# 1 Introduction

Some history and aspects of the quantum nature of light

A)

The first introduction of a possible quantum nature of light was given by Max Planck in 1900.

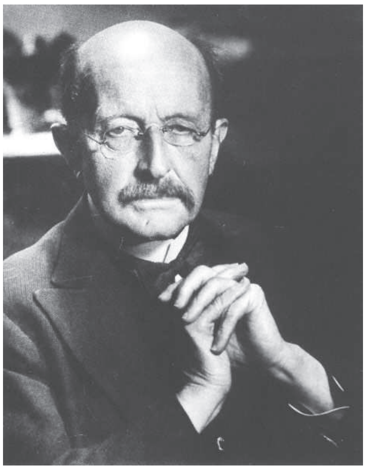

Figure 1: Max Planck (1858-1947)

Planck postulated a quantized harmonic oscillator modell in order to derive a correct formula for black-body radiation.

The energy density of a black radiating body is given by:

$$w(\omega)d\omega = \frac{\hbar\omega^3}{\pi^2 c^3} \frac{d\omega}{\exp{(\hbar\omega/k_b T)} - 1}$$

Planck's formula solved the problem of the so-called UV-catastrophe of the Rayleigh-Jeans law. This law is an approximation of Planck's formula for $k_{bT} \gg \hbar\omega$:

$$w(\omega)d\omega = \frac{\omega^2 k_b T}{\pi^2 c^3}$$

(This formula diverges for $\omega \to \infty$!)

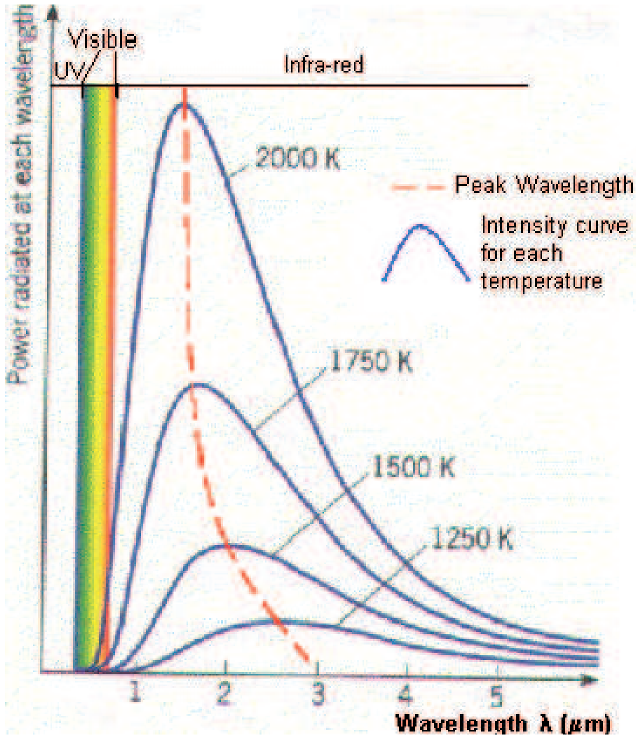


Figure 2: Black body radiation

However, it remained unclear wether a quantized theory for the light field (and not only for matter) was necessary.

Planck's theory assumes quantized harmonic oscillators (in the walls of a black-body) not necessarily the existence of a real quantized fields. Additionally, Taylor performed an interference experiment in 1906 of Young-type, but in the limit of single photons. There was no difference to the classical results!

B)

The first to introduce the concept of photons was Einstein in 1905 in order to explain the photoelectric effect:

$$\hbar\nu = \Phi + W_{electron}$$

where $\hbar\nu$ is the energy of light falling on a metal plate, $\Phi$ the work function of the material and $W_{electron}$ the kinetic energy of the emitted electrons.

