INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION

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COLLEGE ON ATOMIC AND MOLECULAR PHYSICS: PHOTON ASSISTED COLLISIONS IN ATOMS AND MOLECULES

(30 January - 24 February 1989)

Lecture 1 - "GRAMMAR" OF RADIATION-MATTER INTERACTION

Lecture 2 - TECHNIQUES FOR HIGH RES. (SUBDOPPLER) SPECTROSCOPY

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MASSIMO INGUSCIO - HIGH RESOLUTION SPECTROSCOPY

LECTURE n. 1
"GRAMMAR" OF RADIATION-MATTER INTERACTION

a) EINSTEIN COEFF.; LINEAR - NONLINEAR SPECTR.

b) LINESHAPES; HOMOGENEOUS BROADENING (NATURAL, COLLISIONAL, SATURATION); INHOMOGENEOUS BROAD. (DOPPLER EFFECT) VOIGT CONVOLUTION

c) SPECTRAL REGIONS WHERE DOPPLER BROAD. NEGLIGIBLE: EXPERIMENTAL COLLISIONALLY BROADENED AND SHIFTED LINESHAPES.

a) INTRODUCTORY "GRAMMAR"

With spectroscopy we introduce radiation and its interaction with matter.

It is at the basis of modern quantum theory (Understanding of discrete spectra)

Well known from university courses the spectrum of the atom of hydrogen (Fig 1.1) for the interpretation of which it was necessary to assume discrete energy levels:

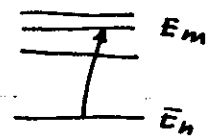
$$E_n = \frac{2\pi^2 e^4 m}{h^2}\frac{Z^2}{n^2} = R\frac{Z^2}{n^2}$$

e (electron charge) $= 1.60217733(49)\ 10^{-19}$ Coul.
m (" mass) $= 9.1093897(54)\ 10^{-31}$ Kg
h (Plank constant) $= 6.6260755(40)\ 10^{-34}$ J s

R (Rydberg constant) $= 10973731.534\ m^{-1}$

Line frequencies:

$$\nu_{n,m} = \frac{E_m - E_n}{h}$$



n=1 Lyman UV
n=2 Balmer visible
n=3 Paschen infrared
...

RYDBERG
BOHR

$$\frac{1}{\lambda} = R\left[\frac{1}{m^2} - \frac{1}{n^2}\right]$$

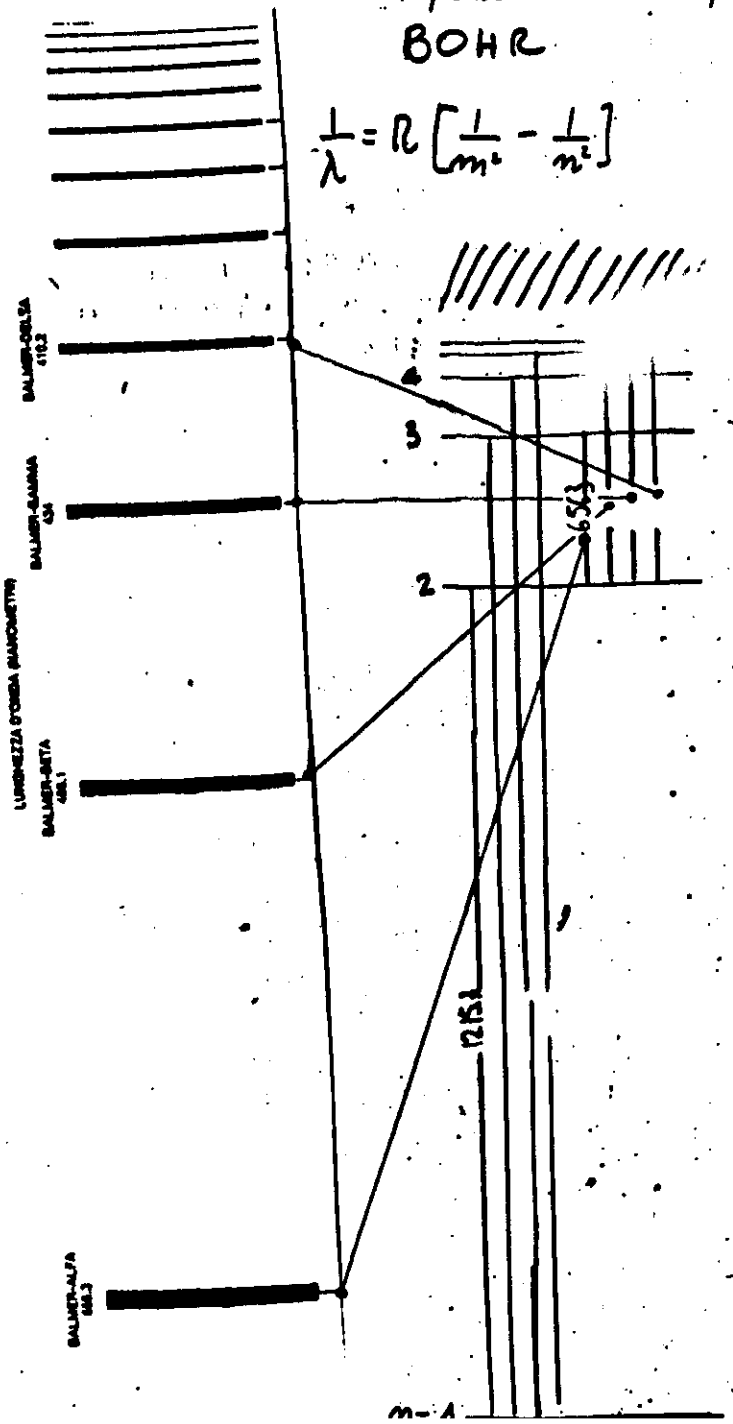
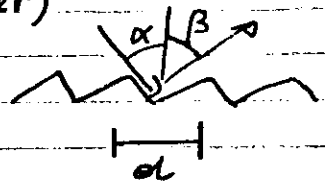


