H. Concepts of Metastable States (long τ) and Stimulated Emission are crucial for LASER

"light"

Light Amplification by the Stimulated Emission of Radiation

higher —— N_2 ← put $N_2 > N_1$ atoms here [out of equilibrium] (population inversion)

lower —— N_1 then stimulated emission

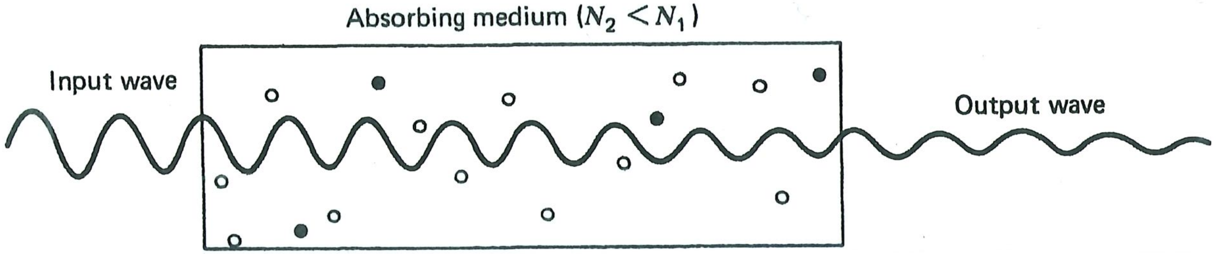
Idea: higher state has long lifetime [metastable state][+]

⇒ atoms there can wait

Thermal Equilibrium situation won't work as $N_2 < N_1$

[+] Yet the metastable state has a weakly allowed transition to a lower energy state for lasing.

Ordinary Situation $(N_2 < N_1)$



• Atoms in upper state 2 (E_2)

∘ Atoms in lower state 1 (E_1)

$I_\nu(0)$ ← freq. ν

$I_\nu(L)$

Absorbing medium $I_\nu(L) = I_\nu(0)\, e^{-\alpha L}$

$$\alpha \sim (N_1 - N_2) \cdot (\text{stimulated transition rate}) \cdot h\nu$$

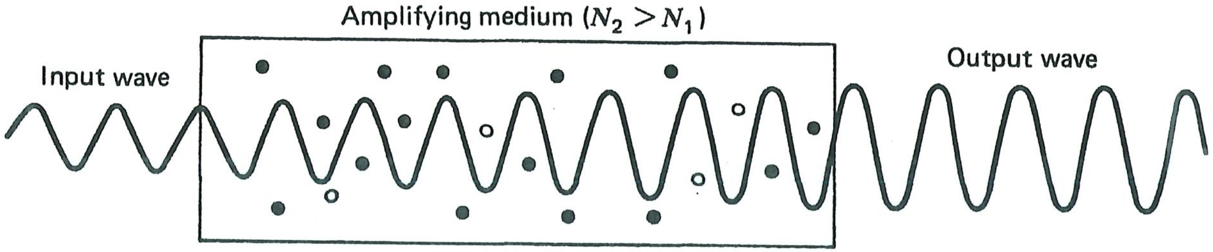
N_1: take energy out; N_2: put energy in

stimulated transition rate $\sim B \cdot U(\omega) = \dfrac{\pi e^2}{3\varepsilon_0 \hbar^2} |r_{21}|^2 U(\omega)$, with $U(\omega) \sim I_\nu(0)$

