

Lecture 11: Specific Lasers

- Solid
- Gas
- Liquid
- Semiconductor

To build a laser, you need

- Two mirrors
- Gain medium (liquid, solid, gas)
- Pump

Atoms (again):

- Different atoms have different energy levels
- All atoms have ground state, excited states, and continuum
- We are interested in ground + first few excited state only.
- Energy levels, lifetimes, gain-bandwidth different for different atoms
- “One atom, one color...” (not exactly)

Solid lasers

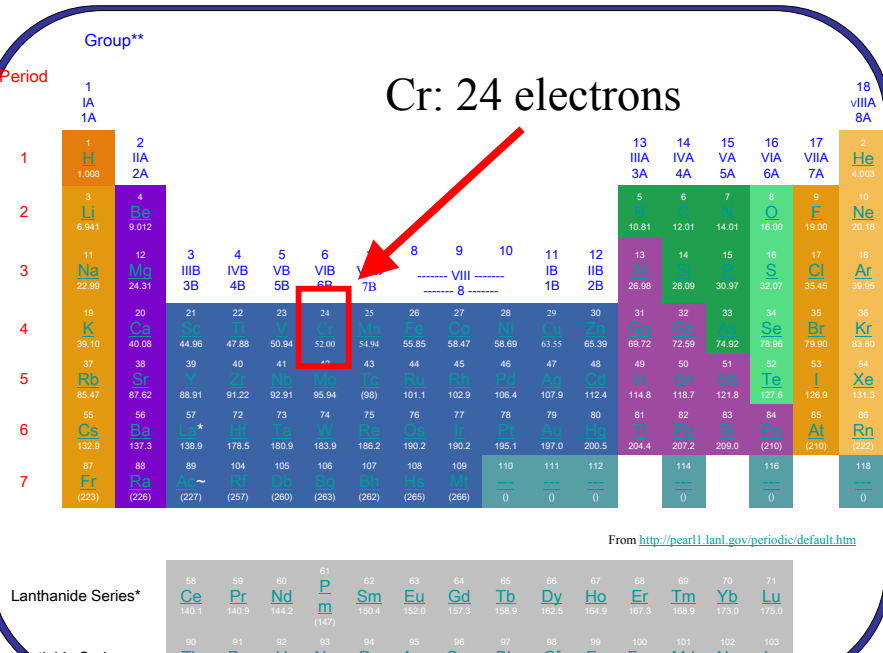
- Optically active atoms are embedded in a solid, usually at 1% or less fraction
- => 99% of solid “irrelevant”
- Atoms are trapped in place
- Solid must be optically transparent
- Examples of suitable host solids:
 - 1) Glass
 - 2) Sapphire: single crystal Al_2O_3
 - 3) YAG: yttrium aluminum garnet $\text{Y}_3\text{Al}_5\text{O}_{12}$

Solid lasers

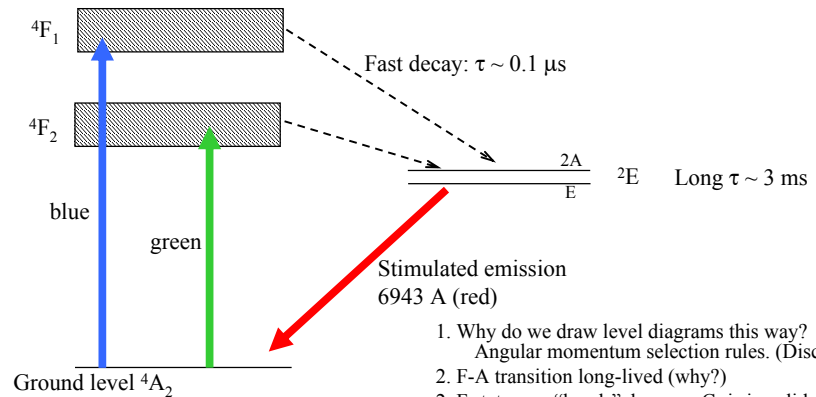
- Ruby laser
- Nd:YAG
- Nd:Glass
- Ti:Sapphire

Ruby laser

- First optical laser, developed at Hughes in Malibu, [T.H Maiman, Phys. Rev. Lett. 4, 564 \(1960\)](#)
- Host solid is sapphire (Al_2O_3)
- Optically atoms Cr, doped 0.05% by weight
- No longer in widespread use because of limited efficiency, spiking behavior

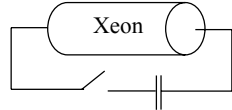
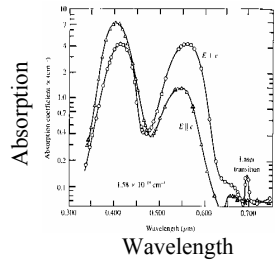