Fig. 1.1

Emission spectrum observed from a discharge by means of a grating spectrometer (The collimated parallel light is sent to a reflection grating consisting of many straight grooves "ruled" onto an optically smooth substrate – plus highly reflecting layer)



N illuminated grooves

Constructive interference for

$$d(\sin\alpha \pm \sin\beta) = m\lambda$$

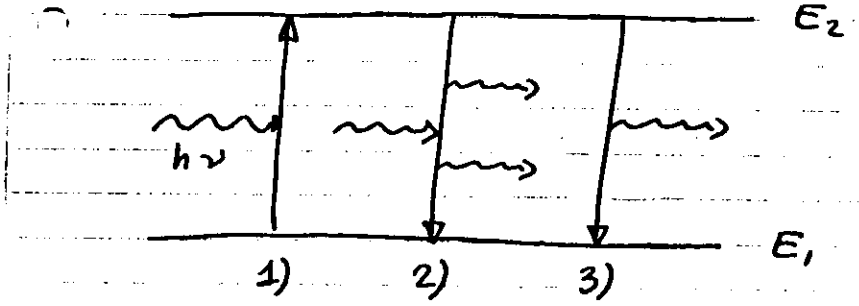
(dispersion at different m orders) ⇒

$$\frac{\lambda}{\Delta\lambda} = \frac{\nu}{\Delta\nu} = \frac{Nd(\sin\alpha \pm \sin\beta)}{\lambda} = \text{Res. Power} = mN$$

Typical resolving power $10^4 \sim 10^5$ ⇒

in the visible $\Delta\lambda \gtrsim 10^{-1}$ Å ; $\Delta\nu \gtrsim 10$ GHz

Interaction radiation-matter not only described by spontaneous emission but, more completely, by: 1) Absorption 2) Induced emission 3) Spontaneous emission.



The probabilities per second of the three events:

1) $\frac{d}{dt} P_{12} = B_{12}\, \rho(\nu)$ radiation en. density $\rho(\nu)$

2) $\frac{d}{dt} P_{21} = B_{21}\, \rho(\nu)$ "

3) $\frac{d}{dt} P_{21}^{spont} = A_{21}$ no radiation

$$\Downarrow$$

$$B_{12} = \frac{g_2}{g_1} B_{21} \; ; \; A_{21} = \frac{8\pi h \nu^3}{c^3} B_{21}$$

dipole approximation : $A \propto \nu^3 d^2$

el. dip. $(d_e)^2 \simeq (e a_0)^2$

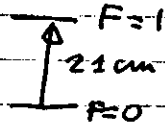
magn. dip. $(d_m)^2 \simeq (\mu_0)^2$

$$(d_e)^2 \sim 10^5 (d_m)^2$$

In the visible, for an allowed el. dip. transition $A \sim 10^8\ sec^{-1} \rightarrow \tau = \frac{1}{A} \sim 10^{-8}$ sec.

