INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION

INTERNATIONAL CENTRE FOR SCIENCE AND HIGH TECHNOLOGY
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Second Training College on Physics and Technology of Lasers and Optical Fibres

21 January - 15 February 1991

GAS LASERS

M.W. Sigrist
ETH, Institute of Quantum Electronics
CH 8093 Zürich, Switzerland

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Active Laser medium

- Gas or vapor
- Most gases, particularly rare gases
  Each offers various laser transitions,
  e.g Neon: ca. 200 laser lines
  between 0,2 μm and 133 μm
- In total more than 4000 laser lines of gas lasers
  between UV and FIR

Classification

- Neutral atom lasers	:	e.g. HeNe, metal vapor (Cu, Au)
- Ion Lasers	:	e.g. Ar^+,HeCd
- Excimer lasers	:	e.g. KrF, XeCl
- Molecular gas lasers	:	e.g. CO_2, CO, N_2, CH_3F

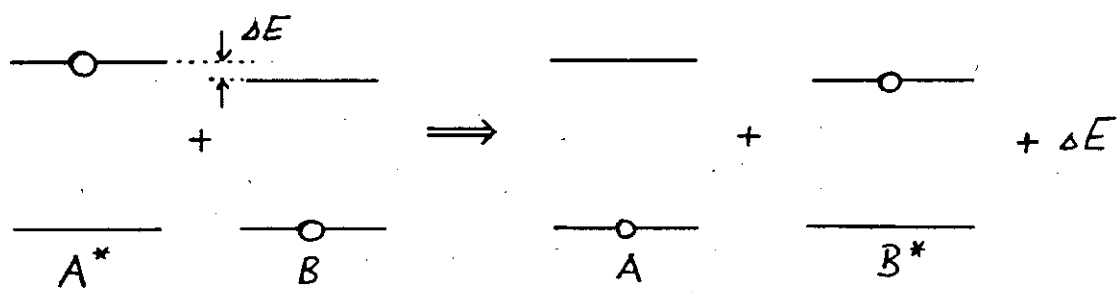
Excitation

- Usually electrical excitation by gas discharge (dc, rf or pulsed)
- Gas dynamic expansion
- Chemical pumping
- Optical pumping by means of another laser

Electrical discharge

i) Excitation by electron impact:
$e + X \rightarrow X^* + e$
collision of the 1st kind

ii) Excitation by "resonant" energy transfer:
$A^* + B \rightarrow A + B^* + \Delta E$, $\Delta E < kT$
collision of the 2nd kind



Deexcitation of excited level

- Collisions of 2nd kind
- Collisions between atoms or molecules
- Collisions with walls of container
- Stimulated and spontaneous emission

Population inversion

A population inversion between two given levels will occur when:

i) excitation rate R is greater for upper laser level(2) than for lower laser level(1),
i.e. $R_2 > R_1$

and / or

ii) decay of upper level is slower than that of lower level, i.e. $\tau_2 > \tau_1$,

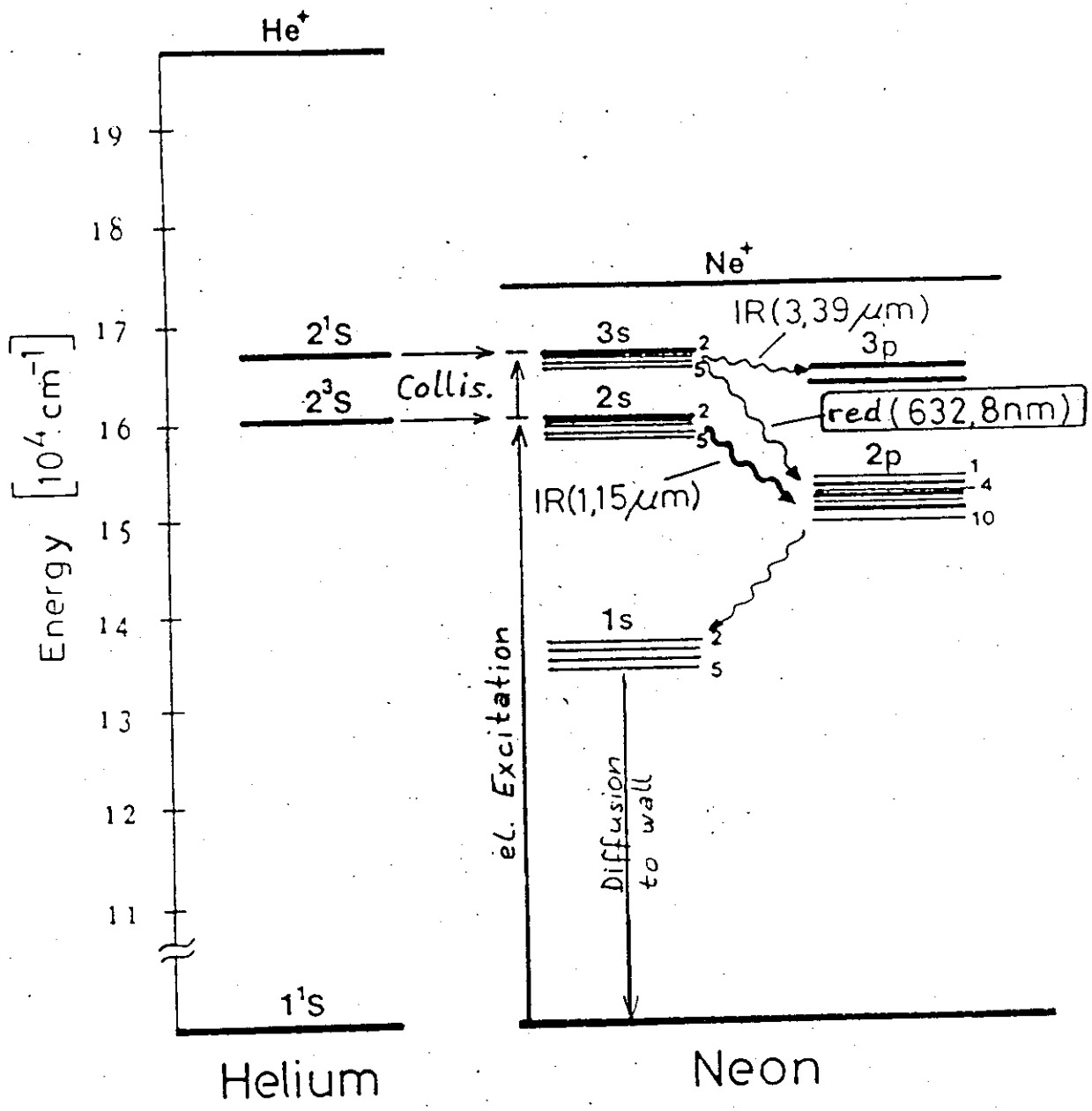
$\tau 2 > \tau_1$,: necessary condition for cw operation. If $\tau_2 > \tau_1$, but i) fulfilled: only pulsed laser action possible
(self-terminating lasers, e.g. metal vapor lasers).

