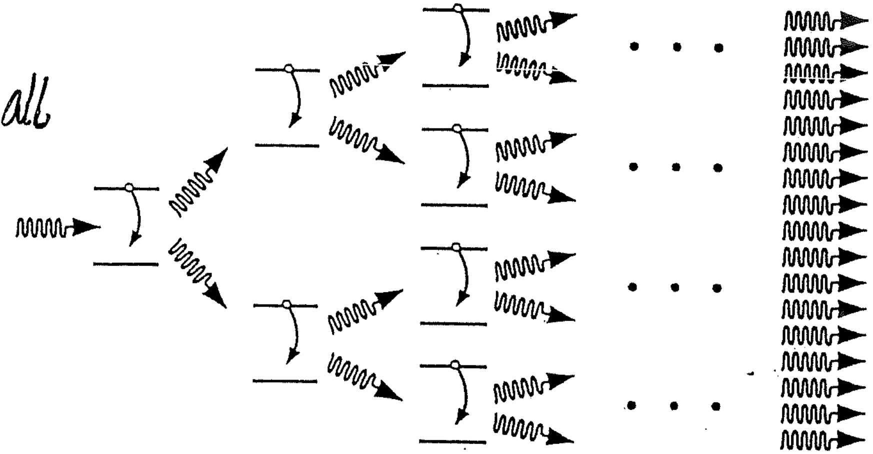
I. LASER: Light Amplification by the Stimulated Emission of Radiation

- Need Stimulated Emission (in principal) & Metastable State(s) (in Practice)

1 photon + Excited Atoms → 2 photons → 4 photons → 8 photons → . . .

Collection of atoms all in the same excited state



Buildup of intense beam in a laser. Each emitted photon interacts with an excited atom and produces two photons.

[Taken from Krane, "Modern Physics"]

Treating Light Quantum Mechanically,

- these photons are all in phase$^+$ ("coherent") and moving in same direction$^+$
- intense beam

$^+$ We don't quantize EM fields in our course. Thus it is beyond our scope. A simple idea is to think in terms of harmonic oscillator. "n-photon state" is one quantum state ψ_n.

Difficulties

- $\lambda_{2\to1} = \lambda_{1\to2}$ (OR $B_{12} = B_{21}$)

  ⇒ Photons may be absorbed to excite atoms (not only to stimulate emission)

- To have amplification, need $\underset{\#\text{ atoms in excited state } E_2}{N_2} > \underset{\#\text{ atoms in excited state } E_1}{N_1}$

$N_2 > N_1$ is called Population Inversion

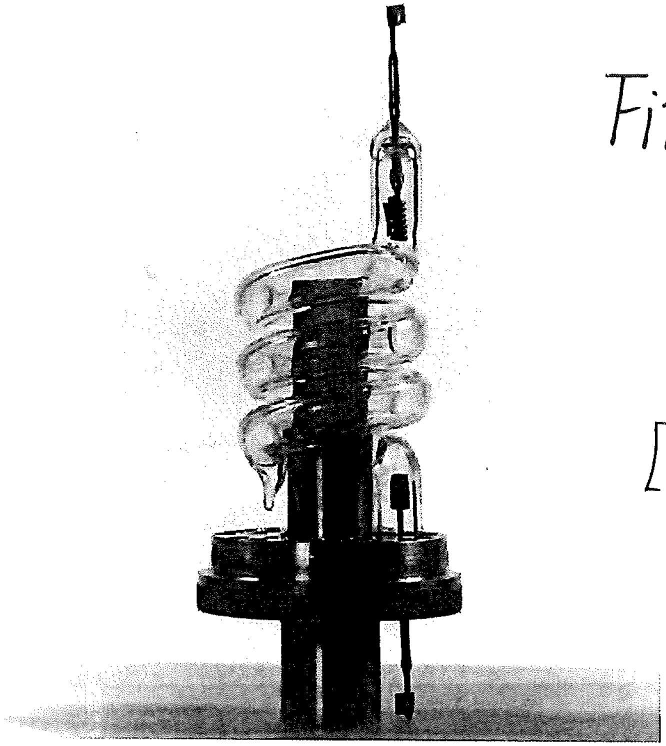
Out of Equilibrium

Achieve it by artifical methods

- Recall: Higher state tends to have shorter life time

To keep atoms excited until "stimulation", need "2" to be metastable

(a) Pulsed Laser [typically 3-level operation (3-level system)]



First Laser (1960) [red]
Ruby laser

[From Taylor et al. "Modern Physics"]

The original laser, built by Maiman at the Hughes Research Lab. The ruby rod, about 1 cm in diameter, can be seen inside the coiled flash lamp.