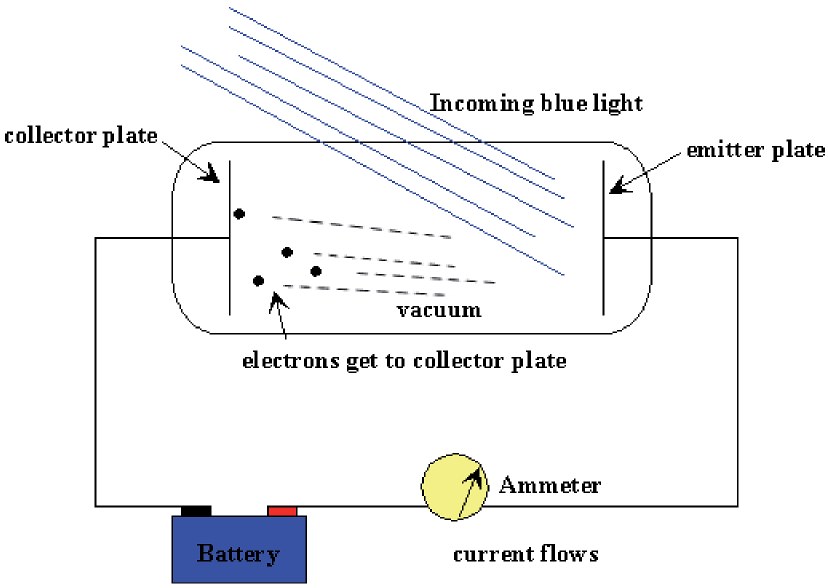


Figure 3: Measuring the photoelectric effect

The photoelectric effect has three features which all are explained easily by Einstein's assumption of the existence of photons:

1. The photocurrent depends on the frequency of the impinging light.
2. The photocurrent is proportional to the electric field squared.
3. There is basically no time delay betwen the electron ejection and the onset of the illumination.

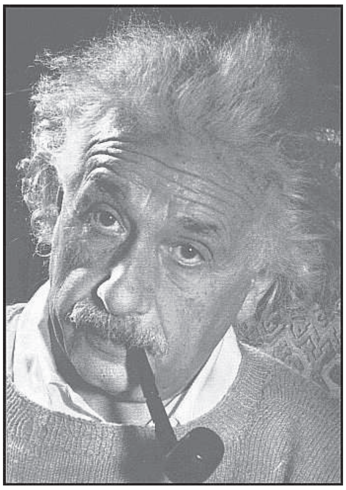

Figure 4: Albert Einstein (1879-1955)

It was shown later (Wentzel 1927) that the featutres 1 and 2 can also be explained by a semiclassical theory.

**Semiclassical theory = quantized matter and classical fields**

Point 3 however violates energy conservation in a semiclassical theory!

C)

Introduction of the **spontaneous and stimulated emission** by Einstein in 1917.

The process of a spontaneous emission was required since an atom in an excited state is in an eigenstate $|e\rangle$. No polarisation is introduced which would act as a source for radiation. Thus, an atom should stay forever in the excited state $|e\rangle$.

Introduction of the spontaneous emission rate A $\Leftrightarrow$ vacuum fluctuations

One can oversimplify that quantum fields are classical fields plus fluctuations.

D)

Invention of the maser (microwave amplification by stimulated emission of radiation) by C. Towns in 1955 and the laser (infrared or optical maser) by Maiman in 1960 (ruby laser).