Dependence on ν^3 → much longer lifetimes in the microwaves or radio frequency

For instance H ground state



magnetic dipole, gigahertz region

$\tau = \frac{1}{A} \sim 10^7$ years

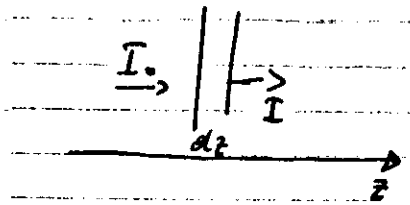
(Emission observable only from very low density interstellar H clouds).

Stimulated transitions earlier in the microwaves; in the visible only after the advent of lasers (enough $\rho(\nu)$)

LINEAR AND NONLINEAR ABSORPTION

Optically thin layer the infinitesimal absorption dI/dz is proportional to the incident intensity I

$$dI = -\alpha I\, dz$$

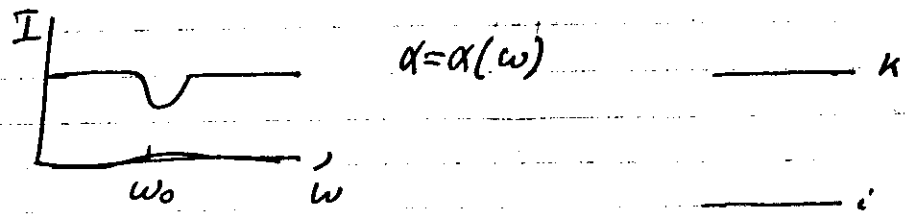


$$\Downarrow$$

$$I(z) = I_0\, e^{-\alpha z}$$

α absorption coefficient (proportional to the imaginary part of the complex

index of refraction)



Total absorption $\int \alpha_{ik}(\omega)\, d\omega = \left(\frac{\hbar \omega_{ik}}{c}\right)\left(N_i - N_k \frac{g_i}{g_k}\right) B_{ik}$

definition of absorption cross section σ_{ik}

$$\alpha_{ik} = \sigma_{ik}\left(N_i - N_k \frac{g_i}{g_k}\right);$$

$$\int \sigma_{ik}\, d\nu = \left(h\nu_{ik}/c\right) B_{ik} = \left(\lambda^2/8\pi\right) A_{ik}$$

We have $I(z) = I_0 e^{-\alpha z} = I_0 e^{-\sigma_{ik}\left[N_i - \left(\frac{g_i}{g_k}\right) N_k\right] z}$

LINEAR ABSORPTION (As long as the population densities N_i and N_k of the two levels E_i and E_k are not noticeably altered by the interaction with the radiation field (weak signal approximation) one can regard them as constant.

At larger intensities I, N_i decreases, N_k increases
i.e. $N_i = N_i(I)$; $N_k = N_k(I)$
dI is no longer proportional to I
(NONLINEAR ABSORPTION)

Simple two non degenerate levels

$g_2 = g_1 = 1$ $\quad N = N_1 + N_2 = \text{constant}$

$B_{12} = B_{21} = B$ $\quad \Delta N = N_1 - N_2$

We also allow additional collisional induced transitions (non radiative) coeff.: C_{12} and C_{21}

Evolution of populations

$$\frac{dN_2}{dt} = B\rho(\omega)\left[N_2 - N_1\right] + \underbrace{\left(A_{21} + C_{21}\right)}_{R_2} N_2 - \underbrace{C_{12}}_{R_1} N_1$$

under stationary conditions

$$\frac{dN_1}{dt} = -\frac{dN_2}{dt} = 0 \quad \text{hence:}$$

$$\Delta N = \frac{\Delta N_0}{1 + 2B\rho(\omega)/(R_1 + R_2)} = \frac{\Delta N_0}{1 + S}$$

where $\Delta N_0 = N_0 (R_2 - R_1)/(R_2 + R_1)$ is the population difference for $\rho = 0$

The saturation parameter

$$S = \frac{2B\rho(\omega)}{R_1 + R_2} = \frac{B\rho(\omega)}{R}$$

- represents the ratio of the induced transition probability to the mean relaxation probability $\bar{R} = (R_1+R_2)/2$

