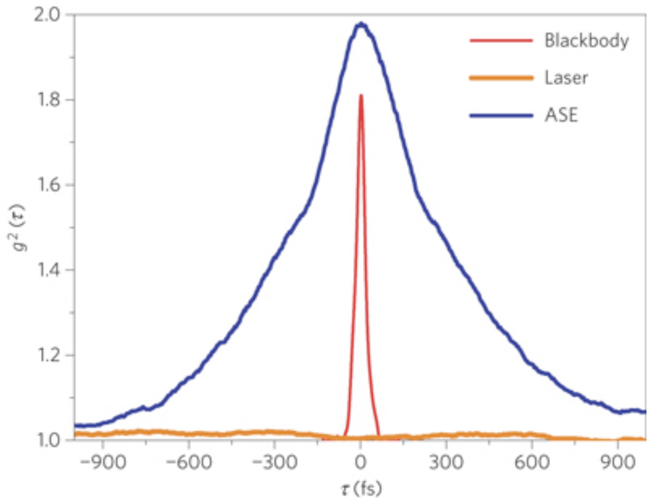
A cold cloud of metastable helium atoms is released at the switch-off of a magnetic trap. The cloud expands and falls under the effect of gravity onto a time-resolved and position-sensitive detector (microchannel plate and delay-line anode) that detects single atoms. The horizontal components of the pair separation *r are denoted x and y. The inset shows conceptually the two 2-particle amplitudes (in black or grey) that interfere to give bunching or antibunching:* S_1 *and* S_2 *refer to the initial positions of two identical atoms jointly detected at* D_1 *and* D_2.

Jeltes et al, Nature (2007)

Measuring photon bunching at ultrashort timescale



a, Two photons absorption (TPA) from valence-band (VB) states to conduction-band (CB) states in a direct-gap semiconductor (such as GaAs). In a phototube, the electrons in the conduction band are emitted when reaching the extraction (or 'vacuum') level.
b, Only photons arriving within time intervals shorter than the 'virtual' state lifetime at midgap can induce TPA transitions.
c, The HBT apparatus is a Michelson interferometer with two arms.



Normalized HBT for 1.55µm diode laser and two highly incoherent sources, an amplified spontaneous emission and a 3000K blackbody sources as determined by the TPA experiments.

Boitier et al, Nature Physics (2009)

Photons

- A photon is a quantum of the electromagnetic field.
- It is the force carrier for the electromagnetic force.
- Photons are governed by quantum mechanics and will exhibit wave-particle duality.