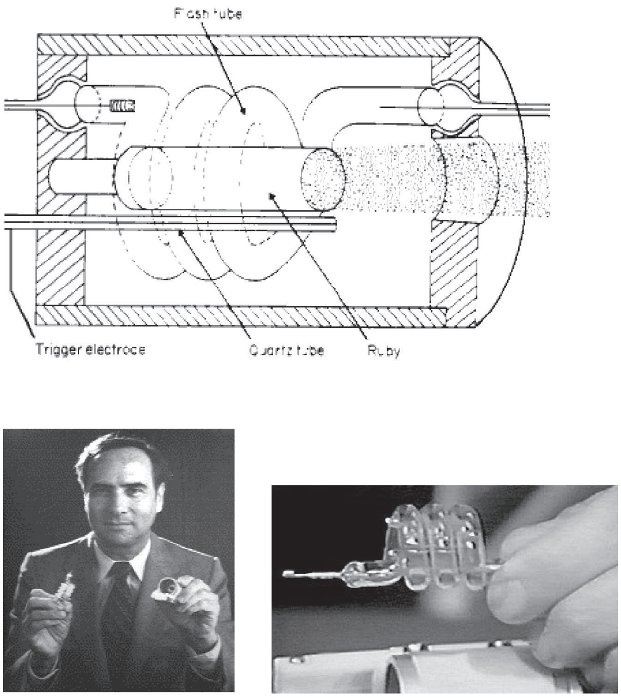


Figure 5: Rubi laser: Schematics (top), flash lamp (bottom right), and T. H. Maiman himself

Lasers and masers have intrinsic properties, which can not be explained with semi-classical theories.

E)

Demonstration of photon anti-bunching (Kimble 1977). This effect is purely quantum in nature and any classical explanation fails. It was considered as the first "direct" proof of the quantum nature of light.

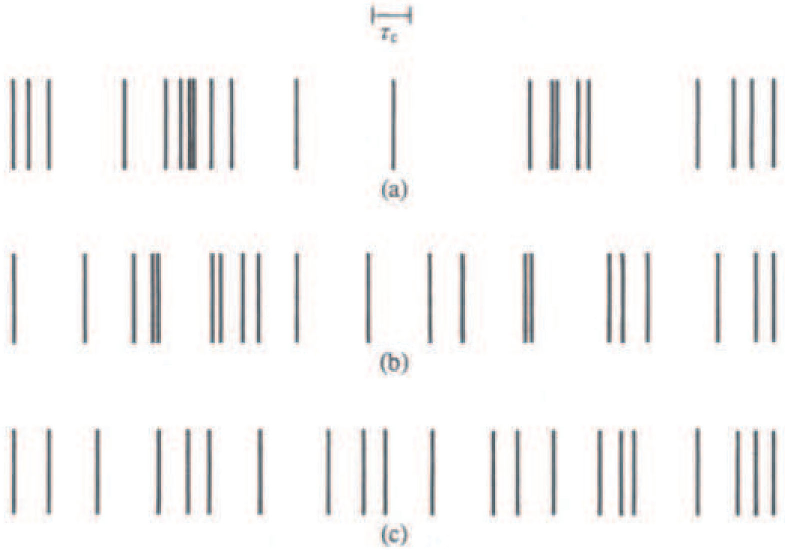


Figure 6: Schematics of bunched (top), coherent (middle) and anti-bunched (bottom) light. [from Loudon "Quantum Theory of Light"]

F)

Modern quantum optics is nowadays still driven by fundamental physics, but has already many applications. A few topics which will be discussed in this lecture are:

- Noise suppression beyond the classical limit (squeezing, Slusher 1985 at AT&T Bell labs)
- Photon correlation and Einstein-Podolski-Rosen (EPR) pairs (Non-locality of quantum mechanic)
- Single photonics
- Laser Trapping and cooling
- Optical quantum information processing.

G)

Recently there were two Nobel prizes awarded realted to achievements in quantum optics.
One was awraded to Glauber, Hall and Hänsch due to their achievements in the quantum theory of light and in precision measurements, respectively.

