Laser Physics 11.

Laser basics, fundamental knowledge about laser operation

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Date	Topic	Lecture Seminar	Date	Topic	Lecture Seminar
24-Oct	Introduction Light-matter inetarction	L	26-Oct	Interaction of light with matter – line broadening	L-S
31-Oct (5-Nov)	Coherent optical amplifier (2)–saturation and noise	L	2_Nov	Coherent optical amplifier (1)– gain, bandwidth, phase	L-S
7-Nov	Fabry-Perot resonators, longitudinal modes	L	9-Nov	Passive optical resonators, stability, modes	S
14-Nov	Properties of Gaussian beams – physical optics	S	16-Nov	break	
21-Nov	Control test	S	23-Nov	Gain conditions, phase condition spectral bandwidth	L
28-Nov	Pulsed mode operation, Q-switching, mode-locking	L	30-Nov	Properties of laser beams – coherence, monochromaticity, brightness	L
5-Dec	Properties of laser beams - spatial coherence, divergence	L-S	7-Dec	Semiconductor lasers and amplifiers, homo and heterojunction, properties	L-S

LASER - acronym

Light **A**mplification by **S**timulated **E**mission of **R**adiation

Stimulated emission – concept: by A. Einstein, **1917**

A. E. deduced the energy density (energy per unit volume and frequency interval) for the emission of electromagnetic radiation of two-level atoms in thermal equilibrium as a function of the temperature (Planck’s law of black-body radiation):

$$\rho(\nu) = \frac{8\pi}{c^3}\nu^2 h\nu \frac{1}{e^{h\nu/kT}\boxed{-1}}$$

First laser - ruby laser in **1960**

What are the special properties of a laser?

Special properties:

Directed beam with small divergence
(1 mrad = 3.4 angular minute),
except for diode lasers (10-30º divergence)

Monochromatic or narrow spectral bandwidth light: 0.1 Hz for short time, 50-100 Hz long-time operation is feasible

Coherent beam: spatial and temporal coherence

Ultra short laser pulses: 10^{-15} s (fs)

Special properties:

Power range: $10^{-9} – 10^{20}$ W

Wavelength range: ($10^{11} – 10^{17}$ Hz)

Far-infrared: 10 – 1000 µm

Mid-infrared: 1 – 10 µm

Near-infrared: 0.7 – 1 µm

Visible: 0.4 – 0.7 µm or 400 – 700 nm (**$10^{14} – 10^{15}$ Hz**)

UV: 0.2 – 0.4 µm or 200 – 400 nm

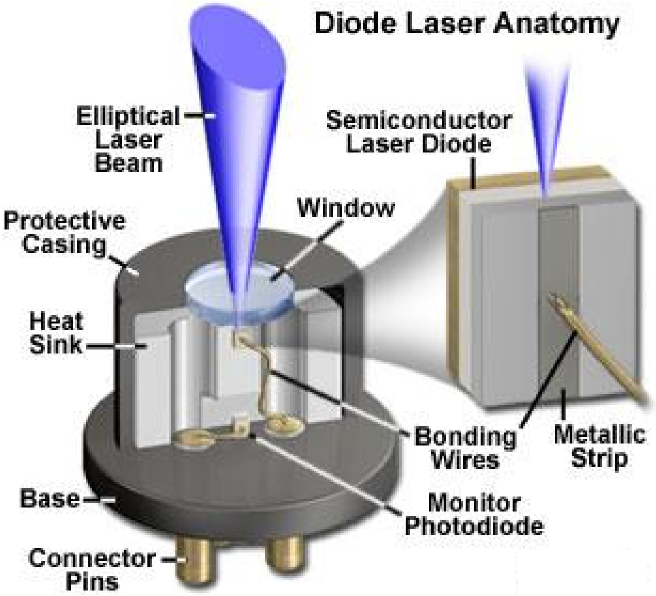
Vacuum UV: 0.1 – 0.2 µm or 100 – 200 nm

E(Extreme)UV: 10 – 100 nm

Soft x-ray: 1 – 20 (30) nm (overlap with EUV)