Helium - Neon (HeNe) Laser

Neutral Atom Laser
First gas laser, first cw laser (1960)

Energy level diagram

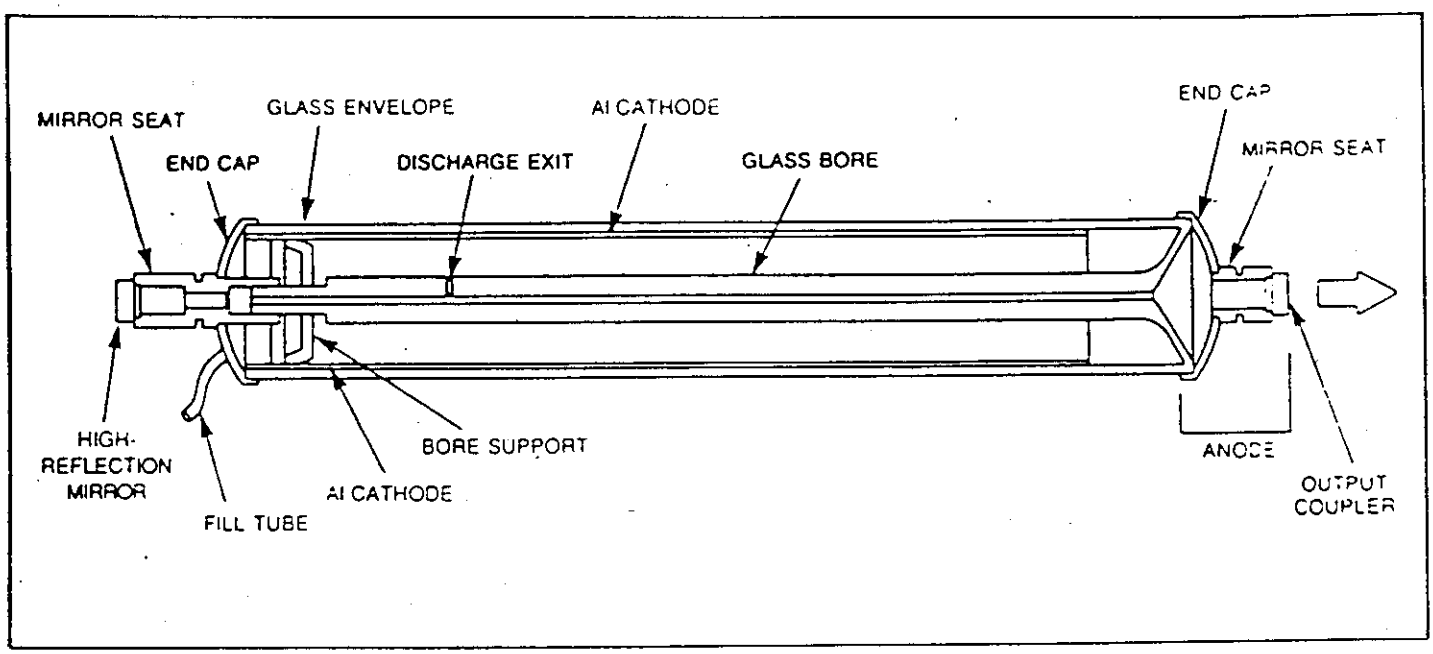
Laser transitions between electronic levels of Ne atom



Operation characteristics of HeNe lasers

Gas pressure	:	mbar
Gas mixture	:	He:Ne ~ 5: 1 .....9:1
Discharge	:	cold cathode, longitudinal, dc voltage: kV, current: mA
Laser power	:	< 1mW to 50mW
Total efficiency	:	$\eta \sim 0.1$ %

Construction



Typical data of HeNe lasers

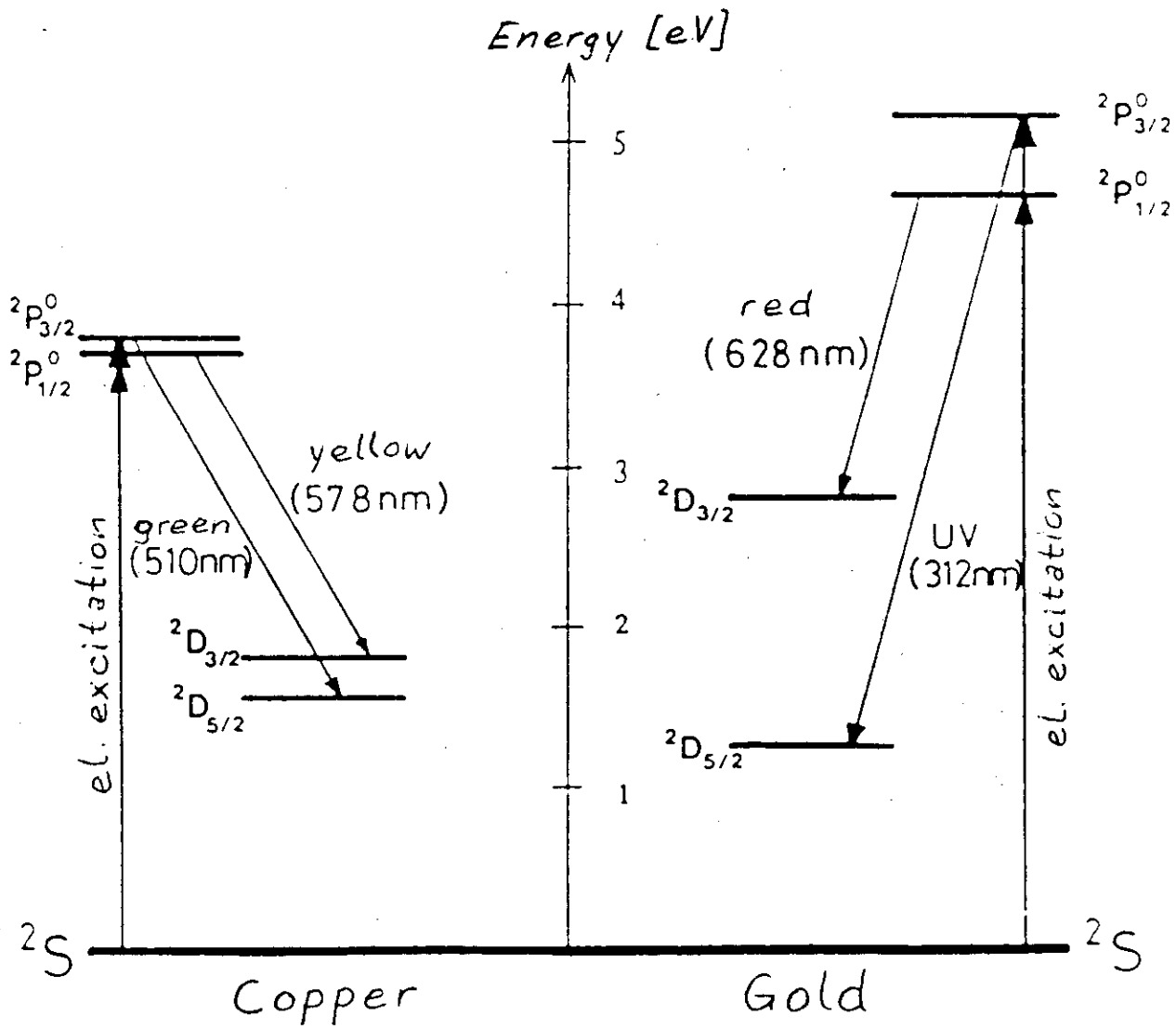
Wavelength [nm]	Laser transition	$\Delta\nu$ [MHz]	Gain [%/m]	Laser power [mW]
543.3 (green)	$3s_2 - 2p_{10}$	1750	0.5	1
594.1 (yellow)	$3s_2 - 2p_8$	1600	0.5	0.5
611.8 (orange)	$3s_2 - 2p_6$	1550	1.7	1
632.8 (red)	$3s_2 - 2p_4$	1500	10	5 (up to 50)
1152.3 (IR)	$2s_2 - 2p_4$	825		1
1523.1 (IR)	$2s_2 - 2p_1$	625		1
3391.3 (IR)	$3s_2 - 3p_4$	280	10^4	10