$$\left[A = \frac{1}{\tau_{spont}} = \frac{\hbar \omega^3}{\pi^2 c^3} B\right]$$

$$\sim \frac{\lambda^2}{\tau_{spont}}$$

Gain / Active / Amplifying Medium



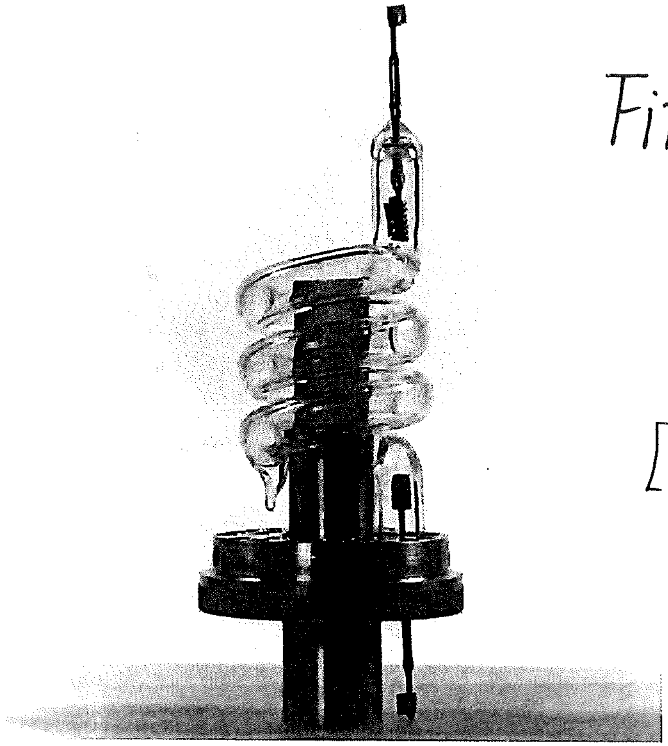
- • Atoms in upper state 2 (E_2)
- ∘ Atoms in lower state 1 (E_1)

then $I_\nu(L) = I_\nu(0)\, e^{\gamma L}$

$$\gamma = -\alpha \sim \underbrace{(N_2 - N_1)}_{\text{Needs } N_2 > N_1} \cdot \underbrace{(\text{rate}) \cdot h\nu}_{\frac{\lambda^2}{\tau_{spont}}}$$

Needs $N_2 > N_1$ → out of equilibrium (population inversion)

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 ($\lambda = 1.25$ cm)

easier than light [$\because A \sim \omega_{21}^3$]

[1964 Nobel Prize]

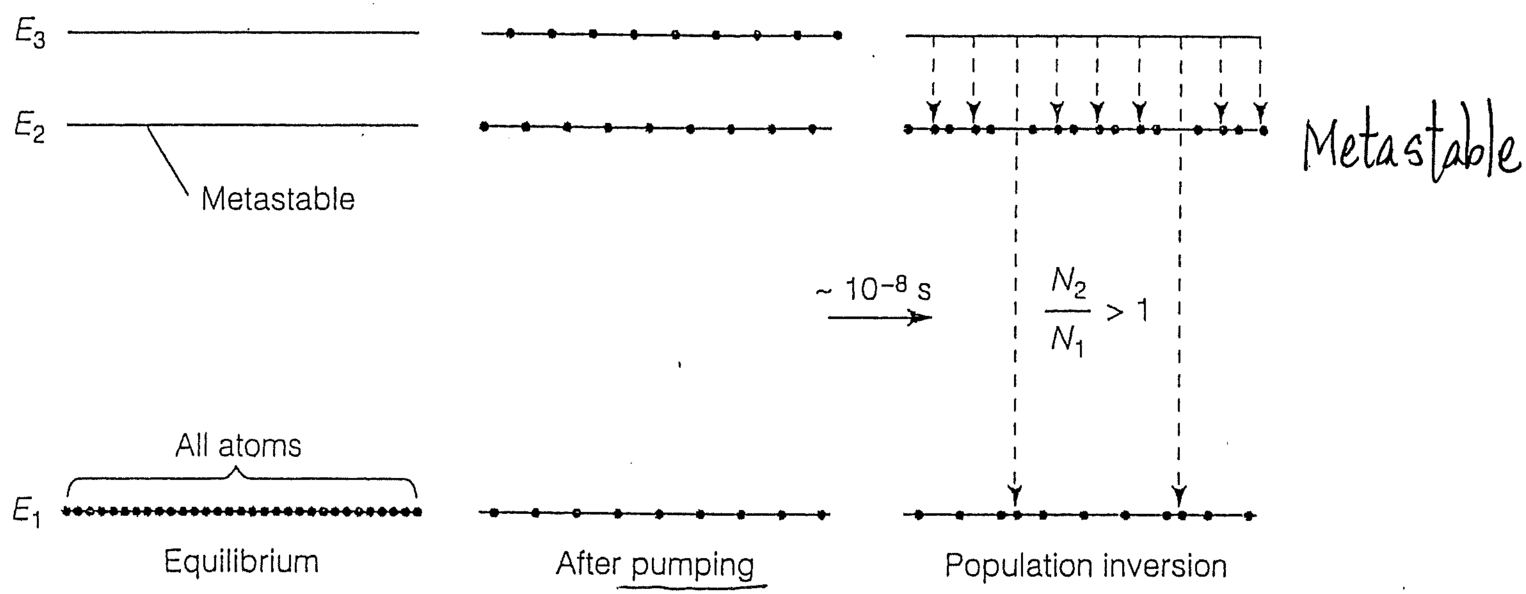
Ruby: Al_2O_3 with Cr (chromium) as impurities [~0.1%]