Ruby laser

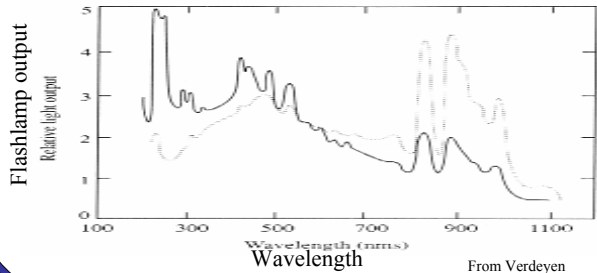


1. Why do we draw level diagrams this way?
Angular momentum selection rules. (Discuss)
2. F-A transition long-lived (why?)
2. F states are "bands", because Cr is in solid matrix, i.e. many states. Good for pumping (why?)
3. This is 3-level in the bad sense.
4. F-E decay non-radiative
5. Pumping?

Ruby pumping: (usually ms pulsed)

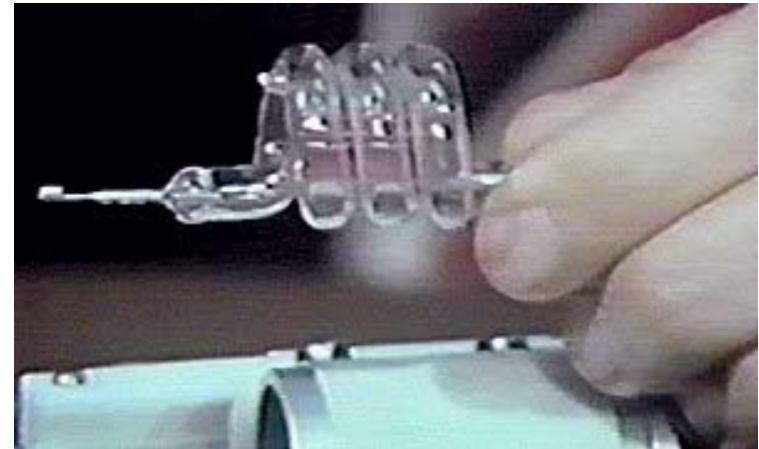


- Because it is three level, need kW/cm³ of pumping for inversion.
- Absorption at laser freq. small
- Absorption band **large** (typical of solid lasers, not gas lasers. This is why gas lasers not optically pumped.)



From Verdeyen

Ruby laser picture:



From <http://home.achilles.net/~jalbot/history/ruby.html>

Nd:YAG

- Four level laser, so easier to pump
- Host solid is single crystal YAG : yttrium aluminum garnet $Y_3Al_5O_{12}$
- Optically active atoms Nd, doped <1% by weight
- Useful for cw operation, because YAG has high thermal conductivity and can handle a lot of heat.
- Useful for pulsed operation because of BW.

Group**

Period

Nd: 60 electrons

1	IA 1A	2	IIA 2A	3	IIIB 3B	4	IVB 4B	5	VB 5B	6	VIB 6B	7	VIIIB 7B	8	VIII 8	9	IX 9	10	X 10	11	IB 1B	12	IIB 2B	13	IIIA 3A	14	IVA 4A	15	VA 5A	16	VIA 6A	17	VIIA 7A	18	VIIIA 8A			
1	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36		
2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36				
3	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
4	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54		
5	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72		
6	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119			
7	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	148		

Lanthanide Series*

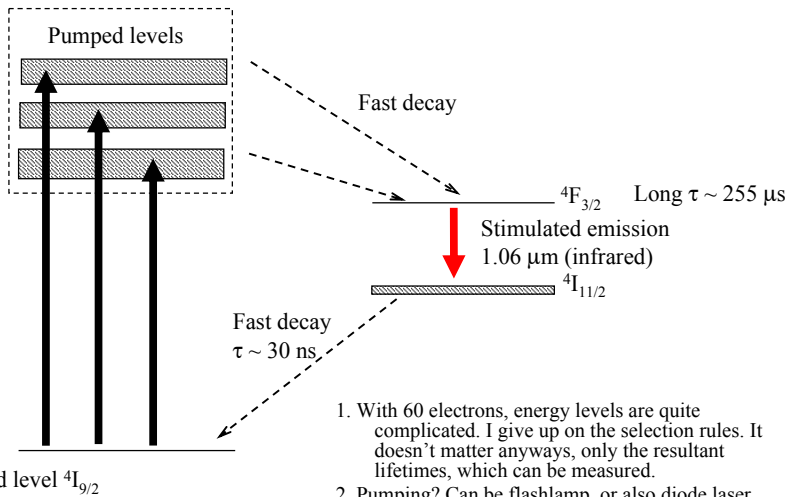
58	59	60	61	62	63	64	65	66	67	68	69	70	71
Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
140.1	140.9	144.2	(147)	150.4	152.0	157.3	158.9	162.5	164.9	167.3	168.9	173.0	175.0