Copper- and Gold-Vapor Lasers

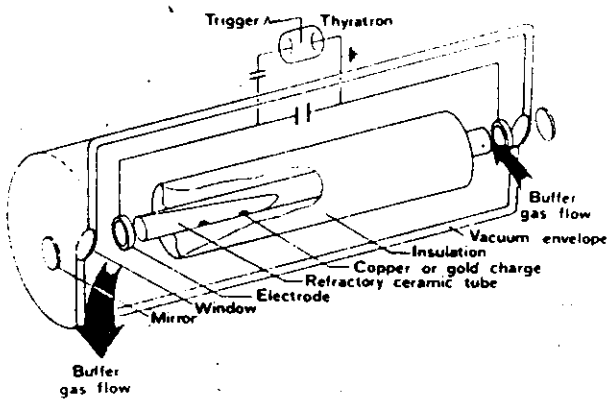
Neutral Atom Metal vapor-Lasers
Pulsed Operation only (self-terminating)

Energy level diagram

Laser transitions between electronic levels of copper or gold atoms



Construction and operation characteristics of metal vapor lasers



(courtesy of Oxford Lasers, Ltd.)

Operation temperature : 1480°C - 1530°C for coppet
1590°C - 1640°C for gold

Buffer gas : Neon
Total efficiency: : ca. 1 %
Gain ca. 10^3 times higher than for Ar^+-Laser!

Typical data of metal-vapor lasers

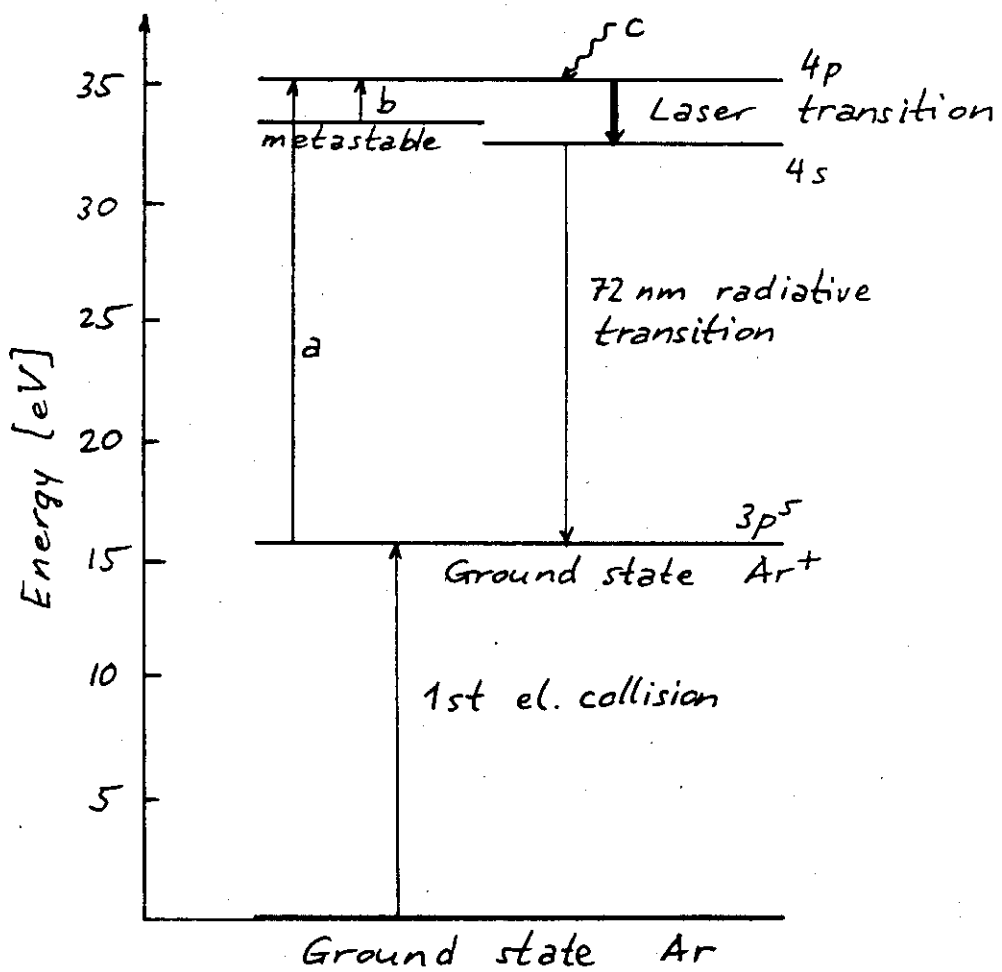
Parameter \ Lasertype	Copper	Gold
Wavelength [nm]	510.6 / 578.2	627.8
Average Power [W]	60	9
Pulse Energy [mJ]	≤ 10	1.5
Pulse Duration [ns]	15-60	15-60
Peak Power [kW]	≤ 300	60
Repetition Rate [kHz]	5-15	6-8
Beam Diameter [mm]	42	42
Beam Divergence [mrad] (with unstable resonator)	0.6	0.6