Lasing effect: using levels in Cr^{3+} ions in Al_2O_3

Schematically, 3-level system

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

To achieve population inversion



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

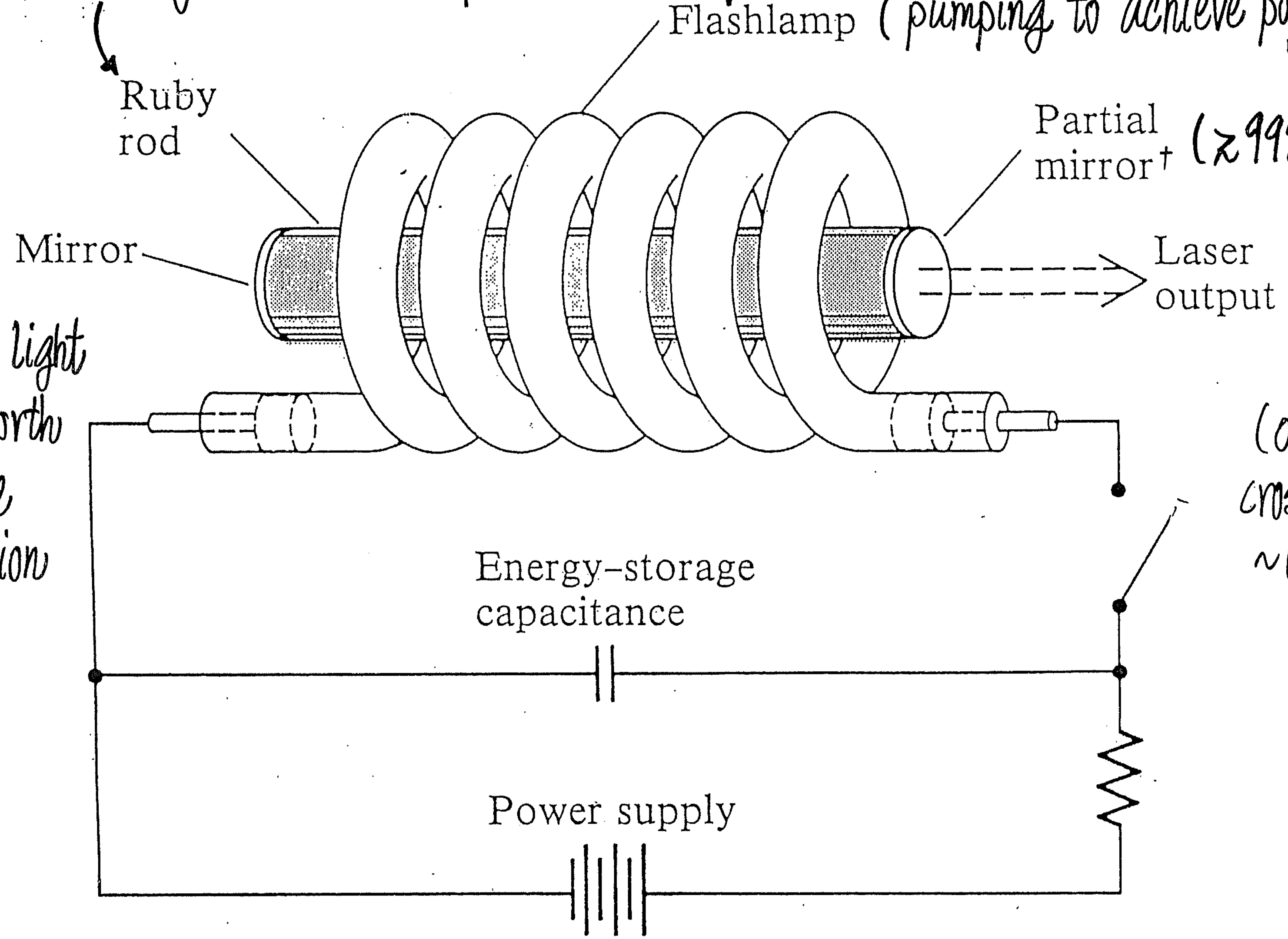
Ready for lasing

Lasing action ends
when $N_1 > N_2$
[only lasts for a short while]
[pulse laser]