Actinide Series*

88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103
Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr		
232	231	238	(237)	(244)	(243)	(247)	(247)	(251)	(252)	(257)	(258)	(261)	(262)		

From <http://pearl1.lanl.gov/periodic/default.htm>

Nd:YAG



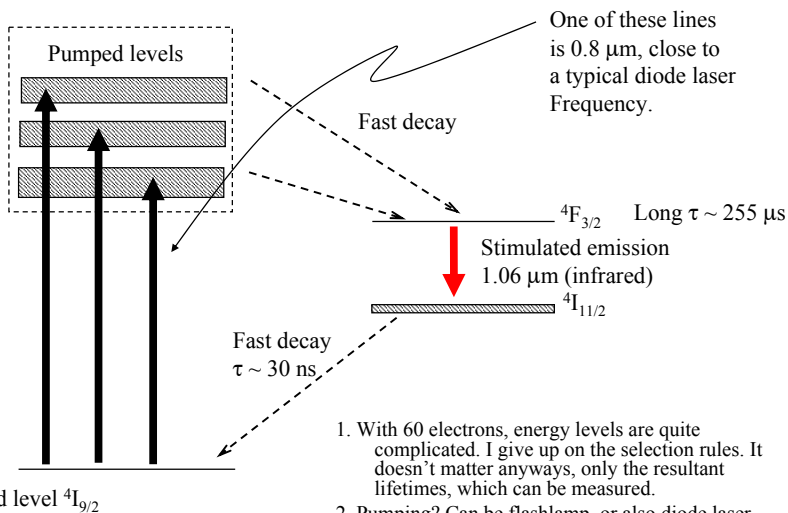
1. With 60 electrons, energy levels are quite complicated. I give up on the selection rules. It doesn't matter anyways, only the resultant lifetimes, which can be measured.
2. Pumping? Can be flashlamp, or also diode laser.
3. Required pumping power 10x lower than ruby.

Nd:YAG

Pumping:

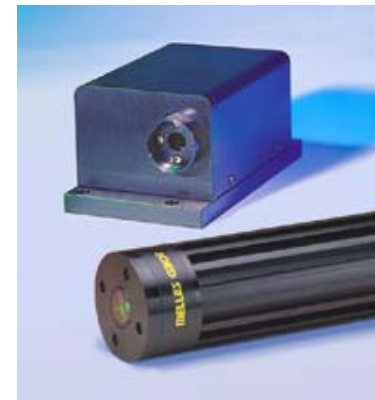
- Flashlamp
- Diode laser

Nd:YAG



1. With 60 electrons, energy levels are quite complicated. I give up on the selection rules. It doesn't matter anyways, only the resultant lifetimes, which can be measured.
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Diode pumped Nd:YAG laser picture:

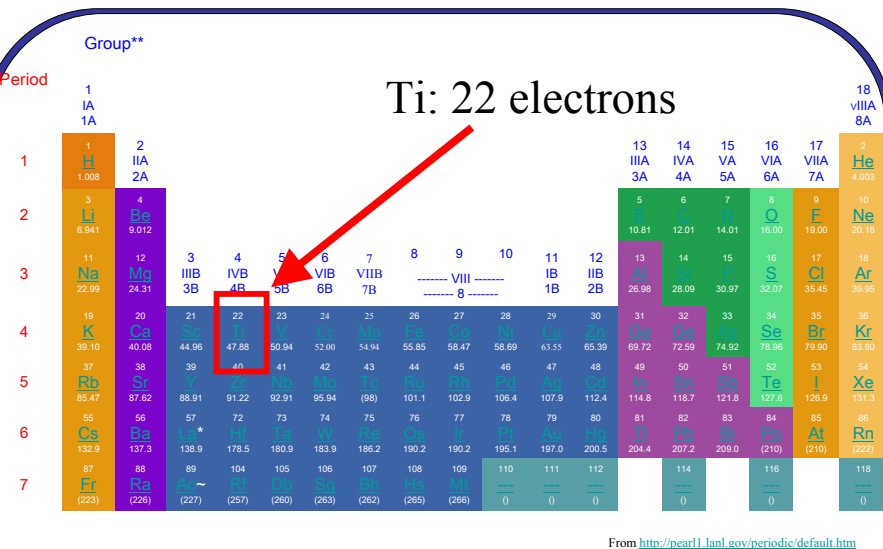


Nd:Glass

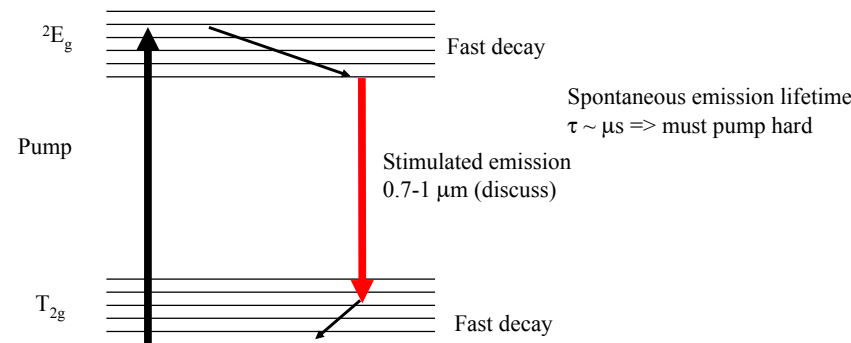
- Similar to Nd:YAG
- Host solid is amorphous glass (SiO_2)
- Less useful for cw operation. (YAG better.)
- Energy levels broadened by amorphous glass (inhomogeneous)
- BW~3 THz; useful for pulsed operation.

Ti:Sapphire laser

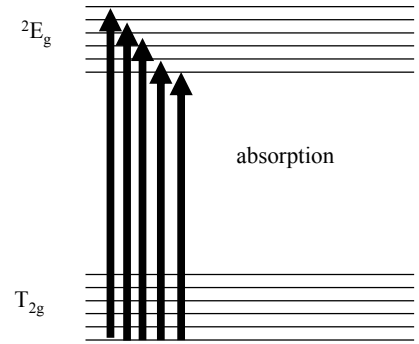
- Optically active atoms TiO_3 <1% by weight
- Host solid is sapphire (Al_2O_3)
- Ti interacts with solid so the E_2 , E_1 broadened significantly.
The atoms in the solid vibrate and interact with the Ti atoms.
- Gain bandwidth huge (100 THz)
- Can use as tunable laser (if you adjust mirrors, discuss HW#1)
- Makes for ultra short pulses



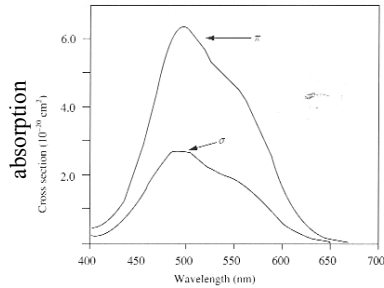
Ti:Sapphire



Ti:Sapphire pumping



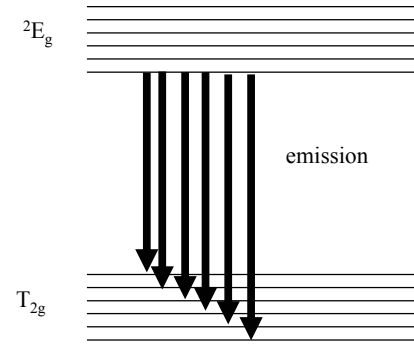
absorption



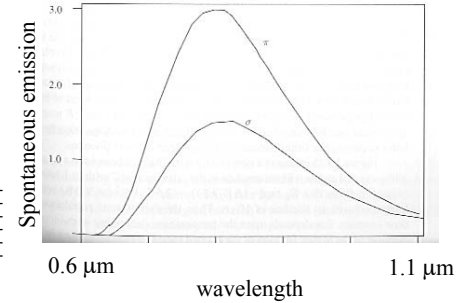
wavelength
From Verdeyen.

So you can pump with any frequency from 400-650 nm.
Usually pumped with Ar ion (480 nm) or doubled Nd:YAG (532 nm)

Ti:Sapphire lasing wavelength



emission



From Verdeyen.

Flourescence = spontaneous emission after being pumped to a higher level.

Conclusion: Gain-bandwidth is HUGE! 100 THz.
Makes for extremely fast mode locked pulses. (how fast?)

Ti:Sapphire picture



Hurricane

The First Diode-Pumped, Ultraviolet Titanium Sapphire Amplifier—All in One Compact Package.

Hurricane brings the ease-of-use and performance of all diode pumped, ultraviolet amplifiers to the compact box size. In a compact design, Hurricane offers all the performance and reliability of a diode pumped, ultraviolet amplifier. Hurricane is equipped with one of the most advanced technologies for the world today, our new Spectra-Physics™ laser for pumping the Ti:Sapphire amplifier. Hurricane also includes a diode pumped amplifier and amplifier in a compact package. Hurricane is the most compact, rugged, and reliable amplifier ever. Hurricane is the most compact, rugged, and reliable amplifier ever. Hurricane is the most compact, rugged, and reliable amplifier ever.