Argon Ion (Ar^+)-Laser

Widely used ion laser

Energy level diagram

Laser transitions between highly excited levels of the argon ion



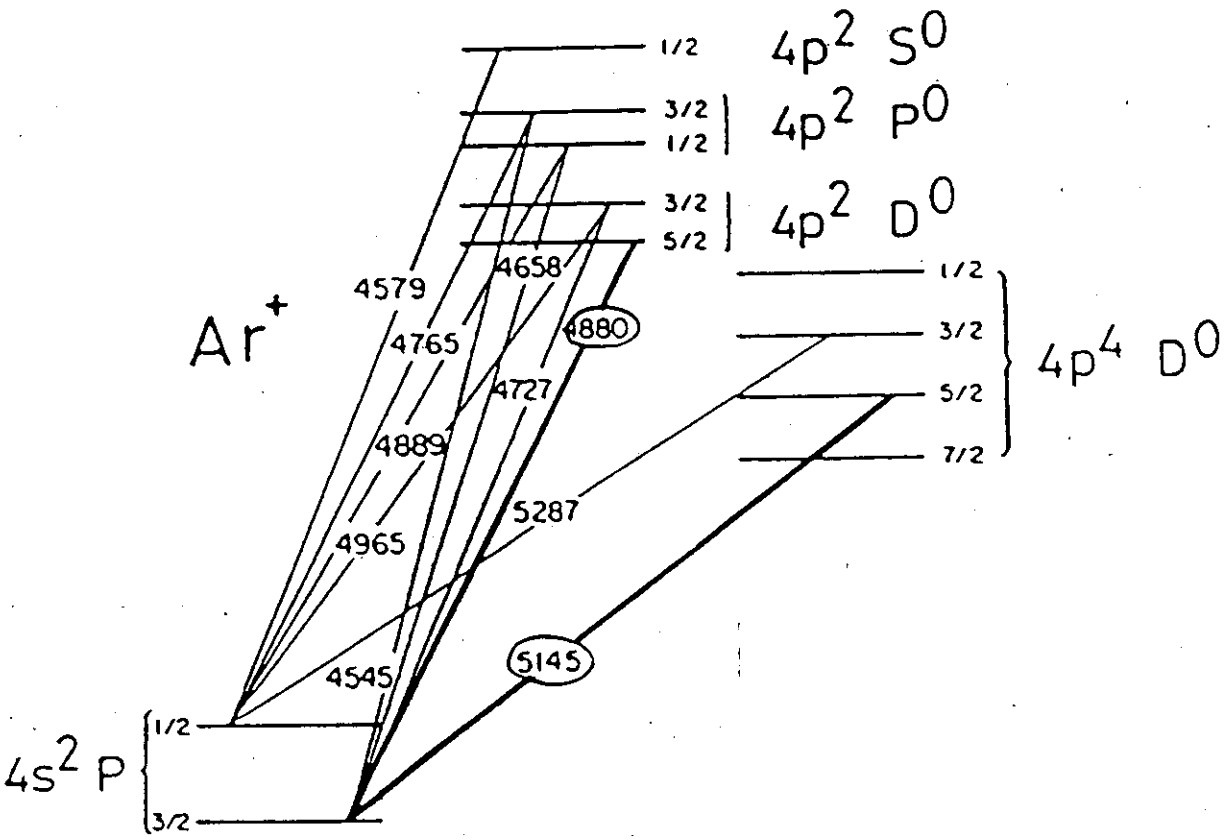
Excitation processes a, b, c :

a : $Ar^+(3p^5) \xrightarrow{e^-\text{-coll.}} Ar^+(4p)$

b : $Ar^+(\text{metastable state}) \xrightarrow{e^-\text{-coll.}} Ar^+(4p)$

c : $Ar^+(\text{higher levels}) \xrightarrow[\text{decay}]{\text{radiative}} Ar^+(4p)$