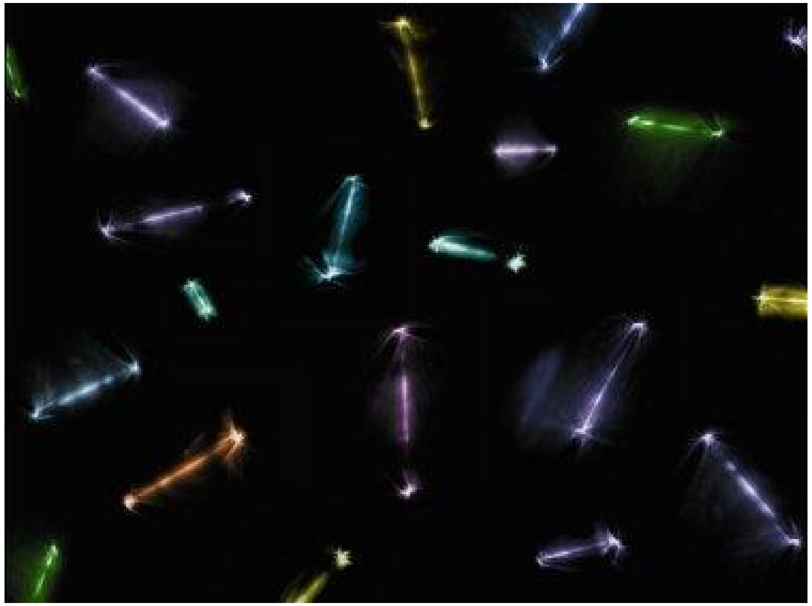
Special properties:

Dimension - small



Laser diode

0.4 µm x 2 µm x 400 µm



Multicolor nanowire lasers

Ø 200 - 400 nm, length 20 – 60 µm

Source: Optics & Laser Europe, August, 2008

Special properties:

Dimension - large

NIF, Lawrence Livermore National Laboratory, laser system with 192 beams: 500 TW, 7456 m laser