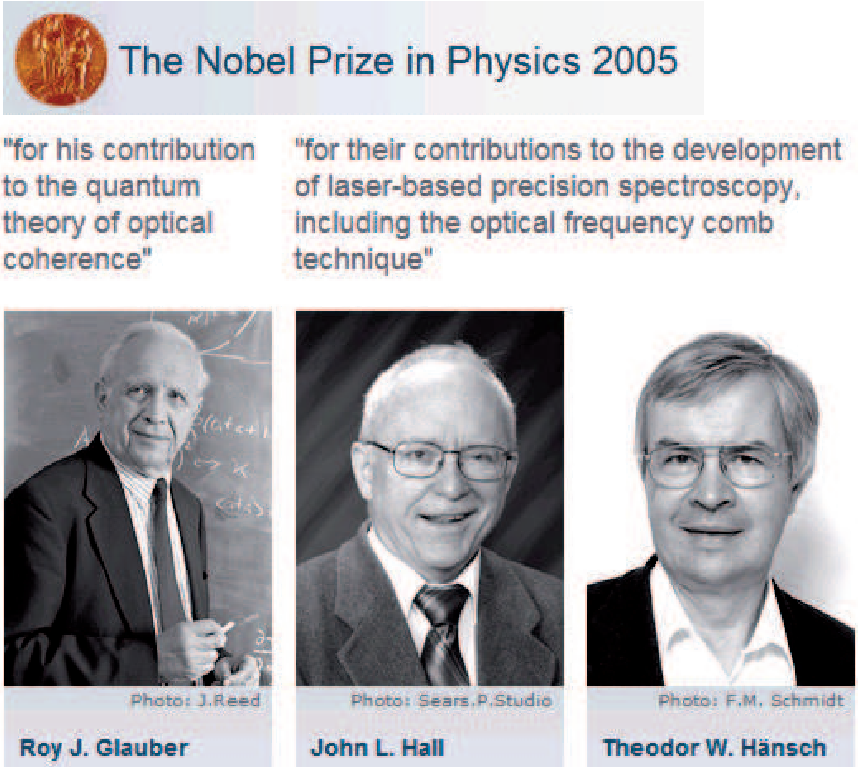


Figure 7: Nobel prize 2005

The other one was awarded in 2001 to Cornell, Ketterle, and Wieman for the realization of Bose-Einstein-Condensation (BEC).

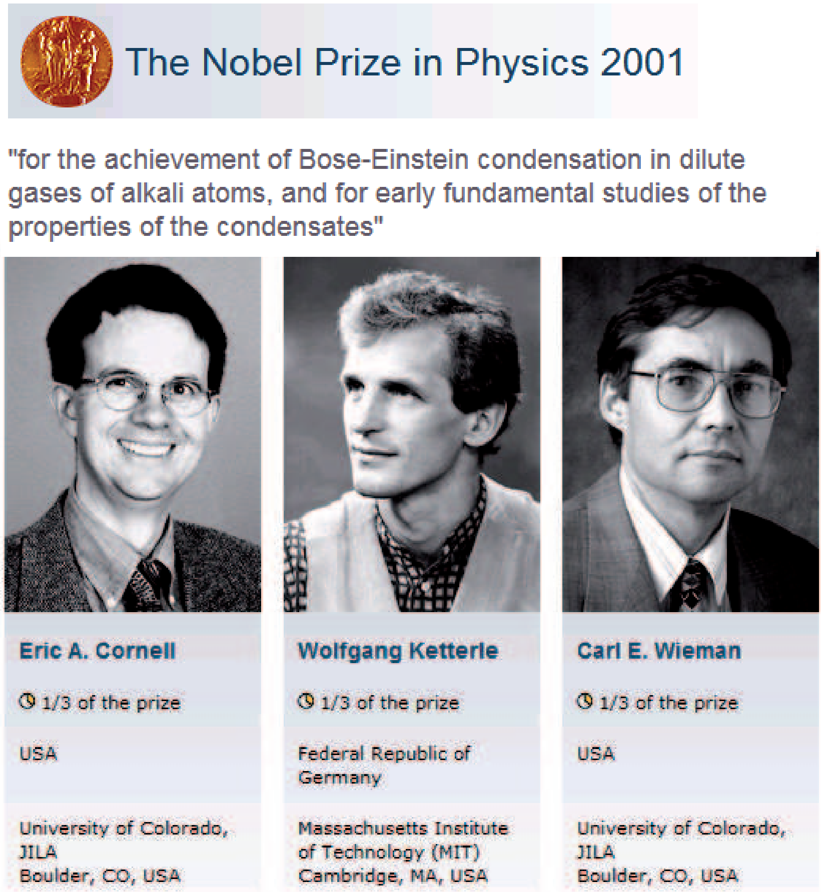


Figure 8: Nobel prize 2001