Ruby Laser

lasing: due to Cr impurities

intense flash to pump system [optical pumping]



Flashlamp (pumping to achieve population inversion)

Partial mirror† (≈ 99% reflectivity)

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

Laser output: $\lambda = 694$ nm (deep red colour) (0.2 - 0.3 ms pulses) cross section of beam ~0.1 mm^2

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

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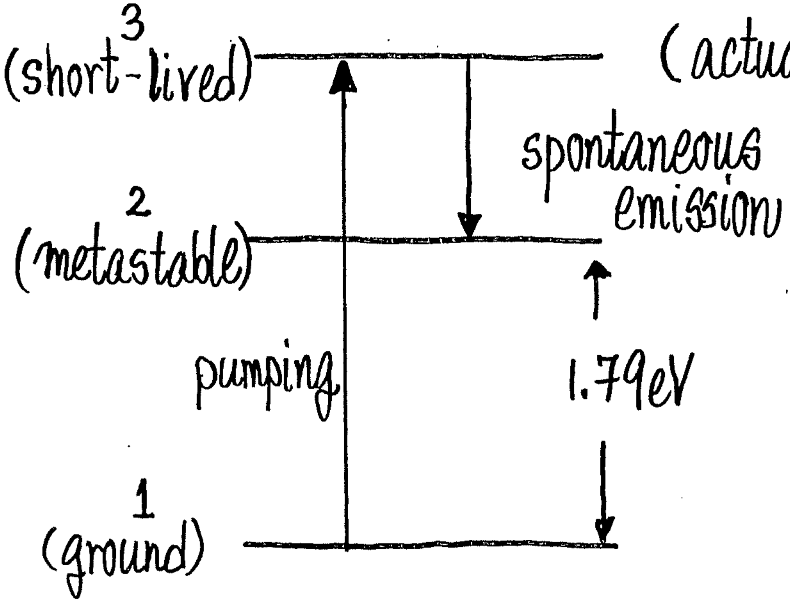
† The idea and technology of creating a laser oscillation are not discussed here.

Consider 3 levels in Cr ion

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

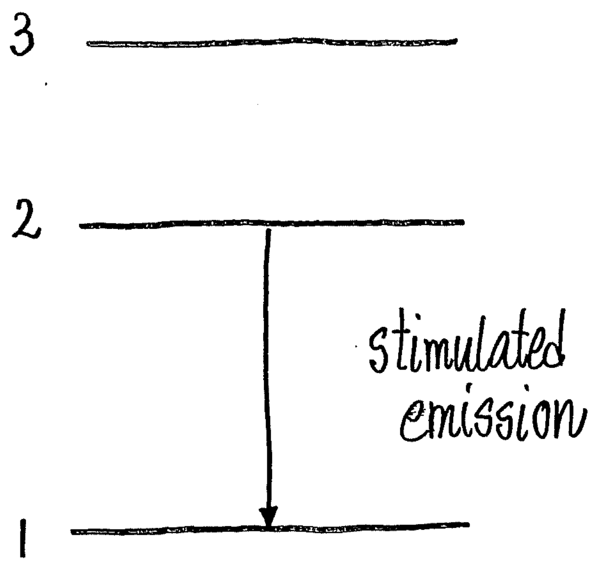
vs

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



Pumping.