- High power (up to 100 W) output at 355 nm
- High repetition rate (up to 10 kHz)
- Compact size (10 x 10 x 10 cm)
- Long life (up to 10,000 hours)
- High beam quality (M² < 1.1)
- High pulse energy (up to 10 mJ)
- High pulse rate (up to 10 kHz)
- High pulse width (up to 10 ns)
- High pulse duration (up to 10 ns)
- High pulse stability (up to 10 ns)
- High pulse accuracy (up to 10 ns)
- High pulse precision (up to 10 ns)
- High pulse resolution (up to 10 ns)
- High pulse contrast (up to 10 ns)
- High pulse contrast ratio (up to 10 ns)
- High pulse contrast ratio (up to 10 ns)
- High pulse contrast ratio (up to 10 ns)



The Solid State Laser Company™

Hurricane Specifications

Output Characteristics	Model 1	Model 2	Notes
Output Wavelength	355 nm	355 nm	355 nm (3rd harmonic of 1064 nm)
Output Power	100 W	100 W	100 W (100 W CW, 100 W pulsed)
Output Pulse Width	10 ns	10 ns	10 ns (10 ns CW, 10 ns pulsed)
Output Pulse Rate	10 kHz	10 kHz	10 kHz (10 kHz CW, 10 kHz pulsed)
Output Pulse Energy	10 mJ	10 mJ	10 mJ (10 mJ CW, 10 mJ pulsed)
Output Pulse Duration	10 ns	10 ns	10 ns (10 ns CW, 10 ns pulsed)
Output Pulse Stability	10 ns	10 ns	10 ns (10 ns CW, 10 ns pulsed)
Output Pulse Accuracy	10 ns	10 ns	10 ns (10 ns CW, 10 ns pulsed)
Output Pulse Precision	10 ns	10 ns	10 ns (10 ns CW, 10 ns pulsed)
Output Pulse Resolution	10 ns	10 ns	10 ns (10 ns CW, 10 ns pulsed)
Output Pulse Contrast	10 ns	10 ns	10 ns (10 ns CW, 10 ns pulsed)
Output Pulse Contrast Ratio	10 ns	10 ns	10 ns (10 ns CW, 10 ns pulsed)
Output Pulse Contrast Ratio	10 ns	10 ns	10 ns (10 ns CW, 10 ns pulsed)
Output Pulse Contrast Ratio	10 ns	10 ns	10 ns (10 ns CW, 10 ns pulsed)

Physical Characteristics

Parameter	Value
Weight	10 kg
Dimensions	10 x 10 x 10 cm
Power Supply	100 W
Operating Temperature	10°C
Storage Temperature	10°C
Humidity	10%
Vibration	10 g
Shock	10 g
MTBF	10,000 hours
Warranty	10 years

Physical Characteristics

Weight: 10 kg
Dimensions: 10 x 10 x 10 cm
Power Supply: 100 W
Operating Temperature: 10°C
Storage Temperature: 10°C
Humidity: 10%
Vibration: 10 g
Shock: 10 g
MTBF: 10,000 hours
Warranty: 10 years

Spectra-Physics
The Solid State Laser Company™

A little bigger because it has two lasers in one box.

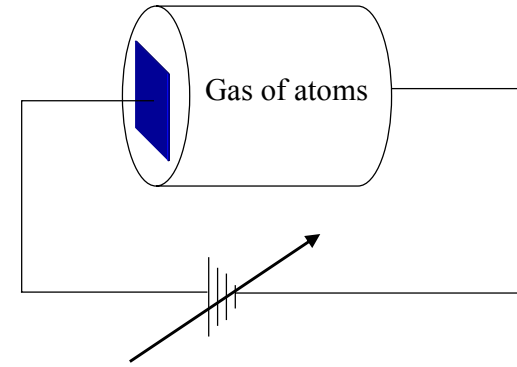
Gas lasers

- HeNe
- CO₂
- Ar⁺

Gas lasers

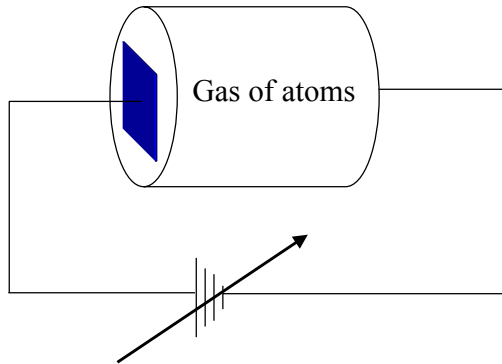
- How do we pump a gas laser?
- Optical pumps not efficient. (Why?)
- We use electrodes with a high voltage, and cause a gas discharge
- This is how “fluorescent” lights work.

