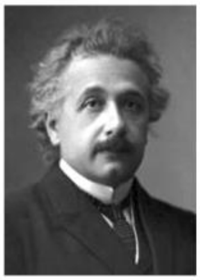
## Atoms and radiation: the Einstein picture



Albert Einstein
Nobel prize in Physics
1921
"especially for his discovery of the law of the photo-electric effect"

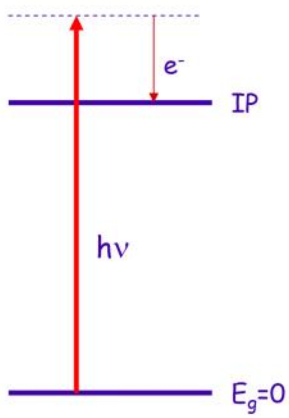
Max Planck
Nobel prize in Physics
1918
"for his discovery of energy quanta"

Charles Townes
Nobel prize in Physics
1954
"for the maser-laser principle"
The ammonia maser

Theodor Maiman

The inventor of the LASER

## The photo-electric effect in atoms




Electrons are released only if the ionization threshold is passed (independent of intensity)

Electron kinetic energy:

$$E(e^-) = \frac{1}{2}mv^2 = h\nu - E_{IP}$$

Note: in solids
IP = "work function"

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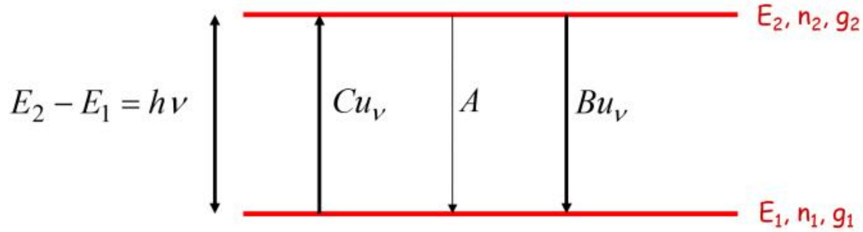
## Radiation in a two-level system

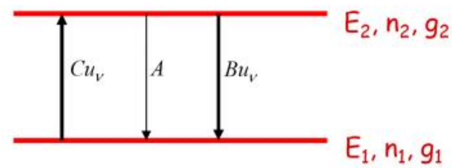



$u_\nu$ the incident radiation field (mode density)

| | |
|---|---|
| $Cu_\nu$ | 1. Absorption process |
| $A$ | 2. Emission process |
| $Bu_\nu$ | 3. Stimulated emission process |

A, B, C are the Einstein coefficients

## Rate equation model




Population of states:

$$\frac{dn_2}{dt} = Cu_\nu n_1 - An_2 - Bu_\nu n_2$$

Impose an equilibrium condition

$$\frac{dn_2}{dt} = 0$$

In steady state:

$$\frac{n_1}{n_2} = \frac{A + Bu_\nu}{Cu_\nu}$$

Statistical Physics: thermal excitation

$$n(T) = \exp(-E/kT)$$ x $n_0$

Relative population:

$$\frac{n_2}{n_1} = \frac{\exp(-E_2/kt)}{\exp(-E_1/kt)} = \exp\left[\frac{h\nu}{kT}\right]$$

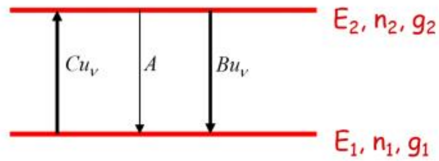
MINUS

Atomic two-level system in equilibrium with radiation field:

$$u_\nu = \frac{A}{C\exp[h\nu/kT] - B}$$

OK

Compare with Planck's model




Einstein scheme

A black body is in equilibrium with a radiation field:

$$u_\nu = \frac{8\pi h \nu^3}{c^3} \frac{1}{\exp[h\nu / kT] - 1}$$

Atomic two-level system in equilibrium with radiation field:

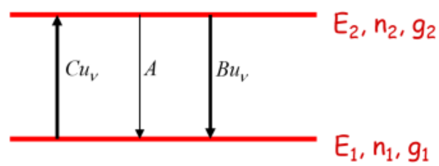
$$u_\nu = \frac{A}{C \exp[h\nu / kT] - B}$$

A two-level atom in equilibrium with a radiation field:

$$C = B$$

$$\frac{A}{B} = \frac{8\pi h \nu^3}{c^3}$$

Results from the Einstein model




A two-level atom in equilibrium
with a radiation field:

$$C = B$$

Stimulated emission is equally strong
as absorption

From a quantum treatment it follows

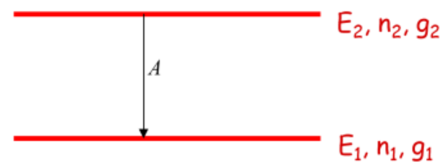
$$B = \frac{\pi e^2}{3\varepsilon_0 \hbar^2} \left| \mu_{ij} \right|^2$$

The B constant related to the
Transition dipole moment
(the QM radiation strength)

The A-constant follows from

$$\frac{A}{B} = \frac{8\pi h \nu^3}{c^3}$$

## Decay of an excited state




In the absence of a radiation field:

$$u_\nu = 0$$

Rate equation reduces:

$$\frac{dn_2}{dt} = -An_2$$

With a boundary condition;

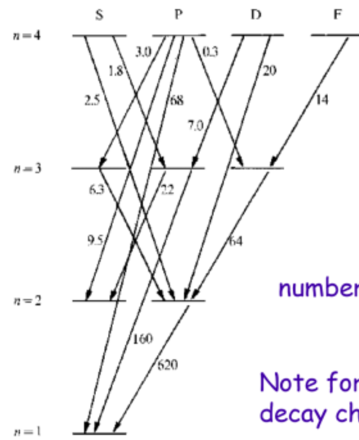
$$n_2(0) = N$$

Solution:

$$n_2(t) = Ne^{-At} = Ne^{-t/\tau}$$

Lifetime of an excited state

$$\tau = \frac{1}{A}$$




numbers in $10^6$ $s^{-1}$

Note for multiple decay channels

$$\tau = \frac{1}{\sum_i A_i}$$

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## Properties of a two-level system

Under all circumstances, i.e.
for arbitrary radiation fields $u_\nu$

$$Cu_\nu < A + Bu_\nu$$

Emission is stronger than absorption

So if we start at

$$n_1(0) = N$$

(all population in the ground state)

It is not possible to reach:

$$n_2 > n_1$$

↓

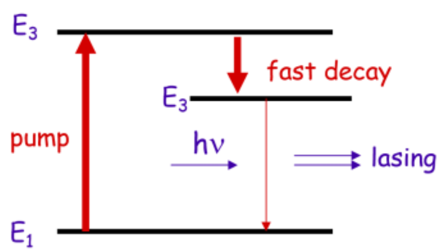
Optical pumping can never result in a population inversion

↓

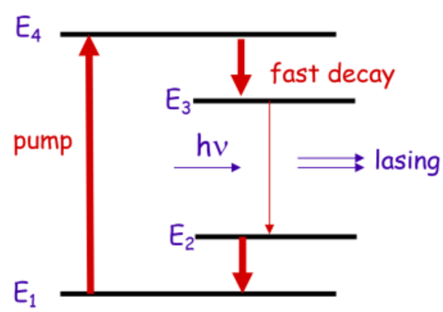
A two-level LASER is impossible

## Level schemes for lasers

Three-level LASER




Four-level LASER

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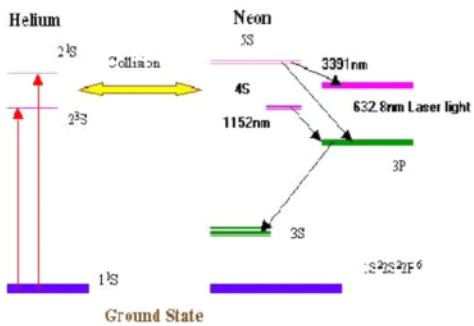
## The He-Ne Laser




## The $CO_2$ Laser