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

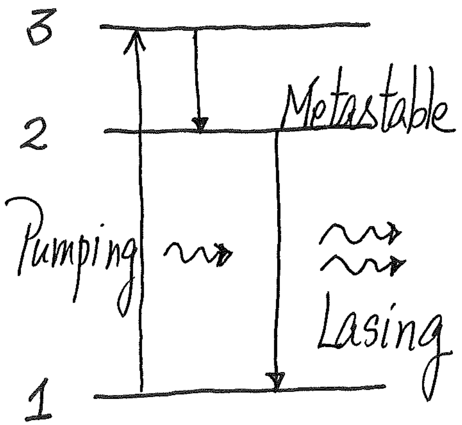


Lasing

$\Delta E = 1.79$ eV

$\Rightarrow \lambda \sim 694$ nm

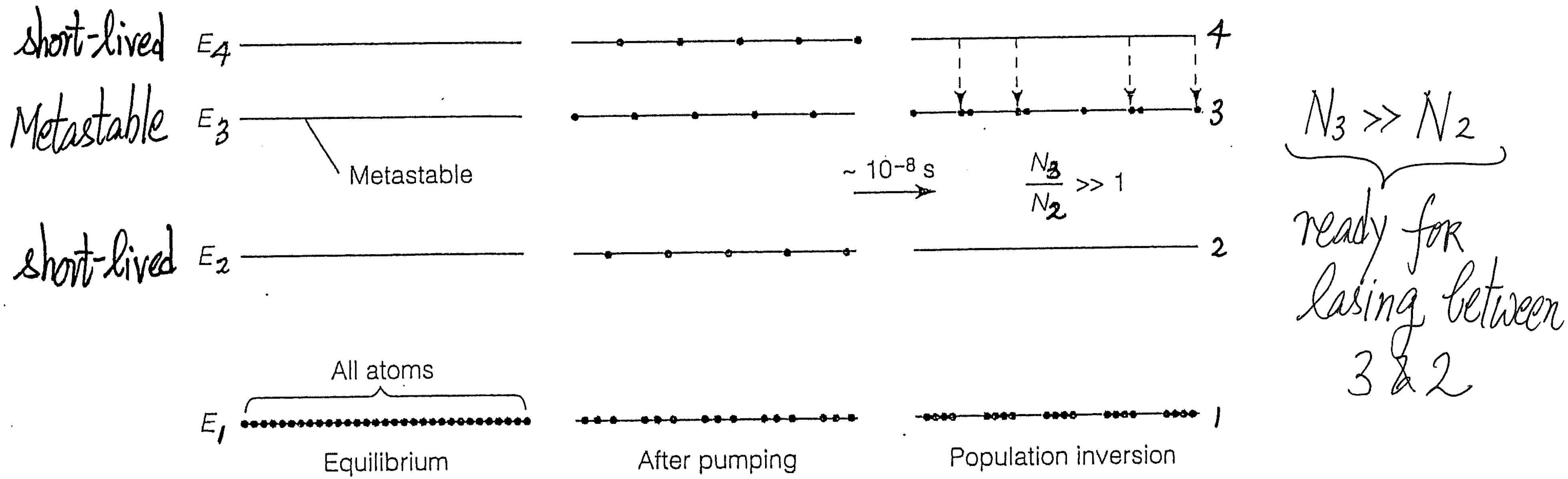
Putting 2 steps together



- 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

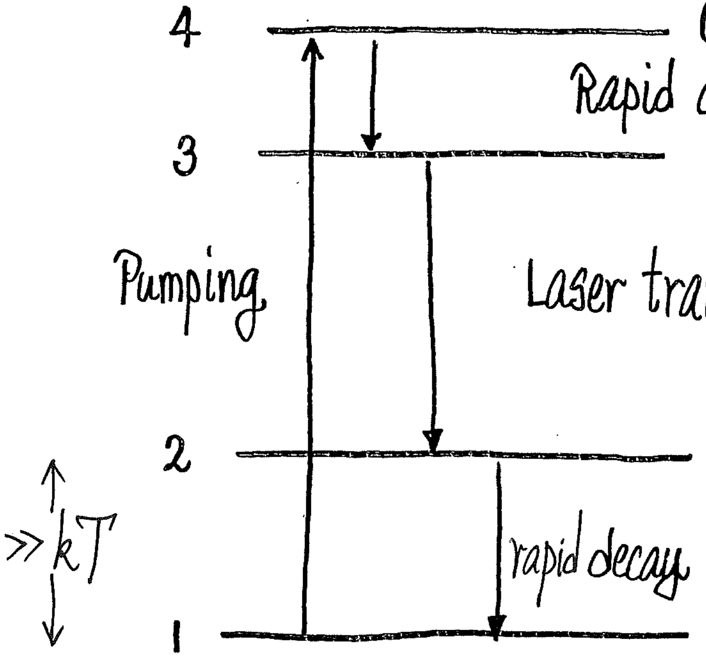
"1" is ground state (generally most populated) $\Rightarrow$ Hard to maintain $N_2 > N_1$
need to excite many ions out of "1" (consume much energy)