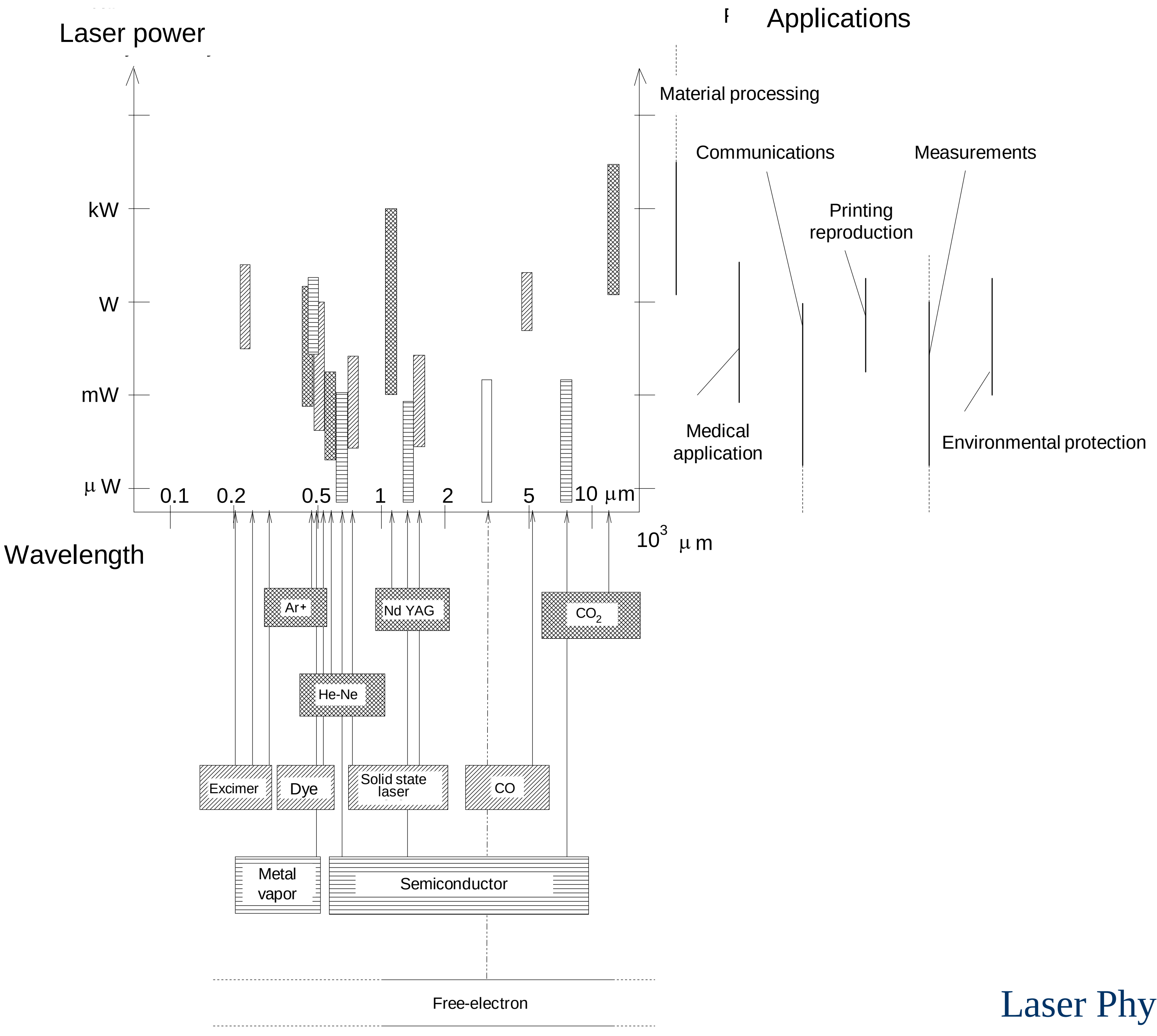
Milestones in the laser history

Date	Event	Person/institute
1917	**Concept of the stimulated emission**	**Albert Einstein**
1951	MASER (Nobel prize in 1964)	Townes, Prohorov, Basov
1960	laser patent 2.929.922	Shawlow and Townes
	first laser – ruby, solid state laser	Th. Maiman, Hughes Labs.
1961	first gas laser He-Ne (infrared, red in 1962)	Bell Laboratories
1962	Pulsed semiconductor laser (GaAs) at liquid N_2 temperature	General Electric
	Ophthalmological applications (rubin and He-Ne)	
1963	first CO_2 laser	K. N. Patel, Bell Labs.
1964	first Nd-YAG laser	Bell Laboratories
	first Ar-ion laser	Hughes Laboratories
	first surgical experiments on animals	
	distance measurement with a laser interferometer	
1965	first chemical laser	California Berkeley Univ.
	first surgical CO_2 laser	
	proposal - fiber optic communications (Nobel prize 2009)	**Charles Kao**
1966	first dye laser	IBM Laboratories
1968	Ar-ion laser application in ophthalmology and urology	
1969	First three lasers for material processing in the car industry	General Motors
	rubin laser distance meter (measurement of the Earth – Moon distance using the mirror installed by the Apollo 11 astronauts on the Moon)	US army
	concept of integrated optics	Stewart Miller

