3.1. Laser basics --The material is taken from BJ, Chap. 15

Preliminary: Einstein A and B coefficients

Consider a two –level system in a radiation field

medium ________________ |2>

________________ |1> $\hbar\omega = E_2 - E_1$

The number of transitions per unit time from |2> to |1> and from |1> to |2> are given by

$$\frac{dN_2}{dt} = B_{21}\rho(\omega)N_1 = W_{21}\,N_1$$

$$\frac{dN_1}{dt} = B_{12}\rho(\omega)N_2 + AN_2$$

Where W is the transition rate, A is the spontaneous emission rate, and the B terms give the absorption or stimulated emission. At thermal equilibrium the two equations above are equal, while $\rho(\omega)$ is given by the Planck distribution law. Since $I = c\rho$, we have $W = B\rho$. Recall that the absorption cross section σ is defined by

$$\sigma = \hbar\omega W_{12}/I,$$

i.e., the ratio of energy absorbed per atom per unit intensity. Einstein has shown that $B_{12} = B_{21}$ and that A is related to B, see BJ, Eq. (4.108b).

1. Masers and Lasers

Consider an EM wave of intensity I, frequency ω, passing thru a medium, let

$\frac{d\rho_a}{dt}$: change of average energy density due to absorption

$\frac{d\rho_s}{dt}$: change of average energy density due to stimulated emission

$$\frac{d\rho_a}{dt} = -N_1\,\hbar\omega\,W_{21}$$

$$\frac{d\rho_s}{dt} = N_2\,\hbar\omega\,W_{12} \qquad\qquad W_{12} = W_{21}$$

(N is large so spontaneous emission is neglected.) The rate of change of total photon energy in the medium is

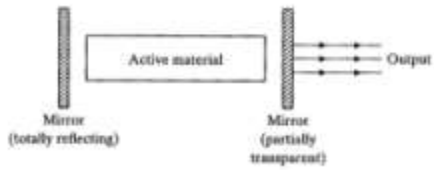
$$\frac{d\rho}{dt} = (N_2\text{-}N_1)\,W_{12}\,\hbar\omega = \sigma\,I\,(N_2\text{-}N_1)$$

If the beam has cross section A along the z-axis, then this equation becomes

$$\boxed{\frac{dI}{dz} = \sigma I(N_2 - N_1)}$$ the lasing condition

This shows that will intensity will grow exponentially with z when population inversion is achieved— such a medium is called an <u>active</u> medium.

Maser (1954): Townes et al.
Lasers (1958): Schawlow and Townes
Amplifiers used: (maser) → use resonant cavity
laser → active materials between two mirrors

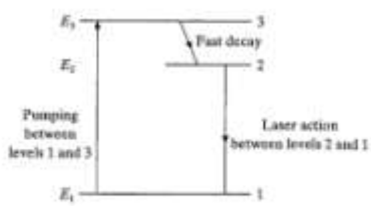


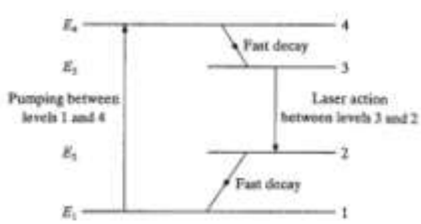
Laser properties:
monochromatic
directional
bright
spatial coherence → between two points P_1 and P_2 → coherent length → coherent area
temporal coherence → between τ at point P → coherence time

2. Methods of Achieving Population Inversion

(a) Amonia maser ⇒ select quantum states by inhomogenous electric field (Townes)
(b) Hydrogen maser ⇒ by magnetic field using inhomogeneous magnetic field (Ramsey)

3. Lasers—of different kinds (mostly 3-level or 4-level systems)





(a) The **ruby laser** (A 3-level system) Red~ **6943°A**
1960 Maiman Al_2O_3 Al^{3+} ions replaced by Cr^{3+}
(b) **YAG lasers** (4-level system) Yb^{3+} replaced by Nd^{3+} $YbAl_5O_{12}$ ← host
Nd:YAG pump 730 nm and 800nm

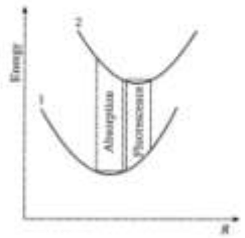
transition $\lambda = 1064\text{nm}$

(c) **Nd:glass**

Replace Yb by phosophate or silicate glasses

$\lambda \sim 1054\text{nm}$ (NOVA)

(d) Ti:sapphire (doping Ti_2O_3 into Al_2O_3)



(e) Dye lasers

→ gives tunable sources of laser radiation

(f) Semiconductor lasers

Normally use hole-electron recombination II-IV or III-V materials normally weaker power.