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



- Lasing between 3 & 2 $\Rightarrow$ 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 less energy) — more efficient
- operate continuously (cw)

Putting Pumping and lasing together



- 4: (actually a group of states, short-lived)
- Rapid decay to metastable state 3
- Laser transition (stimulated emission) between 3 & 2
- 2: (short-lived state)
- rapid decay back to ground state (to remove atoms in state 2) ← maintaining $N_3 > N_2$

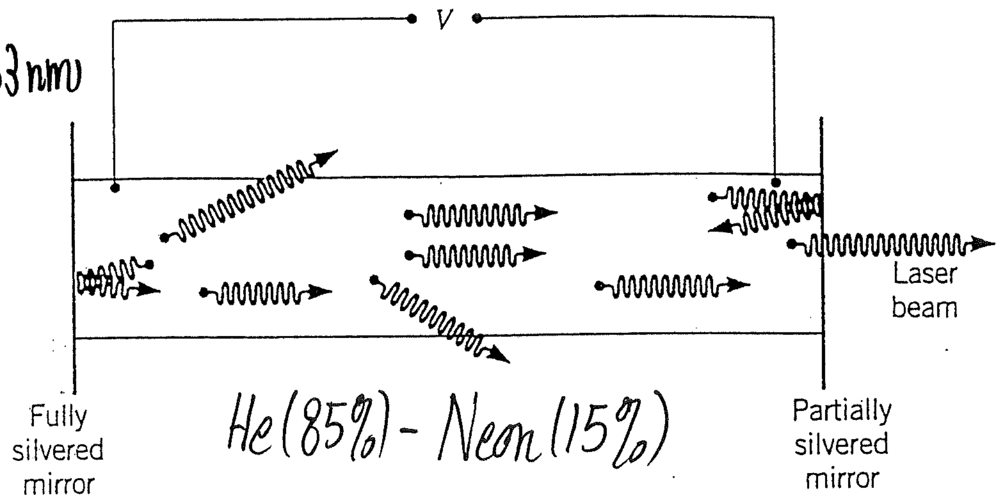
▪ Quickly removing atoms in state "2" helps maintaining $N_3 > N_2$ (population inversion)

$\Rightarrow$ continuous lasing action

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

System: Mixture of He and Ne gas in glass tube

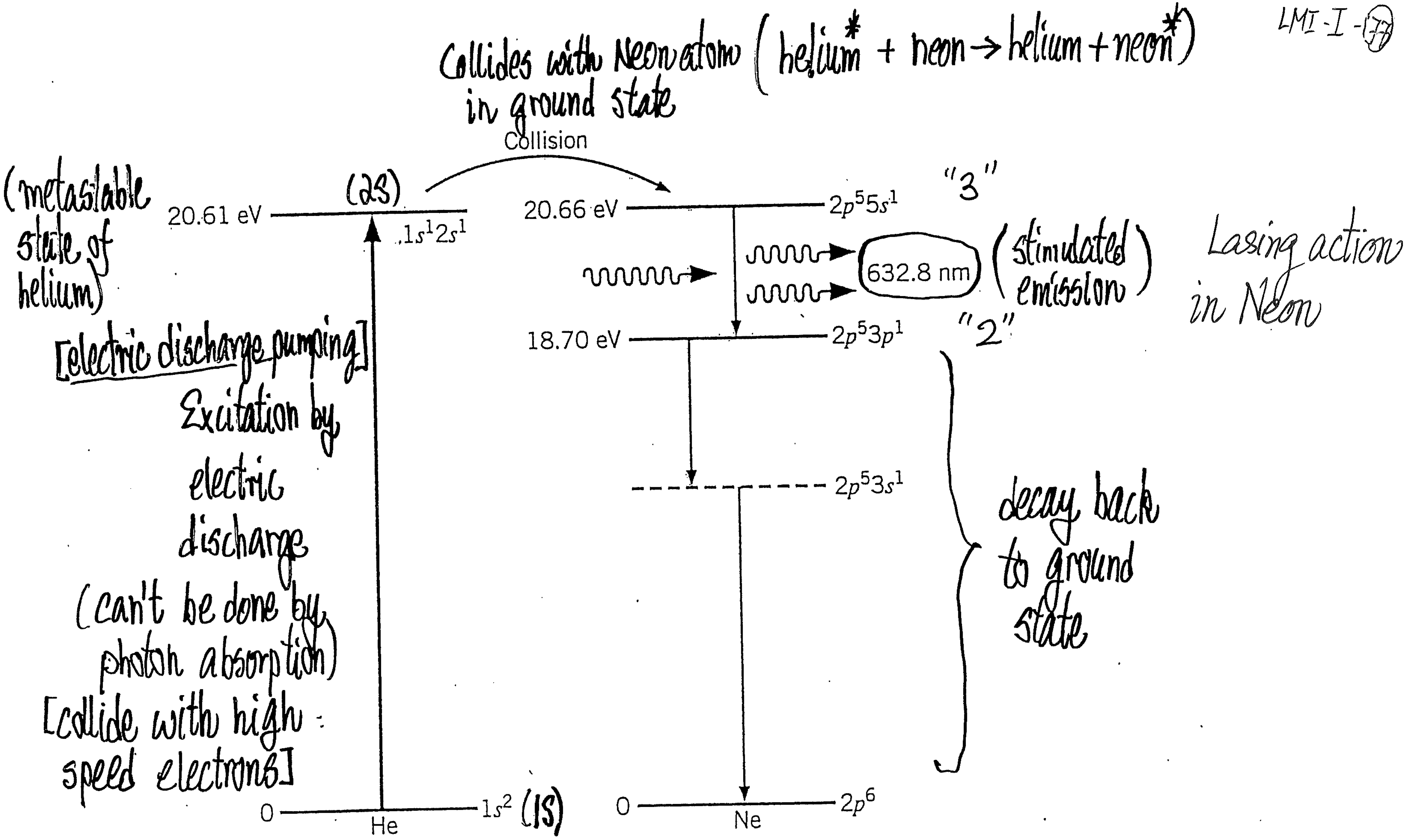
gives $\lambda = 633\,nm$ (red)
also with components at 3392 nm and 1153 nm