Milestones in the laser history

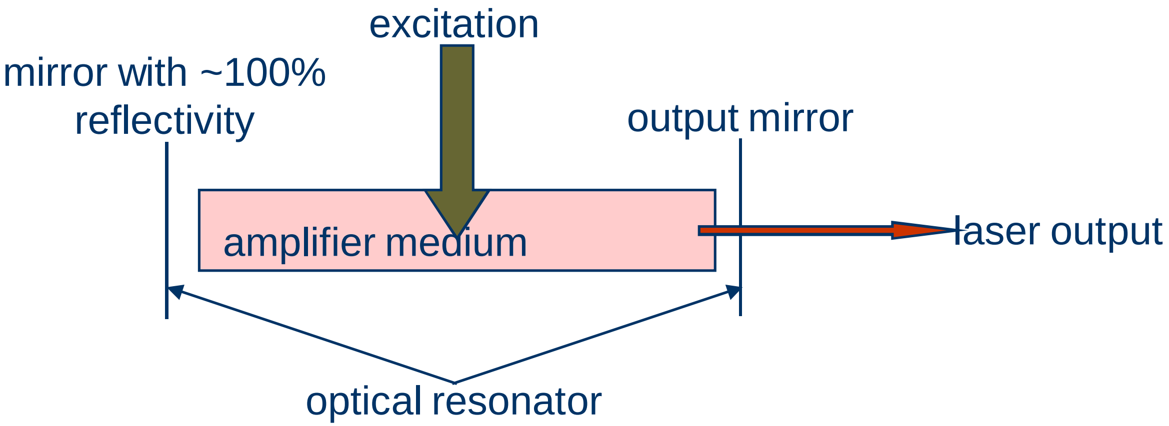
1970	first continuous wave (cw) GaAlAs semiconductor laser (T_{room})	
	20 dB/km	Corning
1971	first N_2 laser	
	Nobel-prize for the development of holography (principle was published in 1948)	Gábor, Dénes
1972	laser target designator: military use in Vietnam	US army
	fiber with 4 dB/km loss	Corning
1973	Argon and Nd-YAG laser coupled to fiber optic endoscope	Nath, Gorish, Kiefbacher
1975	commercial cw semiconductor laser (laser diode - LD)	
	first medical laser symposium	
1984	first laboratory x-ray laser	Lawrence Livermore Lab.
1987	LD-pumped Nd:YAG laser	
	Er-doped fiber amplifier	
	dye laser with 6 fs pulse length	
1992	20 Gbit/s transmission speed for 100 km	
1995-	Green, blue light emitting diode (LED)	
	laser pulse with petawatt (10^{12}W) power	
	23 W fiber laser	
	5 fs Ti-Sapphire laser pulse	
1999	LD of 400 nm	Nichia

Types of lasers



What are needed for a laser?

1. Amplifier medium (gas, liquid, solid state) in which, due to excitation (by light, electric discharge or current, chemical reaction, …) light amplification by stimulated emission is possible
2. Feedback system – optical resonator



Selection of the laser material

Particle with known energy structure (atom, molecule, doping ion in a solid)

Selection of levels E_1 and E_2, in between light emission and absorption are possible

$$\boxed{E_2 - E_1 = h\nu_0,}$$

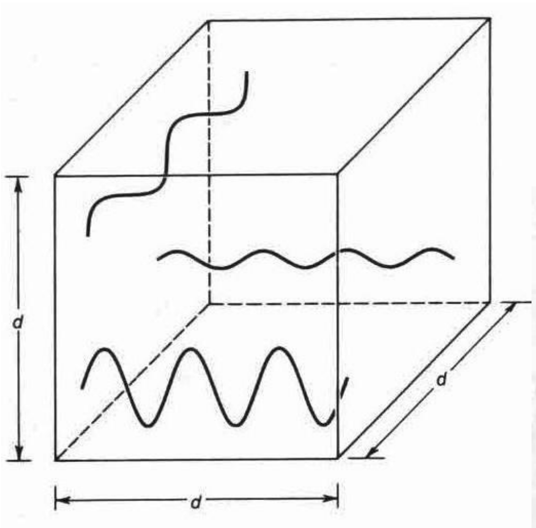
ν_0 is the resonance frequency. E_2 is an excited state, however both E_1 and E_2 can be excited states. In practice, photon emission or absorption is possible in a range of frequencies around $\nu \approx \nu_0$.