If the only relaxation process is spontaneous emission ($R_1=0$, $R_2=A$), then the saturation parameter S yelds the ratio of induced to spontaneous transition rates

$S=1$ means ΔN drops to 1/2 of its unsaturated value ΔN_0

With $I(\omega) = c \cdot g(\omega)$

$$\Delta N = \frac{\Delta N_0}{1+\frac{B\,I(\omega)}{c\cdot\bar{R}}} = \frac{\Delta N_0}{1+I/I_S}$$

Saturation intensity $I_S = c\cdot\frac{\bar{R}}{B}$ stands for that incident intensity which decreases ΔN to $\Delta N_0/2$

Absorption

$$\alpha = \frac{\alpha_0}{1+S} = \frac{\alpha_0}{1+I/I_S}$$

- i.e. in a pure two-level system $\alpha \to 0$ for $I \to \infty$ – Easier to saturate transitions with high B and low R values.

Note that this is just a very elementary introduction, for instance the system should be generalized by allowing additional relaxation paths...

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b) LINESHAPES

E_2 ——— $\Delta E = E_2 - E_1 = h\nu_0$

E_1 ——— But the energy of the states is not exactly defined (because of external perturbations or of indeterminination principle...), hence absorbed or emitted radiation is distributed around ν_0

$I = I(\nu)$ lineshape.

NATURAL BROADENING

Spontaneous decay of excited levels. Coefficient A is independent from time, hence we have an exponential decay of the emitted intensity with a time constant

$$\tau = \frac{1}{A}$$

- The frequency distribution can be computed by means of the Fourier transform of an exponential

- decaying wave

$$I(\nu) = \frac{\Gamma/2\pi}{(\nu-\nu_0)^2 + \left(\frac{\Gamma}{2}\right)^2} \quad \text{LORENTZIAN}$$

with a width $\Gamma = \Gamma_{NAT} = 1/2\pi\tau = \frac{A}{2\pi} = 2\gamma$

- FROM INDETERMINATION PRINCIPLE $\Delta E \cdot \Delta t = h/2\pi$

$\Delta\nu = \frac{\Delta E}{h} = 1/2\pi\tau$

(All this for an excited level decaying only and directly to the ground state)

In general $2\pi\Gamma = \frac{1}{\tau_1} + \frac{1}{\tau_2}$

- LORENTZIAN properties:
very smooth decaying to zero $\propto (\nu-\nu_0)^{-2}$, not negligible absorption even at large distances from the line center.

- Known the lineshape it is possible to compute the cross section of absorption, and in particular its value at center

$$\sigma(\nu_0) = \frac{\lambda^2}{4\pi^2} g_2 \frac{A}{\Gamma} \sim \frac{\lambda^2}{2\pi} g_2$$

i.e. absorption or emission at the center of a naturally broadened line is independent [illegible] (shown from the above argument):

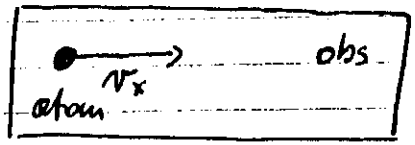
- stronger lines are only larger (note that this is rigously true only for resonance transitions for which $\tau_1^{-1} = 0$ and $\tau_2^{-1} = A$).

NATURAL ONE is an example of homogeneous broadening (broadening identical for each atom of the system and the interaction with a monocromatic radiation beam is the same for all the atoms).

Inhomogeneous lineshape = typical: Doppler effect: each atom has its own lineshape which however is frequency shifted by Doppler effect.

DOPPLER BROADENING

Gas at room temperature $\frac{v}{c} \sim 10^{-6}$ i.e. we can expand in series the relativistic formula and take the first two term



$$\nu = \nu_0 \left[1 + \frac{v_x}{c} - \cancel{\frac{v^2}{2c^2}}\right] \quad (1)$$

$\approx 10^{-12}$ negligible with respect to the natural $\frac{\nu}{\Delta\nu}$ ($10^9 \sim 10^8$)

- Substituting v_x from (1) into the Maxwell velocity distribution, we

obtain

$$I(\nu) = \frac{2}{\Delta\sqrt{\pi}} \exp\left[-4\frac{(\nu-\nu_0)^2}{\Delta^2}\right]$$

When Δ is the width of the Doppler line measured at $\frac{1}{e}$ the maximum.