Schematic diagram of a He-Ne laser.

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

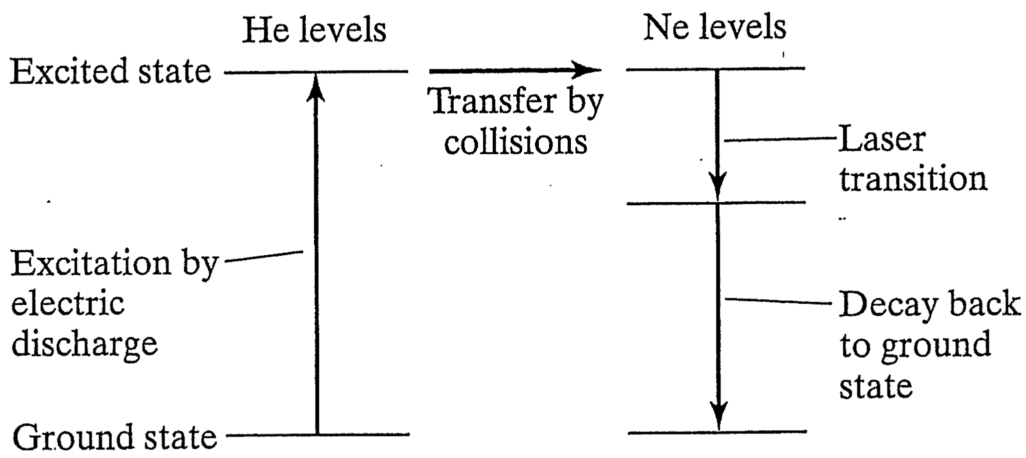
- Excited helium atoms collide with Ne atoms and transfer energy to excite Ne atoms to a state "3"



Sequence of transitions in a He-Ne laser.

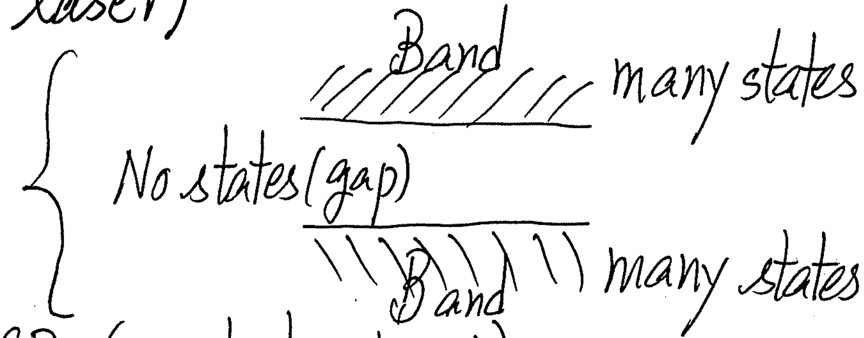
Schematic Summary: He-Ne Laser

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.