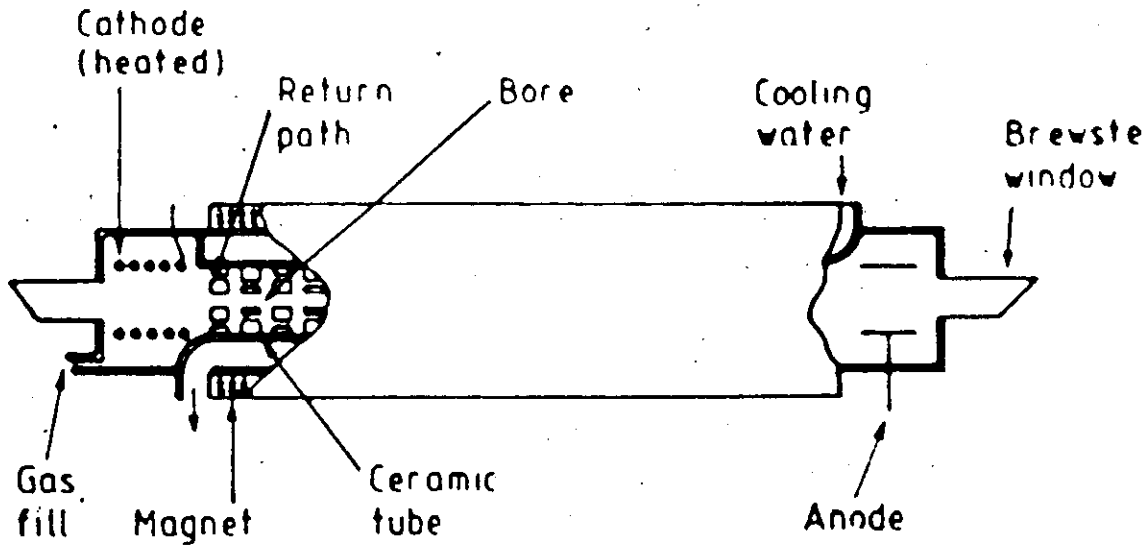
Laser transitions of the Ar+-Laser



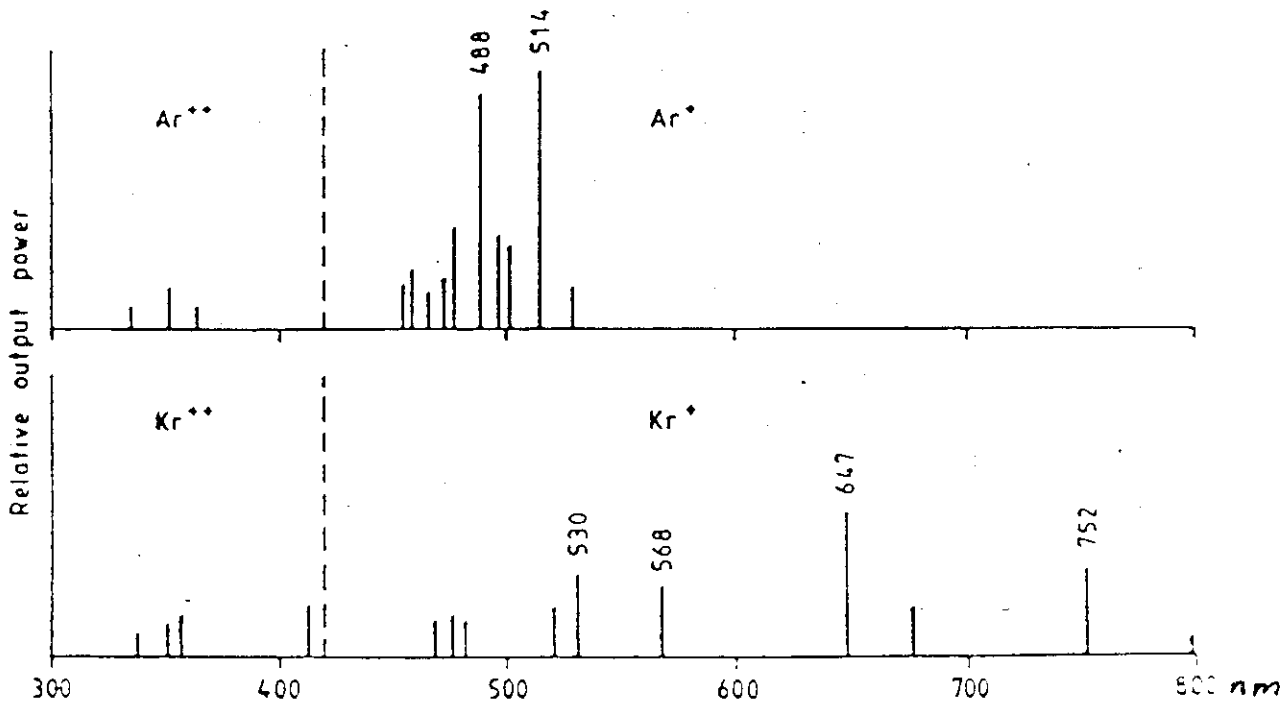
Operation characteristics

Gas pressure	:	mbar
Kind of gas	:	pure argon
Gas discharge	:	hot cathode, longitudinal, dc, high current density (1kA/cm^2) --> special design of ion laser tubes
Laser power	:	several Watts
Total efficiency	:	ca. 0.1 %

Construction of laser tube



Emission wavelengths of rare gas ion lasers



Neon (Ne) [nm]	Argon (Ar) [nm]	Krypton (Kr) [nm]	Xenon (Xe) [nm]
332,4	351,1*	350,7*	460,3
334,5	363,8*	356,4*	541,9
337,8	418,3*	406,7*	597,1
339,3	454,5	413,1*	627,1
371,3	457,9	415,4*	714,9
	465,8	468,0	782,8
	472,7	476,2	798,8
	476,5	482,5	871,6
	488,0	520,8	905,9
	496,5	530,9	969,9
	501,7	568,2	
	514,5	647,1	
	528,7	676,4	
	1092,3	752,5	
		793,1	
		799,3	

Excimer Lasers

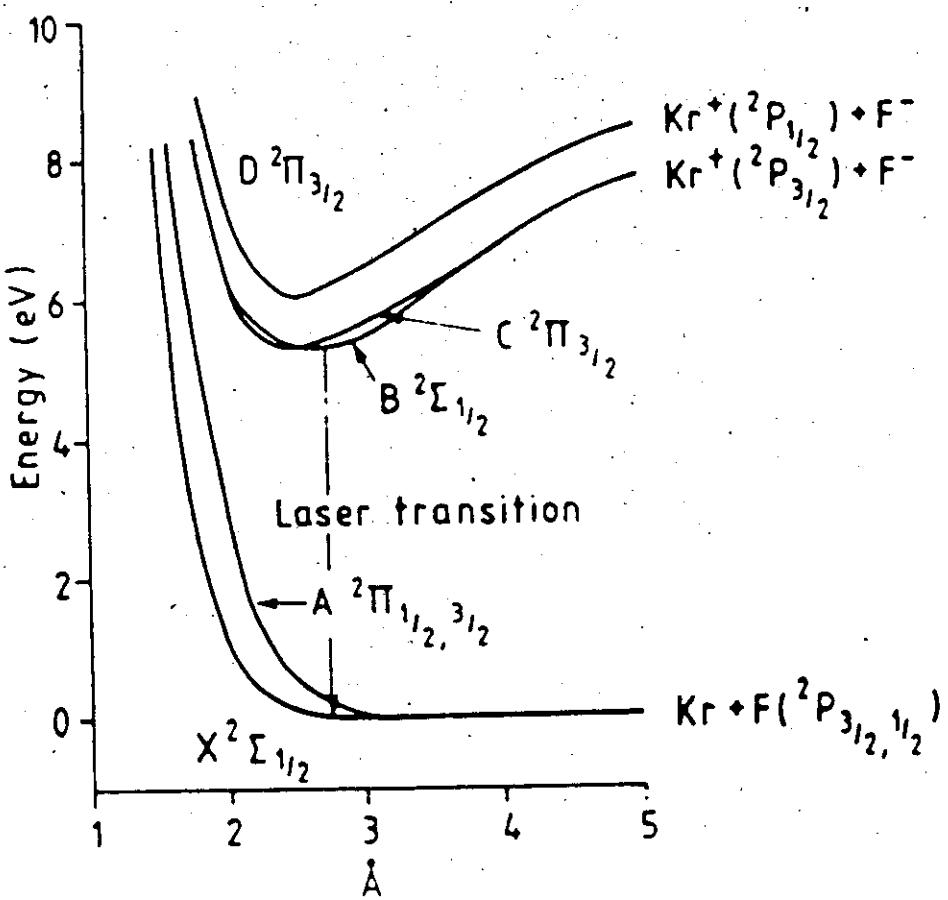
Most intense UV light sources, only pulsed operation

Excimer: excited di-or triatomic complexes, commonly rare gas halides

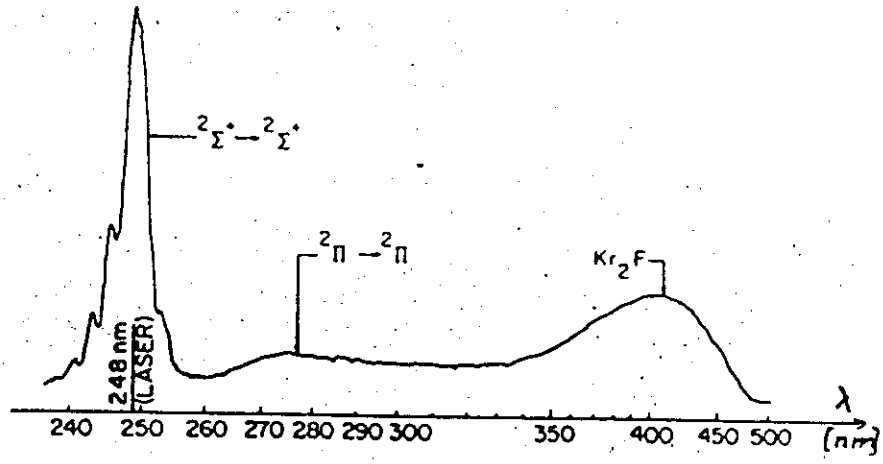
Energy level diagram

Laser transitions between bound excited electronic state and repulsive electronic ground state