Charles H. Townes
1954 invented
Maser
Microwave ($\lambda = 1.25\,\mathrm{cm}$)
easier than light
[$\because A \sim \omega_{21}^3$]
[1964 Nobel Prize]

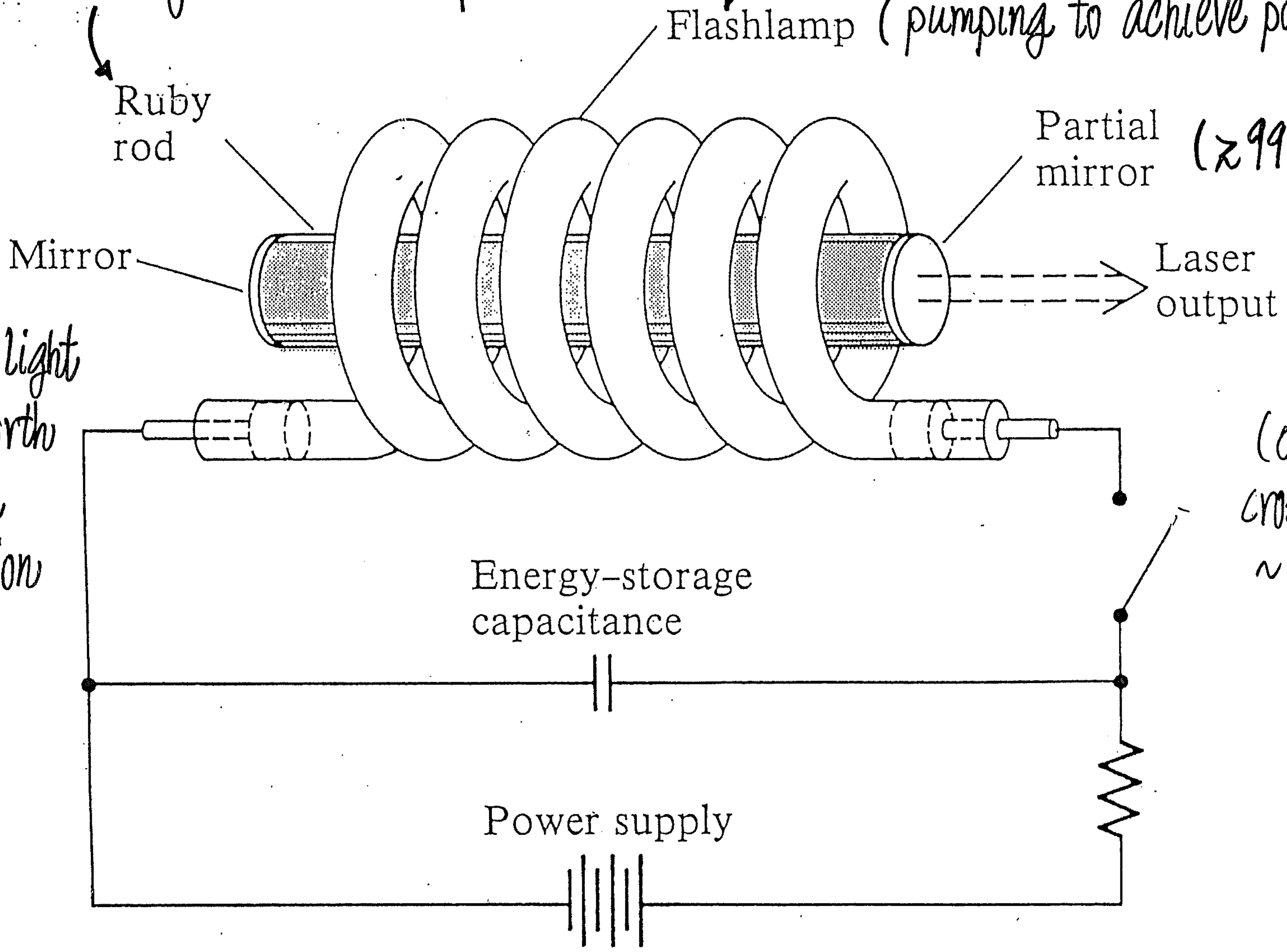
Ruby: Al_2O_3 with Cr (chromium) as impurities [~0.1%]

Lasing effect: using levels in Cr ions

Ruby Laser

lasing: due to Cr impurities

intense flash to pump system [optical pumping]



(pumping to achieve population inversion)