3 kinds of interaction:
spontaneous emission,
absorption
stimulated emission

Laser material in a 3D optical resonator

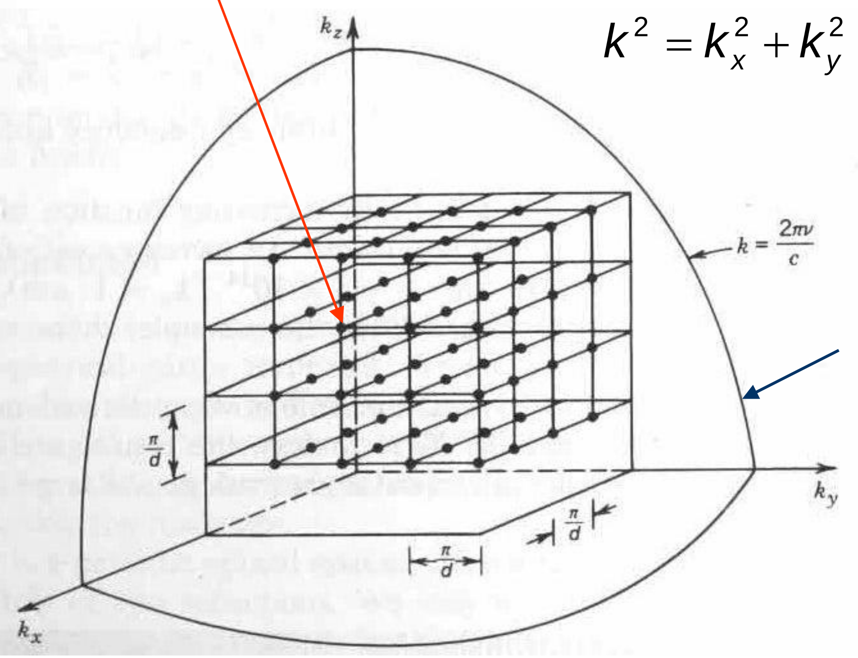
We place the selected laser material into an optical resonator of volume *V*, where $V = d^3$ (*d*: edge of cube with reflecting surfaces). Standing wave solutions: **k** = (k_x, k_y, k_z) discrete values.

$$k_x = \frac{q_x \pi}{d}, \quad k_y = \frac{q_y \pi}{d}, \quad k_z = \frac{q_z \pi}{d}, \quad q_x, q_y, q_z = 1, 2, \ldots$$



Possible frequencies :

$$k^2 = k_x^2 + k_y^2 + k_z^2 = \left(\frac{2\pi\nu}{c}\right)^2$$



Surface of constant frequency

Laser material in a 3D optical resonator

Number of modes in the 0 – ν frequency range; density of modes?

The number of modes with continuum approximation (volume of 1/8 sphere / volume of the cell):

$$2\left(\frac{1}{8}\right)\frac{4\pi k^3/3}{(\pi/d)^3} = \left(\frac{k^3}{3\pi^2}\right)d^3, \quad k = \frac{2\pi\nu}{c}$$

due to polarization

$$\frac{8\pi^3\nu^3}{3c^3\pi^2}d^3 = \frac{8\pi\nu^3}{3c^3}d^3$$

Density of modes (the number of modes in unit volume and frequency interval):

$$\boxed{M(\nu) = \frac{8\pi\nu^2}{c^3}}$$

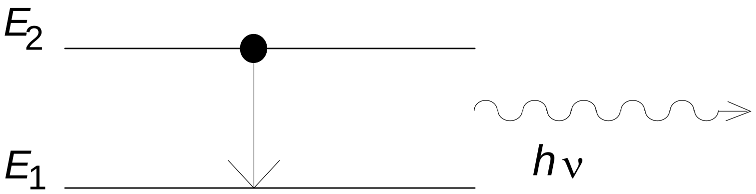
Light-matter interactions

Laser material in an optical resonator of volume V.
$\nu \approx \nu_0$ is the selected mode of the resonator.

We are interested in the possible interactions of the particle with the resonator mode of frequency ν.

Spontaneous emission

The energy of the particle is initially E_2 (upper level). It may decay spontaneously to the lower energy level.



The probability density (per second) or rate - p_{sp} – is a function of the frequency ν.

$$\boxed{p_{sp} = \frac{c}{V}\sigma(\nu) \quad [\mathrm{s}^{-1}],}$$

$\sigma(\nu)$, the transition cross section (with surface dimension) peaks around ν_0, c is the velocity of light in the medium.