Gas discharges:



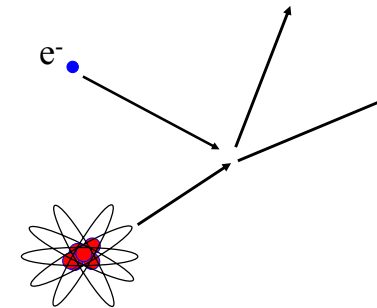
What happens as we turn the voltage up?

Gas discharges:



At first, nothing. Atoms are neutral. (Draw on board).
 Then, one electron gets pulled off of one atom.
 In the large field, the electron gets accelerated and impacts other atoms, knocking off other electrons.
 A current of electrons is now flowing; the positive ions also cause a current. (This reduces the voltage a little, but you can still keep a finite voltage.)
 In steady state, the current is constantly flowing.

Collisions:



Electron (accelerated by the electric field) collides with an atom.
 Energy from the electron is given to the atom, placing it in a higher energy state.
 This is one method of “pumping”.

Before:

— ϵ_2

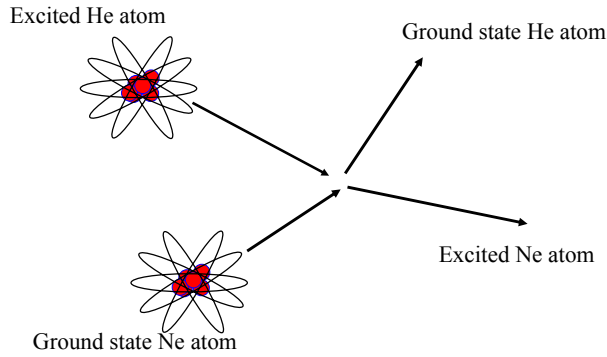
• ϵ_1

After:

• ϵ_2

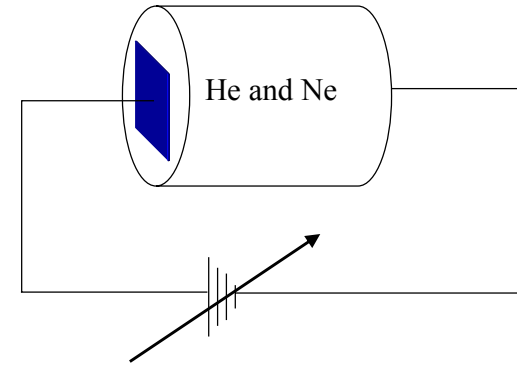
— ϵ_1

Collisions:



He-Ne collisions serve to excite He, de-excite Ne...

HeNe Laser



- Partial pressure of He, Ne (about 1% atmosphere)
- Electrons “pump” He: EXCITED HE IS LONG LIVED!
- He “pumps” Ne
- Ne is active lasing element