Width at half maximum (FWHM = Full Width Half Maximum)

$$\underline{\text{FWHM}} = \Delta\nu_D = \Delta\sqrt{\ln 2} = \frac{2\nu_0}{c}\sqrt{2\ln 2\frac{kT}{m}} =$$

$$= \boxed{7.16\ 10^{-7}\nu_0\sqrt{\frac{T}{M}}}$$

T in kelvin, M atomic or molecular mass.

Note that $\Delta\nu/\nu_0$ is independent from the transition frequency and at room temperature is $\sim 2\cdot 10^{-6}$

Comparison with natural width in the visible:

$$\Delta\nu_D \simeq 10^9\ \text{Hz} \simeq 10^2\,\Delta\nu_{NAT}$$

(MASKING EFFECT).

VOIGT PROFILE

Real situation: natural and Doppler both present as independent processes, hence the lineshape must be computed by a convolution; Voigt integral

$$I(\nu-\nu_0;\frac{\Gamma}{\Delta}) = \frac{\Gamma}{4\pi\sqrt{\pi}}\int_0^\infty \frac{\exp[-4(u-\nu_0)^2/\Delta^2]}{(\nu-u)^2+\frac{\Gamma^2}{4}}\,du$$

- only numerical solution.

Comparison Lorentzian – Gaussian in FIG. 2

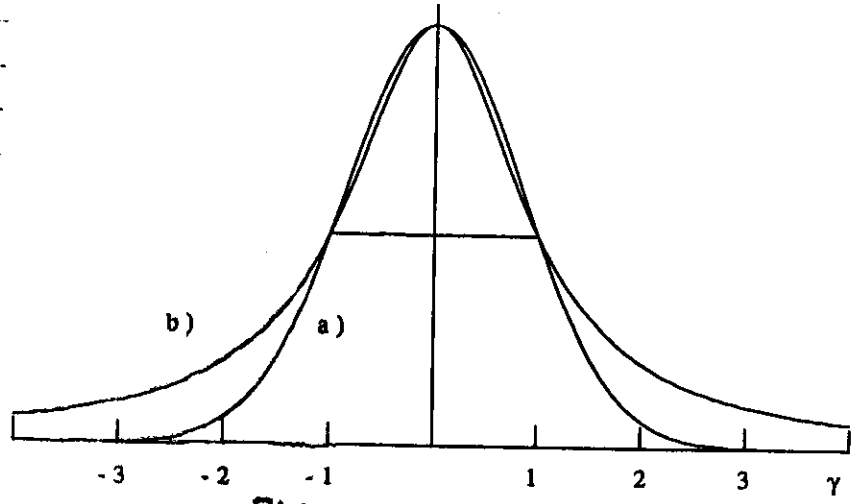


FIG. 2

a) Gaussian; b) Lorentzian same width and height.

Far from the center Lorentzian is predominant; near the center Gaussian is predominant; intermediate region Voigt profile is necessary.

COLLISIONAL (PRESSURE) BROADENING

Time of collision practically instantaneous with respect to radiative time

$$\tau_c \sim \hbar \left(\frac{\sigma}{\pi}\right)^{1/2} / v$$

v relative velocity ; σ cross section $\leq 10^{-15}\,cm^2$

At room temperature $v \sim 10^5\,cm/sec$
and $\tau_c \sim 10^{-12}\,sec$.

Atom then unperturbed until next collision.

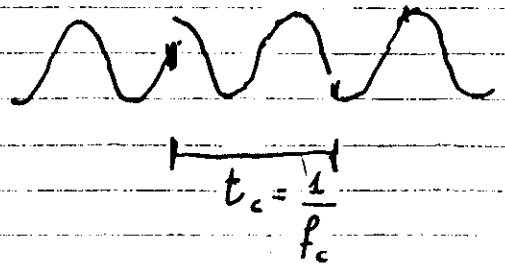
Frequency of collisions: $f_c = \sigma\, \bar{v}_r\, N$

N perturber density ; $\bar{v}_r$ relative mean velocity.

$t_c = \frac{1}{f_c}$ time interval between two consecutive collisions.

For $N \leq 10^{20}/cm^3$ $t_c > \tau_c$ hence collisions are well separated in time ; we can neglect the contribution of multiple simultaneous collisions and all the perturbation effects are proportional (in intensity) to the density of the perturber.
(Under this approximation phenomena are described by impact theories
(treatment of a single collision and then average over velocity distribution

and impact parameters.