Light-matter interactions

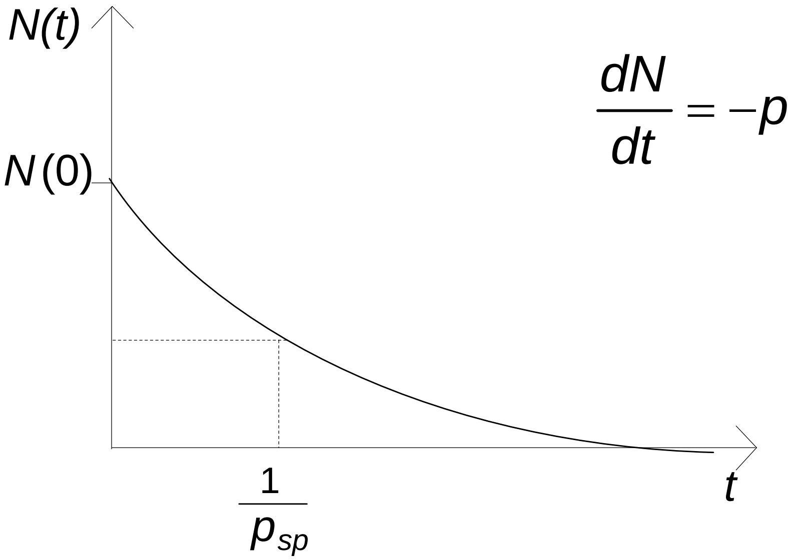
Spontaneous emission (cont.)

$p_{sp}\Delta t$ is the probability, that an emission of photon of frequency ν takes place in the time interval of $[t, t + \Delta t]$. $p_{sp}\Delta t < 1$.

If N is the density of particles in the upper level E_2, then in unit volume ΔN atoms will undergo the transition within Δt:

$$\Delta N = (p_{sp}\Delta t)N$$

The rate of change of atoms per unit volume on level E_2:

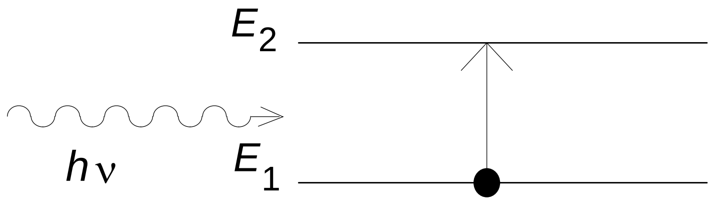


$$\frac{dN}{dt} = -p_{sp}N, \quad N(t) = N(0)e^{-p_{sp}t}.$$

Light-matter interactions

Absorption

If the particle is initially on the lower level E_1, a photon may be absorbed raising the particle to the upper level, E_2. Absorption is a transition induced by the photon.



Effect: the number of photons in frequency mode ν decreases in volume V!

Probability density for the absorption of one photon from the frequency mode ν when one photon is in the mode: when n photons are in the mode:

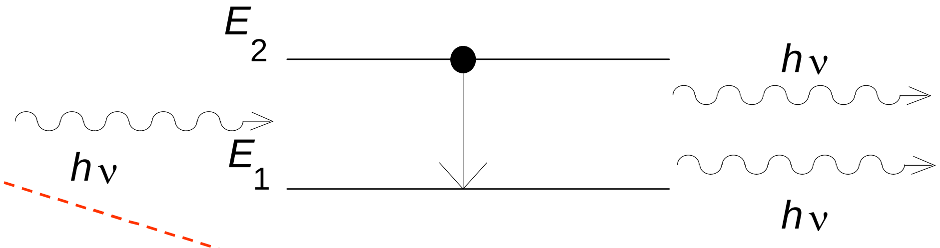
$$\boxed{p_{ab} = \frac{c}{V}\sigma(\nu), \qquad P_{ab} = n\frac{c}{V}\sigma(\nu).}$$

Light-matter interactions

Stimulated emission

A particle in level E_2 is stimulated by a photon of frequency ν to emit another photon into the same mode.