Example: KrF

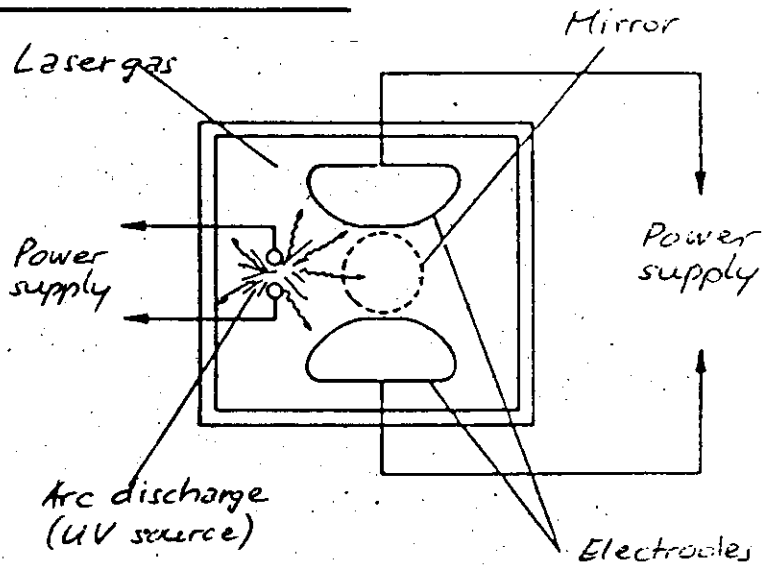


Fluorescence spectrum for p = 3.5 bar

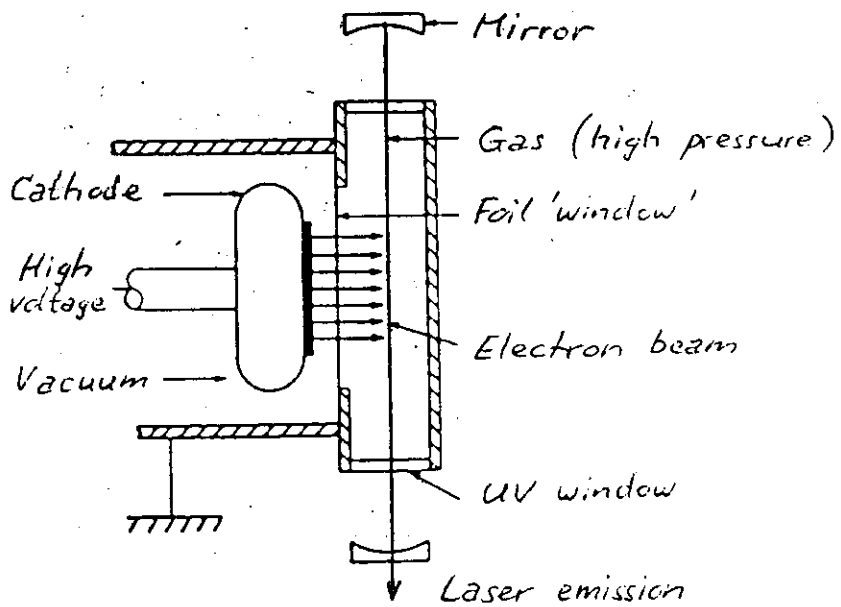


Construction of excimer lasers

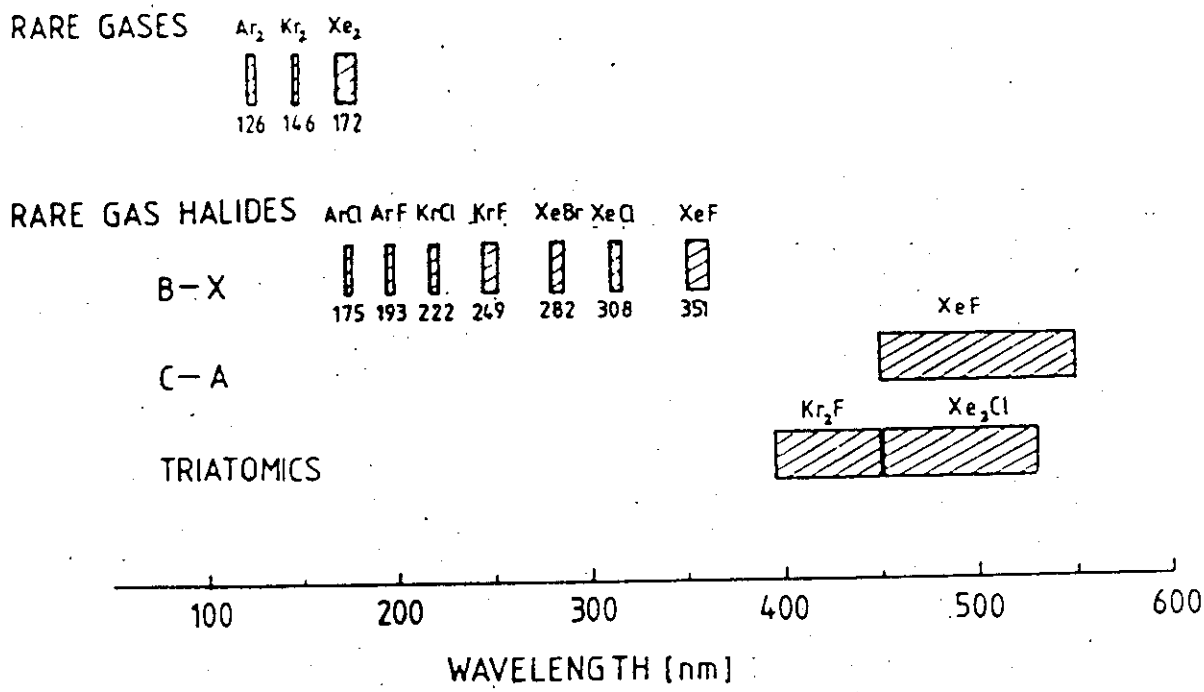
High-pressure transverse gas discharge



Electron-beam pumped



Emission wavelengths of rare gas and rare-gas halide excimer lasers

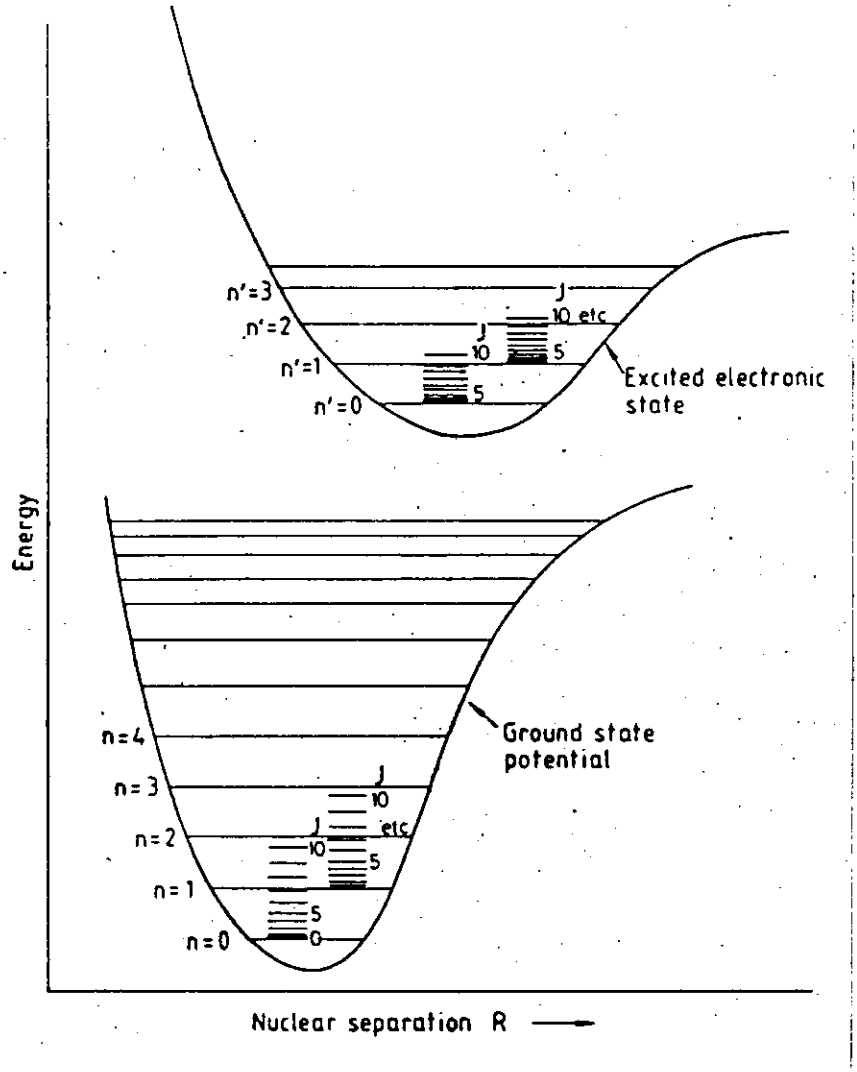


Typical data of commercial excimer lasers

Parameter \ Laser Medium		ArF	KrF	XeCl	XeF
Wavelength	[nm]	193	249	308	351
Pulse energy (at 1 Hz)	[mJ]	500	1000	500	500
Pulse duration	[ns]	14	15	13	14
Peak power (at 1 Hz)	[MW]	10	15	9	6
Repetition rate	[Hz]	≤ 80	≤ 100	≤ 150	≤ 100
Average power	[W]	10	20	10	6

Molecular Gas Lasers

Energy levels of a molecule and possible laser transitions



Different Types according to laser transitions:

i) Vibronic laser transitions between vibrational levels belonging to different electronic states.