Group**

He: 2 electrons

Ne: 10 electrons

“Noble gas” elements don’t react chemically

From <http://pearl.lanl.gov/periodic/default.htm>

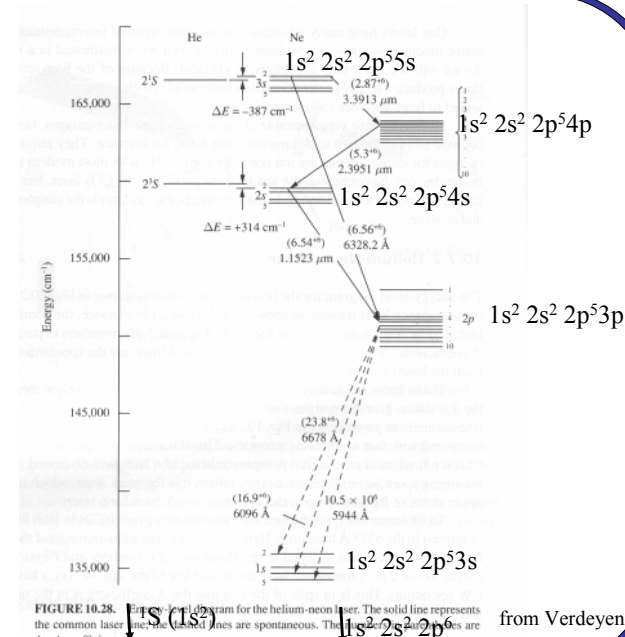
Lanthanide Series*

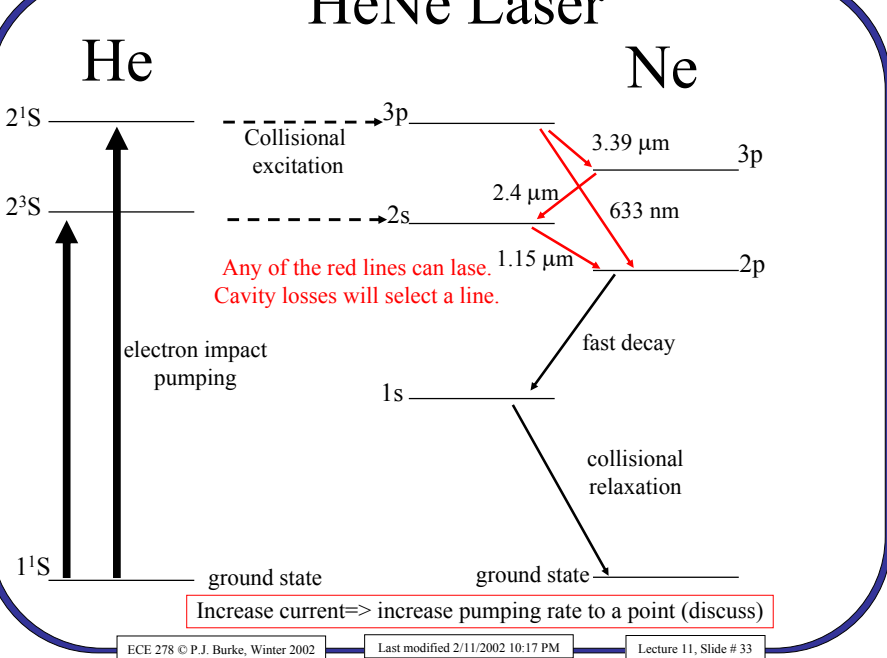
58	59	60	61	62	63	64	65	66	67	68	69	70	71
Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
140.1	140.9	144.2	(141)	150.4	152.0	157.3	158.9	162.5	164.9	167.3	168.9	173.0	175.0

Actinide Series*

80	81	82	83	84	85	86	87	88	89	90	91	92	103
Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr
232.0	231.0	238.0	(237)	(244)	(243)	(247)	(247)	(251)	(252)	(257)	(258)	(261)	(260)