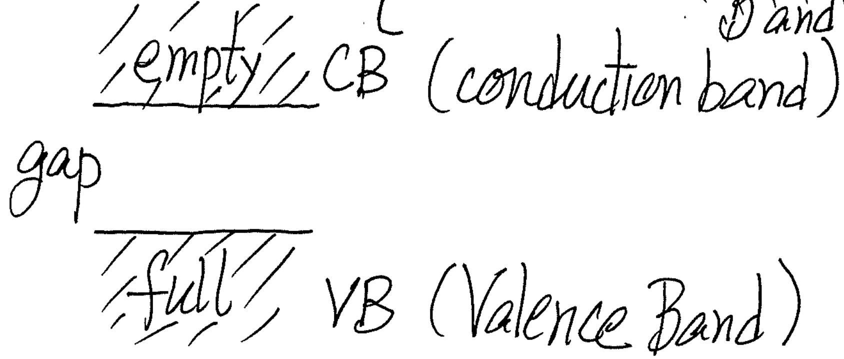
Semiconductor Laser (solid state laser)

- Using electronic states in solids

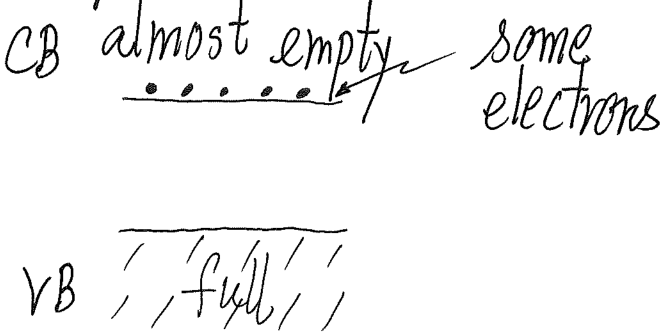


- Pure semiconductors

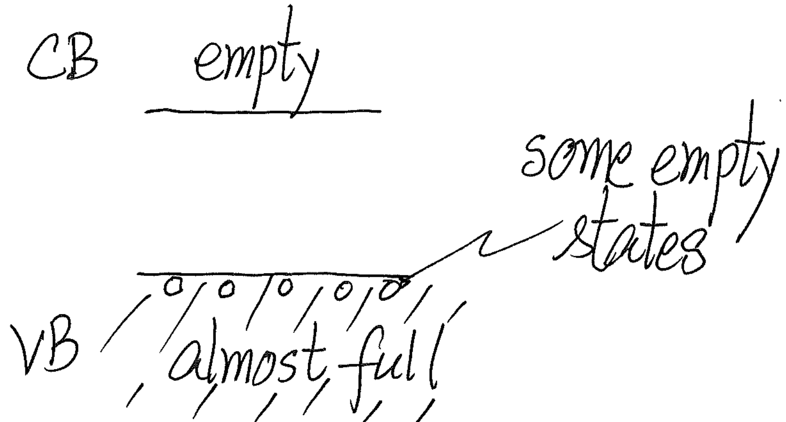
(fill e⁻'s into states with Pauli's Principle)



- Doped Semiconductors



n-type (doped) semiconductor



p-type (doped) semiconductor

- p-n junction
  - Put n-type and p-type together n-type | p-type (← interface)
  - 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>

Final Remark

- Method and Results in "LMI" module are applicable to light (absorption, emission) interacting with matter
  - Atoms (transitions between atomic states)
  - Molecules (transitions between molecular states)
    [electronic, vibrational, rotational]
  - Solids (transitions from valence band to conduction band in semiconductors)

  ⋮

References

- QM treatment on Time-dependent Perturbation Theory
  - Griffiths' book, Rae's book, Bransden & Joachain'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 - Beginning postgraduate level)
  - M. Fox, "A student's guide to Atomic Physics" (~Yr 3 to Yr 4)