Emmission: UV to visible
Example: N_2 Laser ($\lambda = 337$ nm)

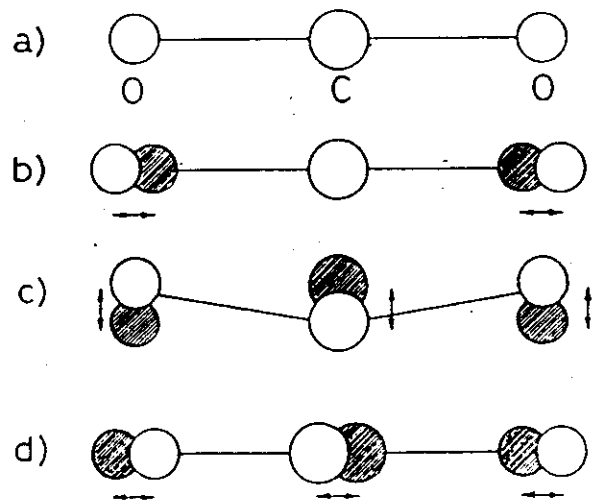
ii) Vibrational-rotational laser transitions between different vibrational and rotational levels of the electronic ground state.
Emission: mid IR to FIR (5 to 350 µm)
Examples: CO_2 Laser (λ = 9 to 11 µm)
CO Laser (λ = 5 to 6 µm)

iii) Rotational laser transitions between different rotational levels within a vibrational state of the electronic ground state.
Emission: FIR (25 µm to 1 mm)
Example: CH_3F-Laser (λ = 496 µm)

Carbon dioxide (CO_2)-Laser

- Widely used molecular gas laser
- Line-tunable emission in mid-IR
- High power and efficiency

Fundamental modes of vibration for a CO_2 molecule

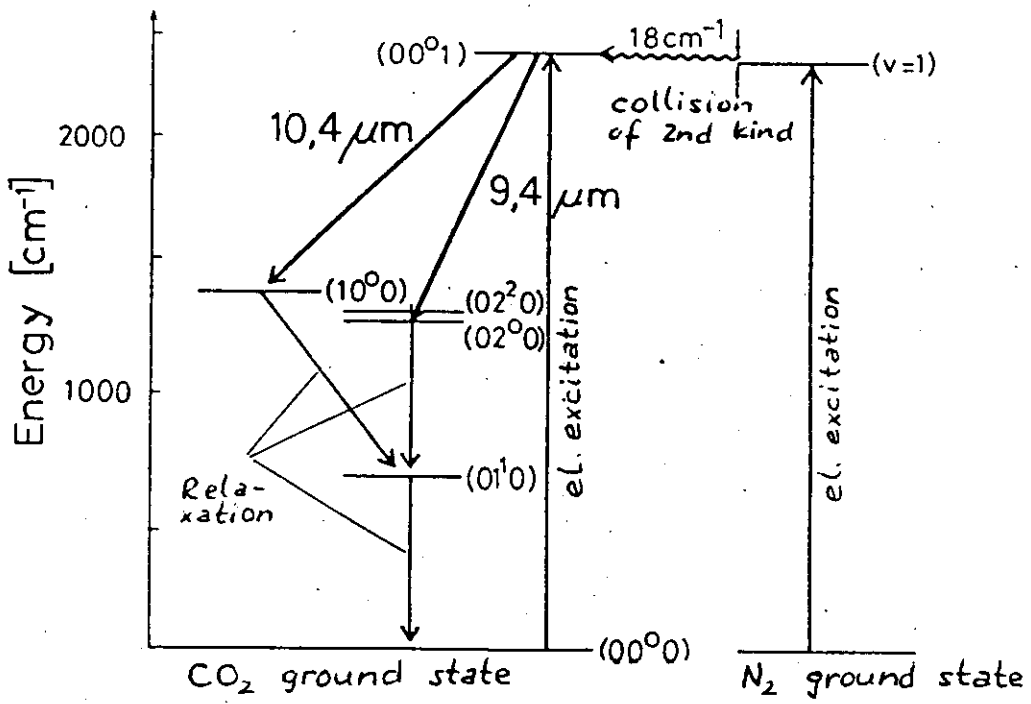


a) symmetric stretching mode υ_1 (n_1, 0°, 0)
b) bending mode υ_2 (0, n_2^l, 0)
c) asymmetric stretching υ_3 (0, 0°, n_3)