(g) Gas lasers (discharge to pump)

Ne-laser

5S → 3p (red, 6330°A) – scanning, low power

4S → 3P

5S → 4p

Ar laser (Ar^+ is the medium) <u>visible</u> region

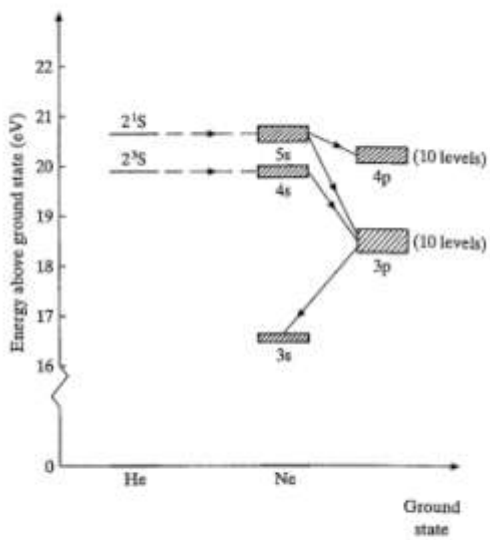
Kr $e^- + Ar \rightarrow Ar^+$

$e^- + Ar^+(3p^{-1}) \rightarrow Ar^+ (3p^4 4s)$ – short

4p → 4s transition

4p – long lifetime

$He^* + Ne \rightarrow He + Ne^*$



used as a pump for solid state lasers

(h) **CO_2 lasers**

-- transitions involving vibrational levels of CO_2

pumped $e^- + N_2 \rightarrow N_2^* + e^-$ $N_2^* + CO \rightarrow CO^*$

$\lambda = 10.6 \mu m$

very powerful, reaches 100kW

(i) excimer lasers (UV regime)

KrF	at 249 nm	very powerful, not narrow
XeCl	308nm	
ArF	193nm	

(j) Free-electron lasers - to reach intense short-wavelength light sources

Relativistic e^- beam in undulators emitted light
scattering by e^- beam : ranges from infrared to new push toward x-rays

Flash (since 2005) : wavelength : from 44 nm to 4.1 nm
Single pulse energy: 10-100 µJ
Pulse duration : 10-70 fs

LCLS(since 2010) : photon energy: 0.5 to 10 keV
Pulse energy: 3 mJ at 8.3 keV and 0.83 keV (10^{12} photons/pulse)
Pulse duration: tens of fs, but hard to know, chaotic

Water window: Between **2.3nm and 4.4 nm**. Water is transparent in this region. Possible to investigate samples in aqueous solution. For biological samples, carbon atoms are higher opaque but the surrounding water is transparent.

(k) **High-intensity lasers/short pulses**

oscillator →trains of pulses of short duration

amplifer

CPA → (1985) Mourou and Strickland

stretch in time by grating $\Rightarrow$

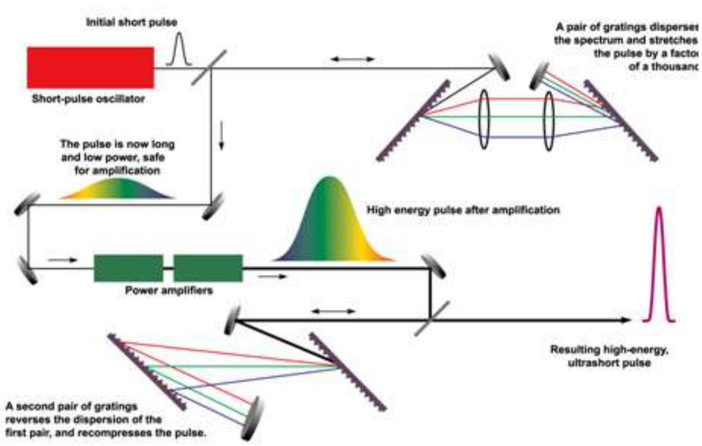
1990's Nd:YAG $\lambda = 1064\text{nm}$,   ps $\Rightarrow 10^{12}$W $\Rightarrow 10^{18}$ W/cm^2

repetition rate 1/shot/min.