($\gtrsim 99\%$ reflectivity)

to reflect light back-and-forth to stimulate more emission

$\lambda = 694$ nm

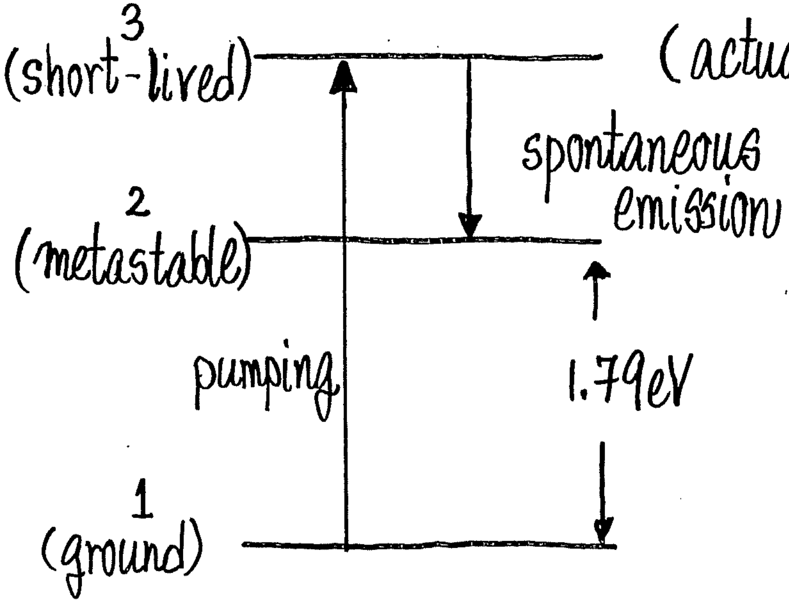
(deep red colour)

(0.2 - 0.3 ms pulses)

cross section of beam $\sim 0.1\ mm^2$

[From Taylor et al., "Modern Physics"]

Consider 3 levels in Cr ion



(actually a group of states)

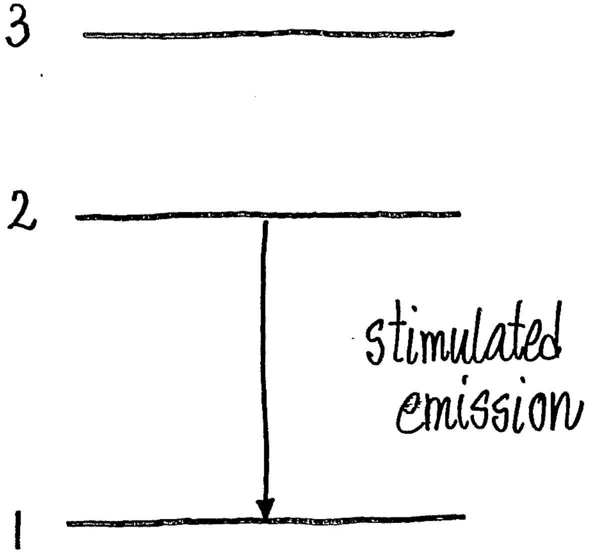
Pumping.

- Pumping by absorption of flashlamp light (1→3) [Need to pump majority of atoms out of 1]
- 3 is short-lived
  ⇒ rapidly (3→2) (spontaneous)
- 2 is metastable
  ⇒ possible to build up
  $N_2 > N_1$
  (population inversion)