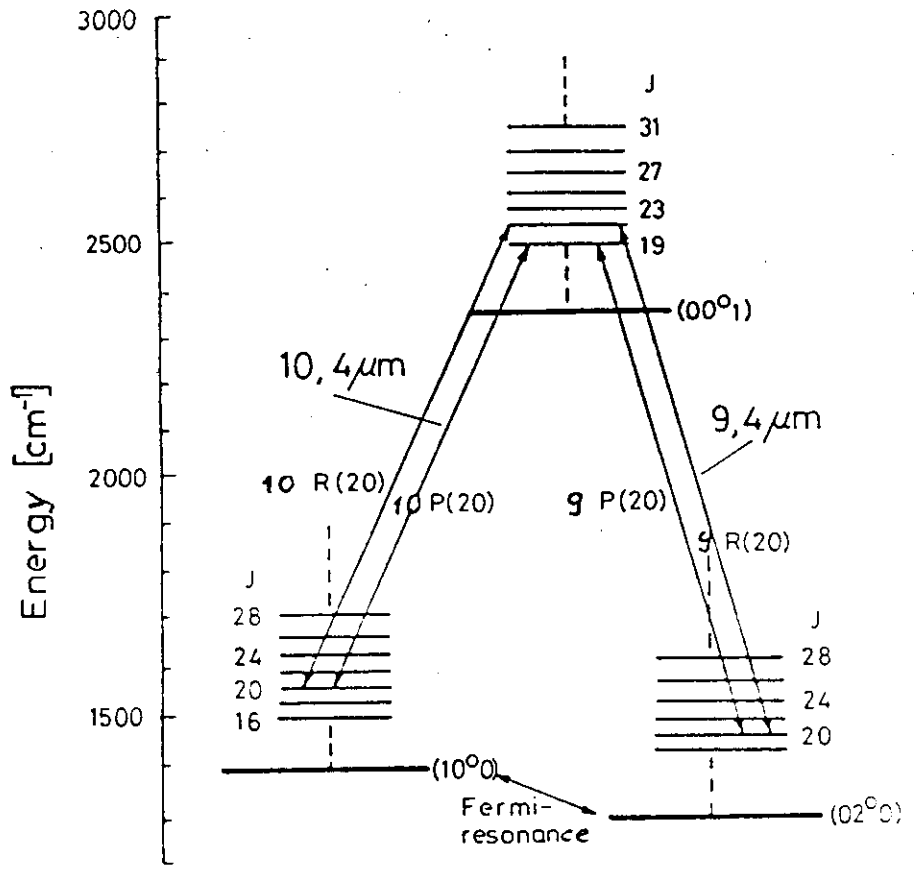
$$E_{vib} = (n_1 + 1/2)\, h\upsilon_1 + (n_2 + 1)\, h\upsilon_2 + (n_3 + 1/2)\, h\upsilon_3$$

Energy level diagram

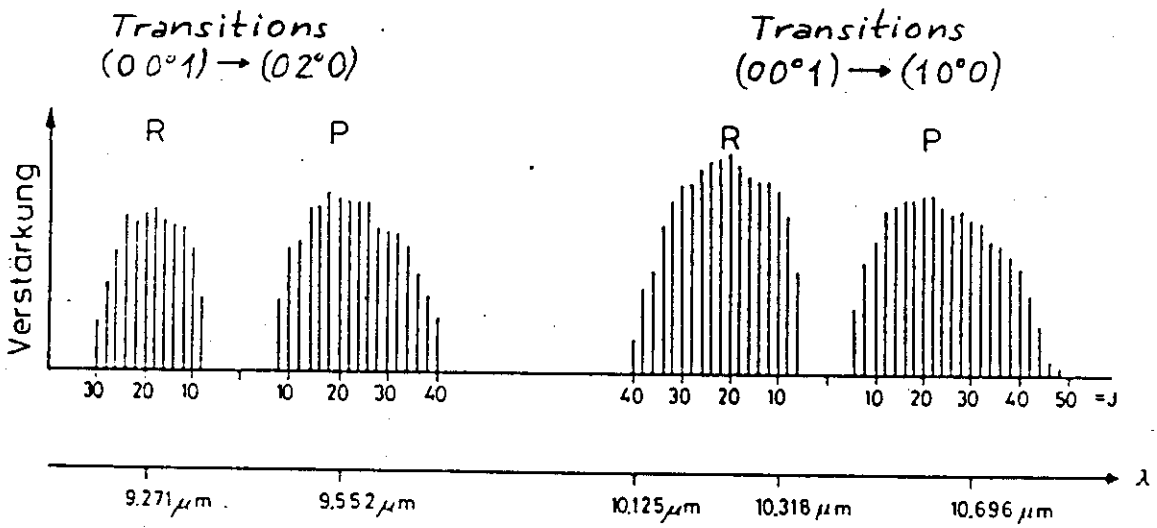
Vibrational - rotational laser transitions within the electronic ground state of the CO_2 molecule



Vibrational - rotational laser transitions



Emission spectrum of CO_2 laser:
grating tunable on ca. 80 transitions, e.g. 10 P(20), 9R(16), etc.



CO_2 - laser constructions

Most types are gas-discharge lasers:

- Lasers with slow axial gas flow
- Sealed-off lasers
- Waveguide lasers
- Lasers with fast axial or transverse flow
- Transversely Excited Atmospheric Pressure (TEA) Laser
- Continuously tunable high pressure lasers
- Gasdynamic lasers

Operation characteristics

- Gas pressure	:	~ mbar	(longitudinal discharge)
-		~ 100 mbar	(waveguide)
		> 1bar	(TEA)
- Gas mixture	:	CO_2: N_2: He ~ 1:1:8	
- Gas discharge	:	dc, rf, pulsed, TEA	
- Laser power	:	W to > 20 kW cw	
		kW to TW pulsed	
- Total efficieny	:	$\eta \gtrsim 10$ % !	

Typical data of CO_2 laser types

Laser type	Excitation	Operation	Gain	Power	Pulse parameter			
					Energy	Peak power	Pulse duration	Repetition rate
Slow axial gas flow	dc discharge	cw	≈ 5%/cm	≤ 80W/m				
	pulsed disch.	pulsed			1J/ℓ	kW/m	>, µs	≤ 100 Hz
	Q-switched	pulsed				10 kW/m	100ns/µs	≤ 1 kHz / ≤ 100kHz
sealed-off	discharge, rf	cw		≤ 60W/m				
waveguide	discharge, rf	cw	~ 8.5%/cm	~ 0.2W/cm				
fast gas flow	discharge	cw	≤ 6%/cm	> 1kW/m				
TEA	discharge with UV preioniz.	pulsed			>5J/ℓ	MW-GW	100ns main pulse	≤ 1 Hz sealed ≤ kHz gas flow
	discharge with e-beam preioniz	pulsed			50J/ℓ		> µs	
Gasdynamic	adiabatic expansion	cw pulsed		≤ 100kW	≈ 10J	≈ kW	≈ ms	

Applications of Gas Lasers

HeNe Laser	- Alignment - Metrology - Bar Code scanner - Interferometry and optical inspection - Holography - Video disk memories - Medicine / Cosmetics
Copper- and Gold- Vapor Laser	- Pump laser for dye lasers - High-speed photography - Resistor trimming - Medicine (photodynamic therapy)
Ion Lasers	- Pump laser for cw dye lasers and some tunable solid state lasers - Laser printers - Holography - Medicine (dermatology, surgery, ophthalmology) - Laser entertainment
Excimer Lasers	- Pump laser for pulsed dye lasers - Micromachining (e.g. electronic printed circuits) - strong UV source (e.g. for photochemistry) - Medicine (e.g. radial keratomy of cornea)
CO_2 - Lasers	- Material processing of all kinds (cutting, welding, drilling, marking, hardening) - Resistor trimming - Analytical applications - Laser surgery