Effect: the number of photons of frequency ν increases with one in V!



The clone photon has the same energy, direction and preserves polarization and phase of the mode!!

Probability density for one or n photons:

$$p_{ie} = \frac{c}{V}\sigma(\nu), \qquad P_{ie} = n\frac{c}{V}\sigma(\nu).$$

$$P_{ie} = P_{ab} = W_i$$

Spontaneous and stimulated emission together:

$$p_{sp} + P_{ie} = (n+1)\frac{c}{V}\sigma(\nu).$$

Light-matter interactions

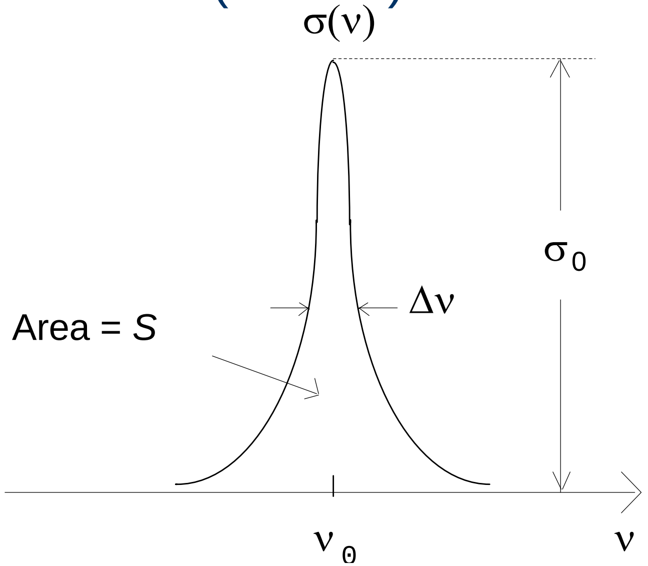
The lineshape function

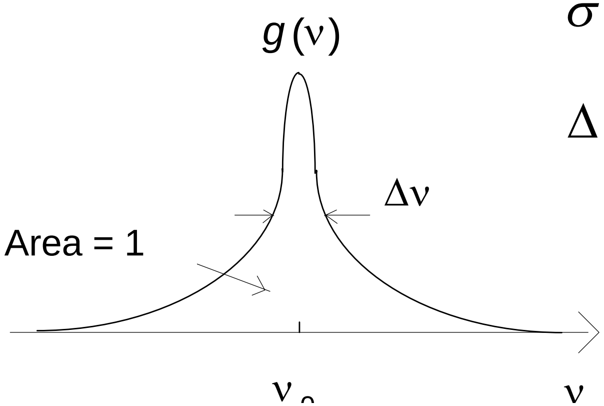
The transition cross section $\sigma(\nu)$ specifies the character of the interactions. Its area represents the strength of the interaction, its shape characterizes the relative frequency dependence of the interaction:

$$\boxed{S = \int_0^\infty \sigma(\nu) d\nu \quad [\mathrm{cm^2 s^{-1}}],}$$

$$\boxed{g(\nu) = \frac{\sigma(\nu)}{S}.}$$

$g(\nu)$ is the normalized lineshape function. $\Delta\nu$ is the full width of $g(\nu)$ at half maximum (FWHM).





$$\sigma(\nu) = S \cdot g(\nu)$$

$$\sigma(\nu_0) = \sigma_0$$

$$\Delta\nu \propto \frac{1}{g(\nu_0)}$$

Light-matter interactions

Total spontaneous emission into all modes

Spontaneous emission is possible in *V* into all modes with frequency within the spectral width of $\sigma(\nu)$:

$$P_{sp} = \int_0^\infty \underbrace{\left[\frac{c}{V}\sigma(\nu)\right]}_{p_{sp}} \underbrace{[M(\nu)\cdot V]}_{\text{density of modes}} d\nu = c\int_o^\infty \sigma(\nu)M(\nu)d\nu.$$