Metastable states have $\tau \sim 10^{-3}$ s

vs

$\tau \sim 10^{-8}$ s for electric dipole allowed spontaneous emission

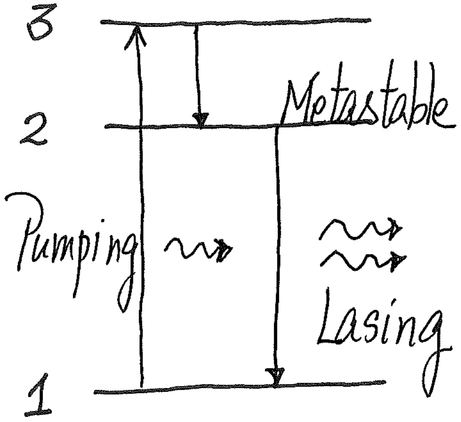


Lasing

$\Delta E = 1.79\,\text{eV}$

$\Rightarrow \lambda \sim 694\,\text{nm}$

Putting 2 steps together



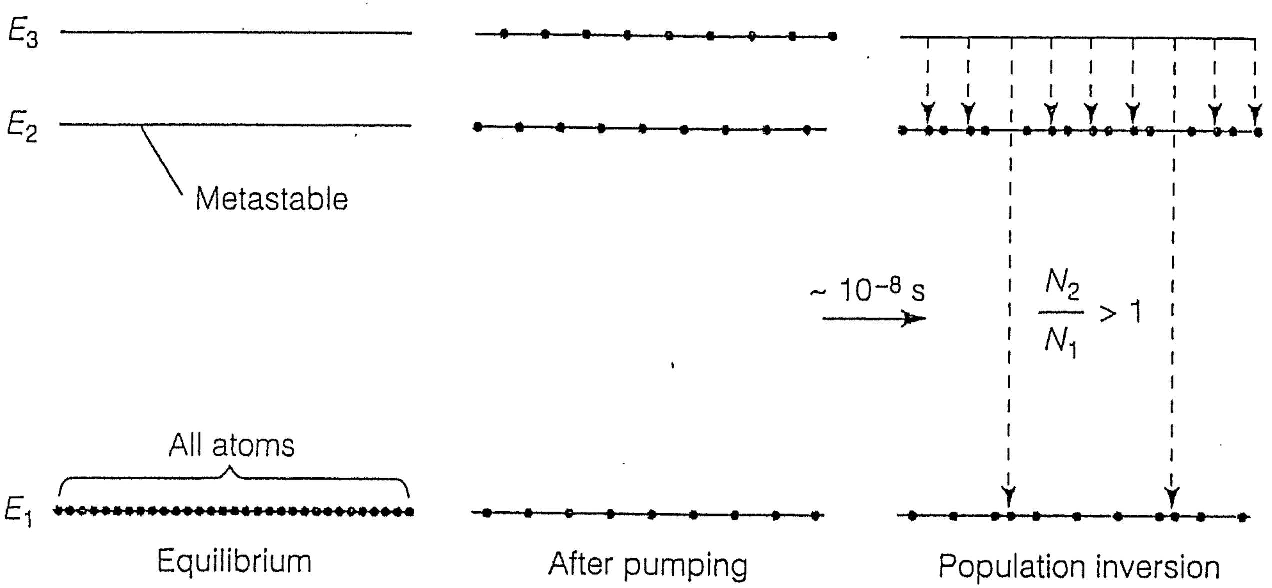
- Mirrors (tricky design)
  - enhance triggering of atom
  - Distance between mirrors carefully chosen $L = \frac{n\lambda}{2}$ to ensure constructive interference of multiply reflected waves (more directional, monochromatic)
- Right after lasing, $N_2 \downarrow$ and $N_1 \uparrow$, then comes $N_2 < N_1$
  $\Rightarrow$ laser action ends $\Rightarrow$ Pulsed Laser (~100 μs)
- Very intense flash of light needed [Heat generation]
- Pulse of instantaneous power ~ 100 kW

"1" is ground state (generally $\underbrace{\text{most}}$ populated) $\Rightarrow$ Hard to maintain $N_2 > N_1$
need to excite many ions out of "1" (consume much energy)