Ti: Sapphire--

stretch-- amplify-compres

http://en.wikipedia.org/wiki/Chirped_pulse_amplification



4. High-resolution spectroscopy

4.1. Doppler broadening

ω: lab frame, ω': moving frame

$\omega' = \omega - kv = \omega(1 - v/c)$ $k = \omega/c = 2\pi/\lambda$

$$\Rightarrow \omega' = \omega - kv \xrightarrow[v]{} \quad \Leftarrow \omega'' = \omega + kv$$

Let ω_o be the rest frame frequency of the atom, $\omega' = \omega_o$,

Atoms moving with v absorbs ω when $\omega = \omega_o + \delta = \omega_o + kv$ or $\dfrac{\delta}{\omega_o} = \dfrac{v}{c}$.

Atoms at temperature T follows Maxwell distribution

$$f(v)dv = \sqrt{\frac{M}{\pi 2k_B T}}\ e^{-\frac{Mv^2}{2k_B T}}\ dv = \frac{1}{u\sqrt{\pi}}\ e^{-v^2/u^2}\,dv$$

where $u = \sqrt{2k_B T / M}$ is the most probable speed at T

The absorption has the shape

$$\boxed{g_D(\omega) = \frac{c}{u\omega_o\sqrt{\pi}}\, e^{-\frac{v^2}{u^2}(\omega-\omega_o)^2}} \leftarrow \text{normalized.}$$

The FWHM $$\frac{\Delta\omega_D}{\omega_o} = 2\sqrt{2\ell n 2}\,\frac{u}{c} \simeq 1.7\frac{u}{c}$$

Example: T = 300°K

H	$\Delta\omega_D / \omega_o = 10^{-5}$
Cs	10^{-6}

Thus *Doppler broadening limits resolution to* <u>*10^{-5} or 10^{-6}.*</u>

4.2. Beating Doppler broadening: The Cross Beam Method

use supersonic jets small vertical velocity $\Rightarrow$ lower T
needs high-intensity and narrow-freq. bandwidth of laser light.

4.3 Saturation absorption spectroscopy (see BJ p. 843). First used in 1971

b

a_{ba} $\updownarrow$

a

(1) Use a high intensity laser to saturate the transition a$\leftrightarrow$b so half of the atoms at each level.

(2) For atoms with velocity v, the ω is shifted to $\omega(1 - v/c)$

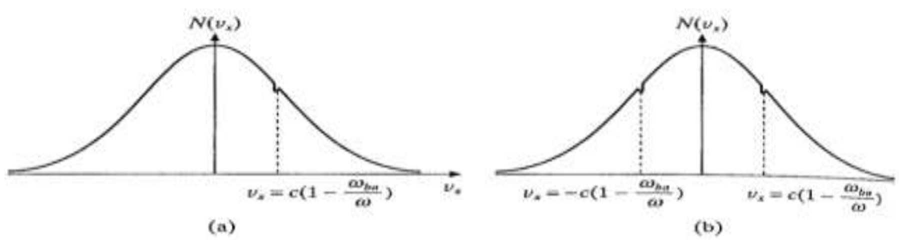
Transition can occur only if

$\omega(1 - v/c) < \Gamma_b / \hbar$ Γ_b : natural width

In the intense laser, atoms with velocity in the range above will be depleted to level b. This causes a depletion in the thermal velocity distribution

$$\Delta v = \frac{c\Gamma_b}{\hbar\omega}$$

When a probe beam is used to scan the resonance, the hole will be observed.



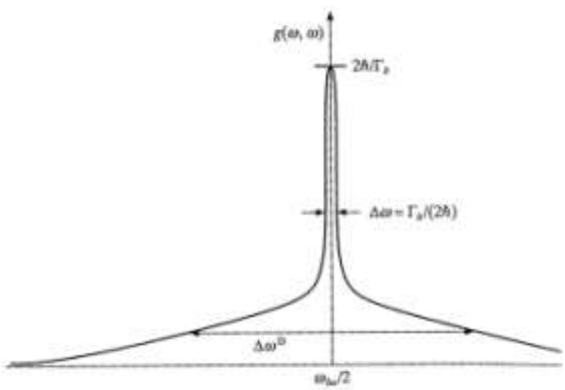
4.4. Doppler-free two-photon transitions(two counter propagating beams)