$\sigma(\nu)$ is narrow in comparison with $M(\nu)$: $P_{sp} = M(\nu_o)cS = \frac{8\pi\nu_o^2}{c^2}S = \frac{8\pi}{\lambda^2}S. \quad \left[s^{-1}\right]$

We define a time constant t_{sp}, known as spontaneous lifetime by:

$\boxed{P_{sp} = \frac{1}{t_{sp}}}$ and $\boxed{S = \frac{\lambda^2}{8\pi t_{sp}}.}$

typical value of t_{sp} is 10^{-8} s, but it can range from 10^{-13} to 100 s.

$$\sigma(\nu) = Sg(\nu) = \frac{\lambda^2}{8\pi t_{sp}}g(\nu)$$

λ is the wavelength in the material.

Light-matter interactions

Transitions in the presence of broadband light

The spectral energy density in V is $\rho\,(\nu)$ (energy per unit bandwidth per unit volume) is broad as compared to the width of the particle's lineshape function.

The number of photons in the $[\nu, \nu + d\nu]$ frequency range $\dfrac{\rho(\nu)V d\nu}{h\nu}$.

$$W_i = \int_0^{\infty} \frac{\rho(\nu)V}{h\nu}\frac{c}{V}\sigma(\nu)d\nu \approx \frac{\rho(\nu_0)}{h\nu_0}c\underbrace{\int_0^{\infty}\sigma(\nu)d\nu}_{S} = \frac{\rho(\nu_0)}{h\nu_0}cS,$$

We assume that $\rho\,(\nu)$ varies slowly in comparison with the sharply peaked $\sigma(\nu)$ function.

$$W_i = \frac{\lambda^3}{8\pi h t_{sp}}\rho(\nu_0)$$

Light-matter interactions

Einstein’s *A* and *B* coefficients

Based on the analysis of the exchange of energy between atoms and radiation field in thermal equilibrium, Einstein postulated expressions for the probability densities for spontaneous-emission and stimulated transitions:

$$P_{sp} = A$$

$$W_i = B\,\rho(\nu)$$

A and *B* are known as Einstein’s *A* and *B* coefficients. By comparing the above with our expressions:

$$A = \frac{1}{t_{sp}}, \quad B = \frac{\lambda^3}{8\pi h t_{sp}}$$

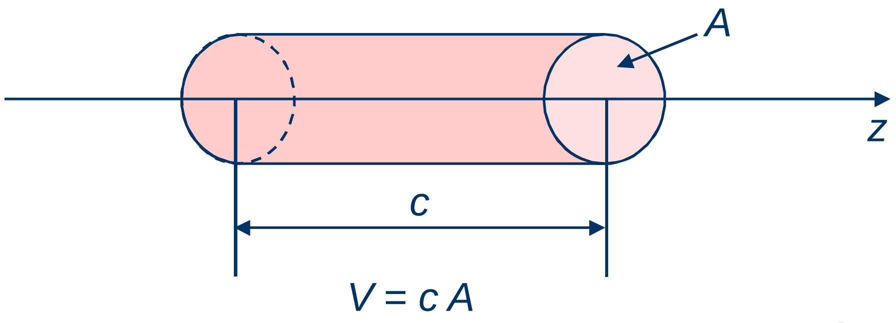
$$\frac{A}{B} = \frac{8\pi h}{\lambda^3}.$$

Light-matter interactions

Transitions induced by monochromatic light

Interaction of a monochromatic photon beam of frequency ν with a particle of resonance frequency ν_0 (laser type interaction). The photon beam has an intensity I and travels into the z direction. The photon-flux density (photons / cm^2 ·s) is:

$$\Phi = \frac{I}{h\nu}. \qquad W_i = P_{ab} = P_{ie}\left(= n\frac{c}{V}\sigma(\nu)\right) = ?, \quad n = ?$$



ΦA photons go through the area A in unit time. As the length of the cylinder is equal to c (velocity of light), all photons will leave the cylinder through its base:

$$n = \Phi A = \Phi\frac{V}{c}, \qquad \boxed{W_i = \Phi\sigma(\nu).}$$