Summary: 3-level system

- For levels in atoms/ions $kT \ll$ energy differences

To achieve population inversion



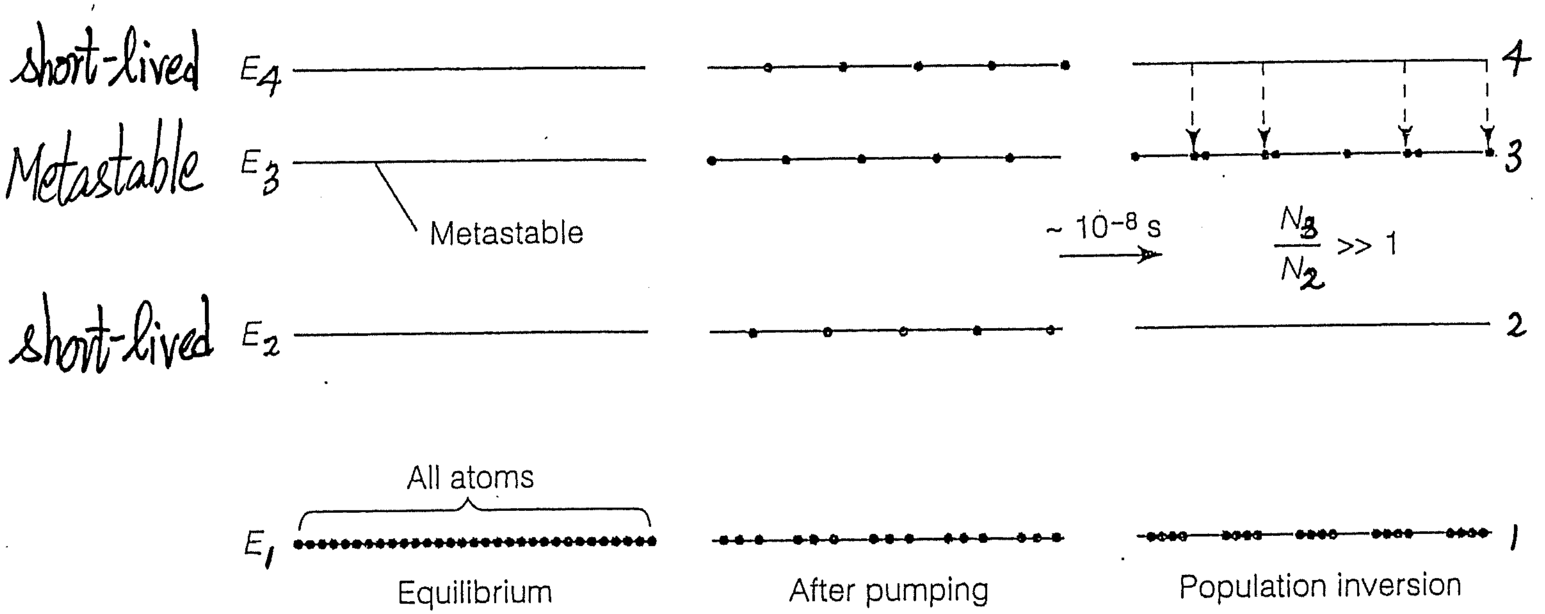
Metastable

Strong pumping
$N_3 \approx N_2 \approx N_1$
right after pumping
[large energy input]

Ready for lasing

Lasing action ends when $N_1 > N_2$

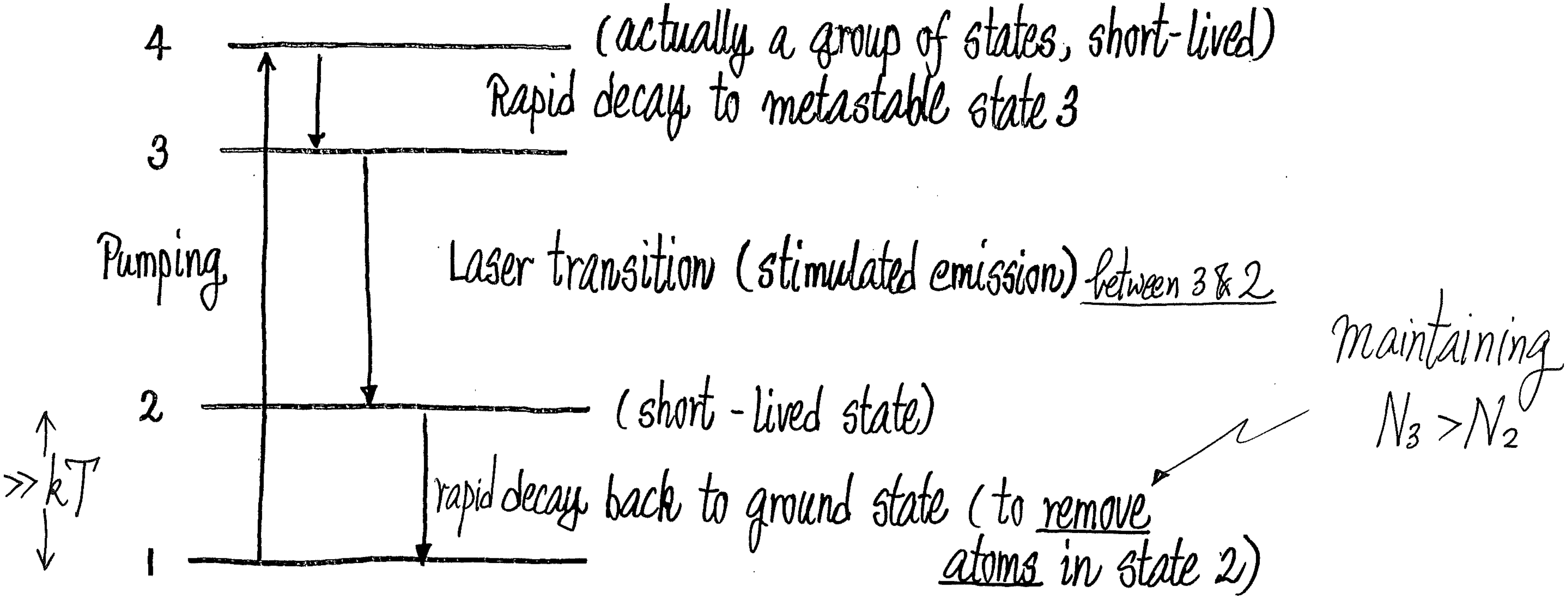
(b) Continuous-wave (cw) laser: 4-level operation/4-level System



$$\underbrace{N_3 \gg N_2}_{\text{ready for lasing between } 3 \,\&\, 2}$$

- Lasing between 3 & 2 ⇒ can maintain $N_3 > N_2$ (as atoms in 2 de-excite to 1 readily by spontaneous emission)
- Need not pump many atoms out of ground state 1 (consume $\underbrace{\text{less energy}}_{\text{more efficient}}$)
- operate continuously (cw)