HeNe laser





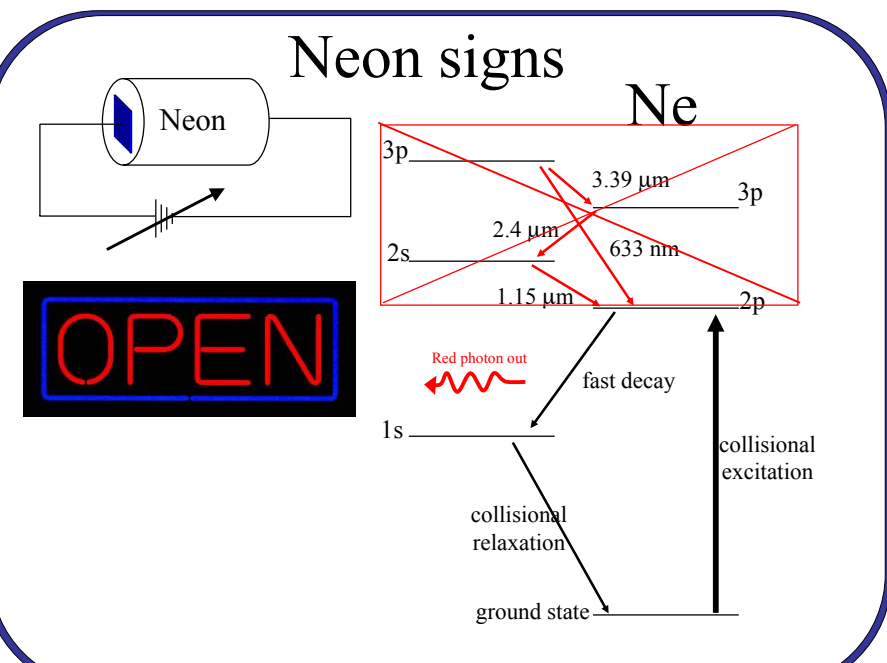
HeNe Laser Picture

- Millions built.
- Very compact (20 cm long)
- ~ 1-10 mW out

Self-contained rectangular helium neon lasers

<http://www.mellesgriot.com/pdf/0044.8-44.9.pdf>

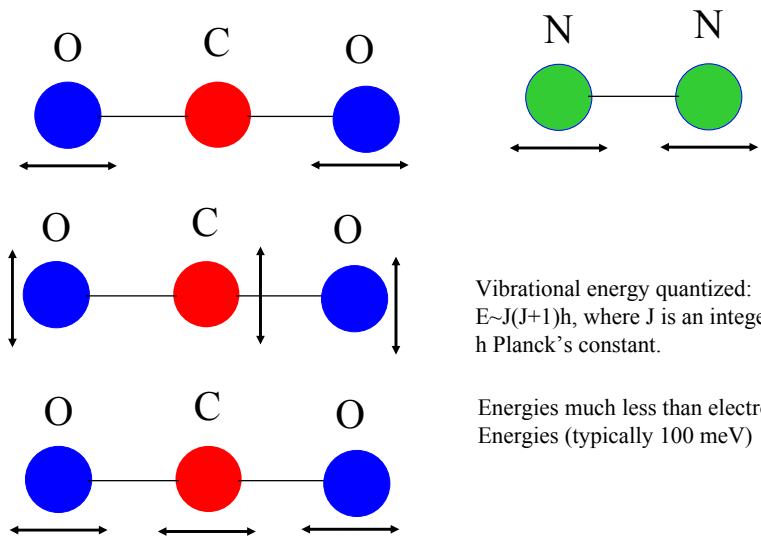
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CO₂ Laser

- > 1 atm pressure of CO₂, N₂, He
- Electrons “pump” N₂ (60% efficient!)
- N₂ “pumps” CO₂
- CO₂ is active lasing element
- 8-18 μm based on vibrational energy levels
- Very high power (kW) possible

Vibrations:

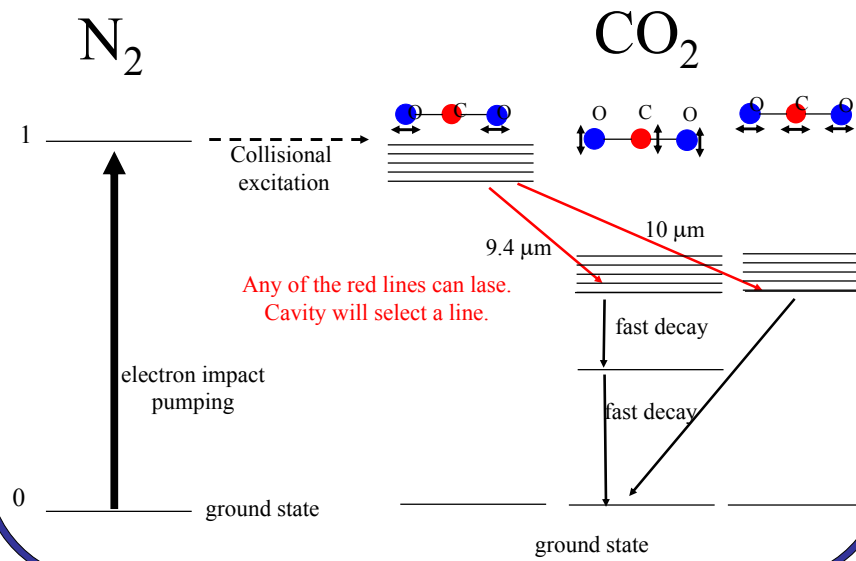


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CO₂ Laser



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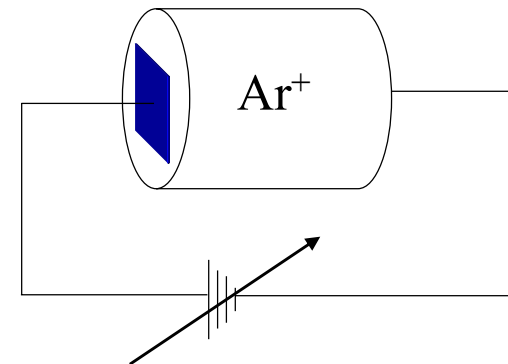
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CO₂ Laser Movie



<http://www.prclaser.com/material.htm>
<http://www.bristolasersystems.com.au/>

Ar Laser



- Multiple electron collisions pump the Ar⁺
- Output from 400-500 nm

“Wall plug” efficiency

Laser	Efficiency
Ar ⁺	0.05%
Rh. Dye	0.005%
HeNe	0.05%
Ruby	0.1%
Ti:Sapphire	0.01%
Nd:glass	1%
Nd:YAG	0.5%
CO ₂	10%
Semiconductor	~50%
Light bulb	~50%

Semiconductor lasers

- This “laundry” list gives only certain wavelengths
- Semiconductor lasers can have an “engineered” wavelength of whatever you want...
- Also can be electrically pumped
- Will start on them in next class