________(b)
________(a)

If the atom absorbs one photon from each beam, then the Doppler Shift cancels out

$$\omega(1+v/c)+\omega(1-v/c)=2\omega=\omega_{ba}$$
$$\omega=\frac{1}{2}\omega_{ba}$$

Typical two-photon absorption profile from two counter-propagating lasers. The *width of the center peak measures the natural width.*



Note: All atoms participate in the Doppler-free two-photon absorption. For saturation spectroscopy, only the atoms with specific velocity are absorbing the photons $\Rightarrow$ measures $\Gamma_b/2\hbar$, i.e., half of the natural width.

4.5. Two-photon spectroscopy of $1s\rightarrow 2s$ transition in atomic hydrogen

$\Gamma_b(2s)=1\,\text{Hz}$ lifetime= $\frac{1}{8}$ sec wavelength=1216°A

Need UV radiation λ ~243 nm (by frequency doubling)

source of errors:

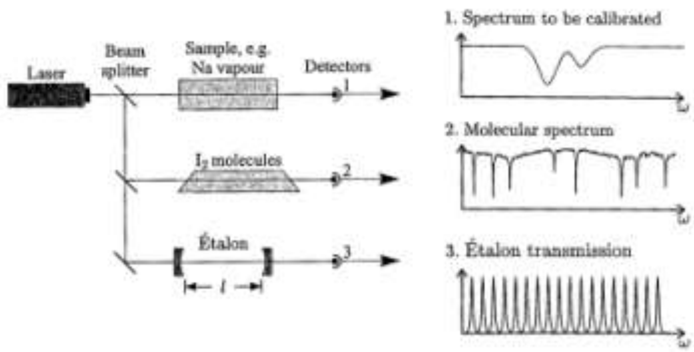
- transition time
- collision broadening
- laser bandwitdth (10ns $\Rightarrow$ 100 MHz)
- second order Doppler effect
- A.C. Stark shift

Lots of experiments continuing to achieve ever higher precision. Also works in He^+ ions.

5. Calibration in laser spectroscopy--how to know the wavelength precisely

Use the frequency of Cs as standard and define the speed of light to define the length.

(1) Calibration of relative frequency.



(2) Absolute calibration

often takes many steps - the old ways

⇒ needs to go to the Cs frequency standard and use chains of lasers to go from microwave to optical

➔ Frequency comb—new way—revolutionalize high-precision spectroscopy, atomic clocks, in combination with cold atoms.

See: Condiff and Jun Ye, RMP 75, 325 (2003)

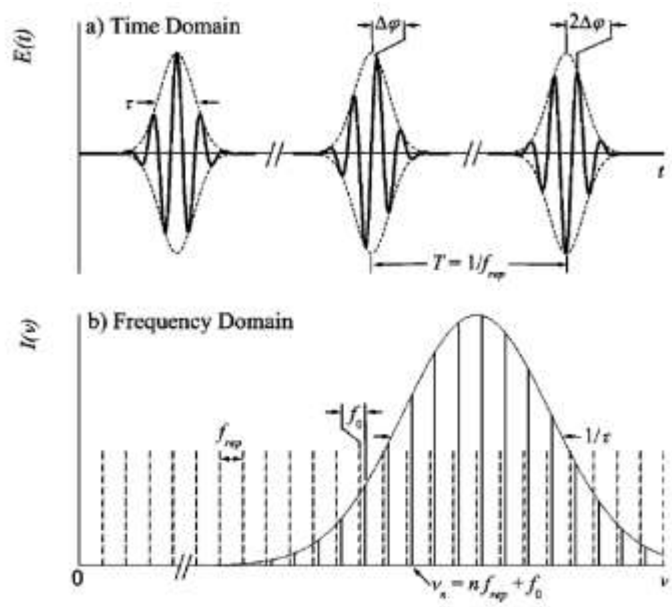


FIG. 5. Summary of the time-frequency correspondence for a pulse train with evolving phase.

The optical frequencies can be expressed as

$$f_n = n f_{rep} + f_0$$

For a broad-band spectra, one can use the second harmonic to beat against the pulse itself, the difference frequency gives

$$2f_n - f_{2n} = 2(nf_{rep} + f_0) - (2nf_{rep} + f_0) = f_0$$

This allows the determination of the frequency offset f_o.