Putting Pumping and lasing together

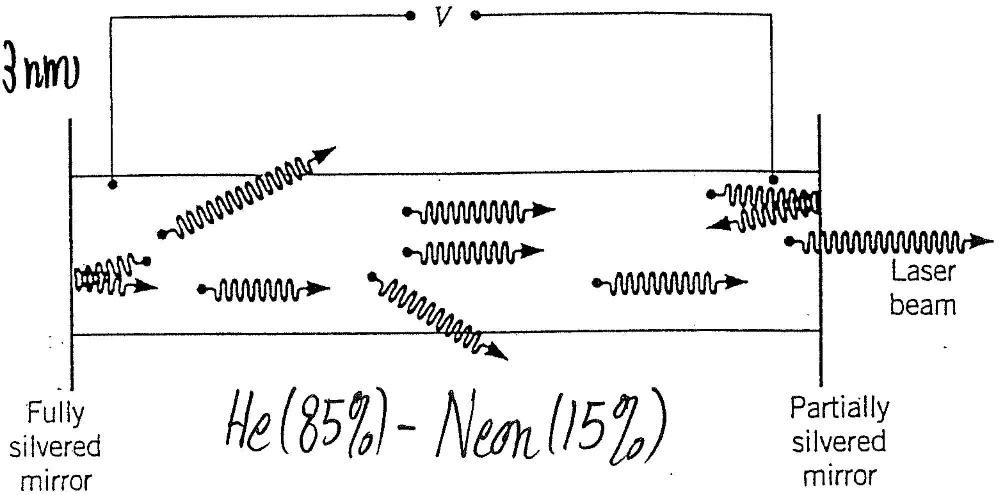


- Quickly removing atoms in state "2" helps maintaining $N_3 > N_2$ (population inversion)
  $\Rightarrow$ continuous lasing action

Example of cw laser: Helium-Neon laser (gas laser)

System: Mixture of He and Ne gas in glass tube

gives $\lambda = 633\,nm$ (red)
also with components at 3392 nm and 1153 nm

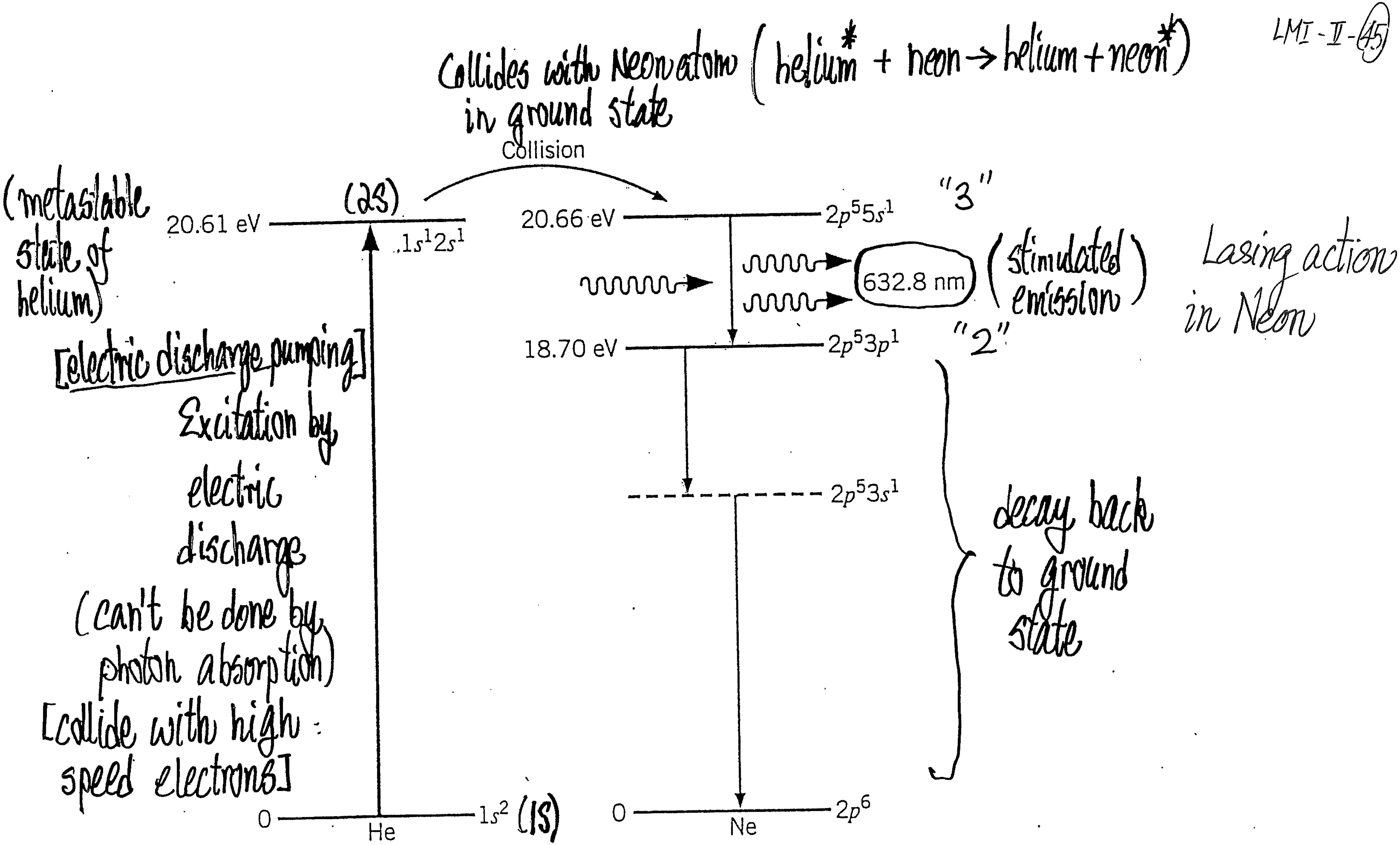


He(85%) - Neon(15%)

Schematic diagram of a He-Ne laser.

Electrodes (Voltage difference V)
⇒ electric discharge
⇒ energetic electrons
⇒ electrons collide with He atoms to excite them to an excite state

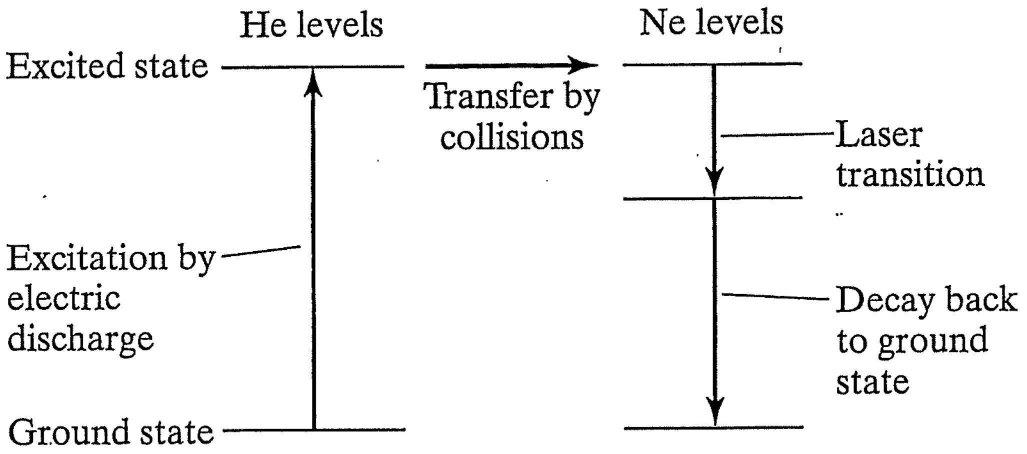
- Excited helium atoms collide with Ne atoms and transfer energy to excite Ne atoms to a state "3"



Sequence of transitions in a He-Ne laser.

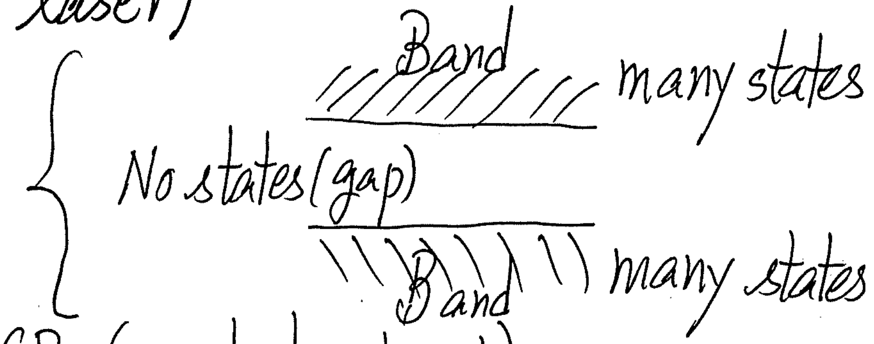
Schematic Summary

The level initially pumped in the He–Ne laser is in the He atoms. Collisions transfer this energy to a level in the Ne atoms, which then produce stimulated emission, terminating in a nearly empty excited state.



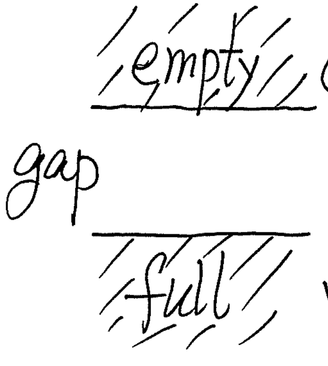
Semiconductor Laser (solid state laser)

- Using electronic states in solids

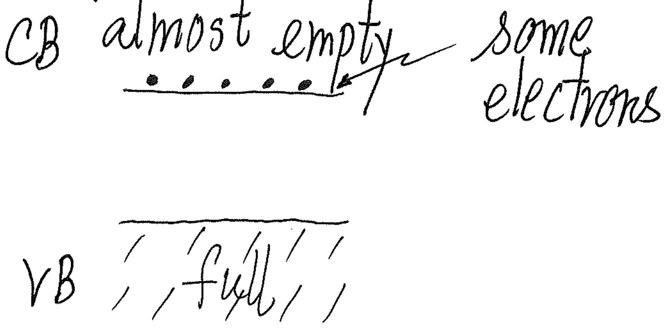


- Pure semiconductors

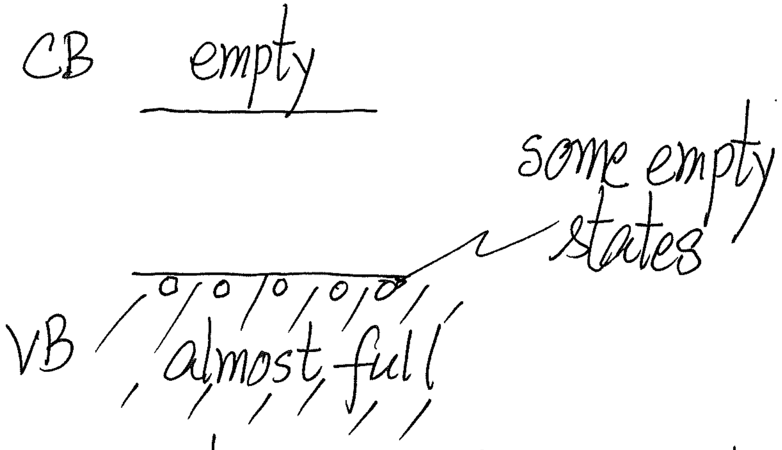
(fill e^-'s into states
with Pauli's Principle)



- Doped Semiconductors

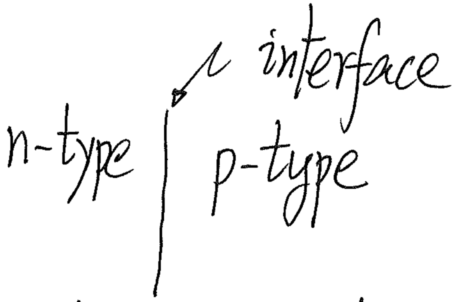


n-type (doped) semiconductor



p-type (doped) semiconductor

- p-n junction
  - Put n-type and p-type together



  - force electrons (higher in energy) meet empty states (lower energy) at interface

⇒ light emission

- at least LED (light-emitting diode)
- properly designed (semiconductor laser)

λ (emitted light) is controlled by <u>band gap</u>

References

- QM treatment on Time-dependent Perturbation Theory
  - Griffiths' book and Rae's book
  - Yariv, "An introduction to the theory and applications of Quantum Mechanics"
    [practical approach, more on laser including semiconductor laser]
- More formal text on Laser
  - A. Yariv, "Quantum Electronics" [Ch. 1-13, out of 24 chapters]
    [You should have the background to read Yariv's book]
- Atomic Physics
  - C. J. Foot, "Atomic Physics" (~ Yr 4 level)
  - M. Fox, "A student's guide to Atomic Physics" (~ Yr 3 to Yr 4)