Long distance interaction between two atoms or molecules described by means of a potential (attractive):

$$\Delta V_K(r) = C_n^K / r^n$$

constants C_n^K depends on the K state of the perturbed atom and on the perturber while n depends on the type of interaction:

- $n=2$ linear Stark effect and charged perturbers (electrons and ions in a plasma).
- $n=3$ resonant dipole interaction.
- $n=4$ quadratic Stark effect.
- $n=6$ dipole — induced dipole.

Short distance (atomic radius) repulsive forces (we neglect)

— k — i During a collision the instantaneous transition frequency between two states k and i, as a function of r, is given by:

$$h\nu_{ki}(r) = E_2 - E_1 + \Delta V_k(r) - \Delta V_i(r)$$

<u>i.e.</u>
change of phase in the emitted radiation (can be computed if you know the trajectory of the collision).

<u>Roughly</u>: Lineshape given by the Fourier transform of an exponentially decaying wave, loosing phase coherence with a frequency f_c.

Again Lorentzian

$$\Delta\nu_c = \Gamma_N + \frac{\bar{\sigma}\bar{v}N}{\pi} = \Gamma_N + \Gamma_c$$

More sophisticated theories evaluate the effect of collisions with high impact parameter, producing only small phase displacements, which summing produce a <u>shift</u> in the center frequency.

Real part of cross section σ_2 → line broadening
Imaginary part (σ_i) → line shift.

Collisional lineshape, again a Lorentzian

$$\frac{\Gamma_N + \Gamma_c}{(\nu - \nu_0 \pm \Delta\nu_s)^2 + (\Gamma_N + \Gamma_c)^2}$$

$$\Delta\nu_s = \sigma_i \bar{v} N / 2\pi$$

for neutral perturbers always $\sigma_i < \sigma_2$

(Pressure shift smaller than pressure broad)

IF WE MOVE FROM VIS. TO LOWER FREQ, WE HAVE DECREASE OF NATURAL WIDTH, DECREASE OF DOPPLER WIDTH, HENCE WE CAN OBSERVE COLLISIONAL LINESHAPES EVEN AT LOW PRESSURES.

WE GIVE EXAMPLES IN THE FAR INFRARED ($\sim 10^{12}$ Hz) FOR PRESSURE BROADENING AND SHIFT OF POLAR MOLECULES (DIPOLE–DIPOLE INTERACTION DURING THE COLLISION).

FAR INFRARED : 30 μm ÷ 1 mm

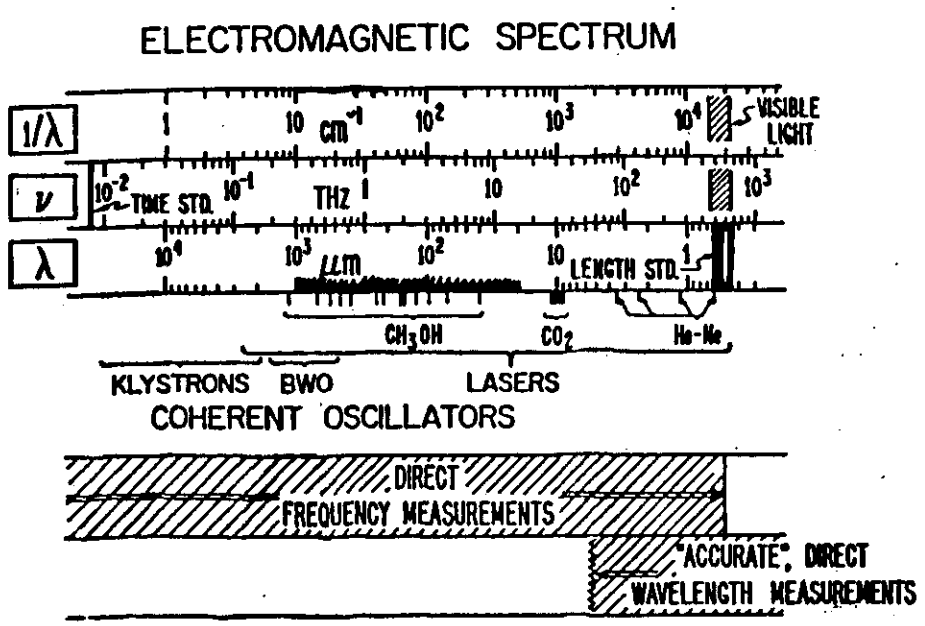
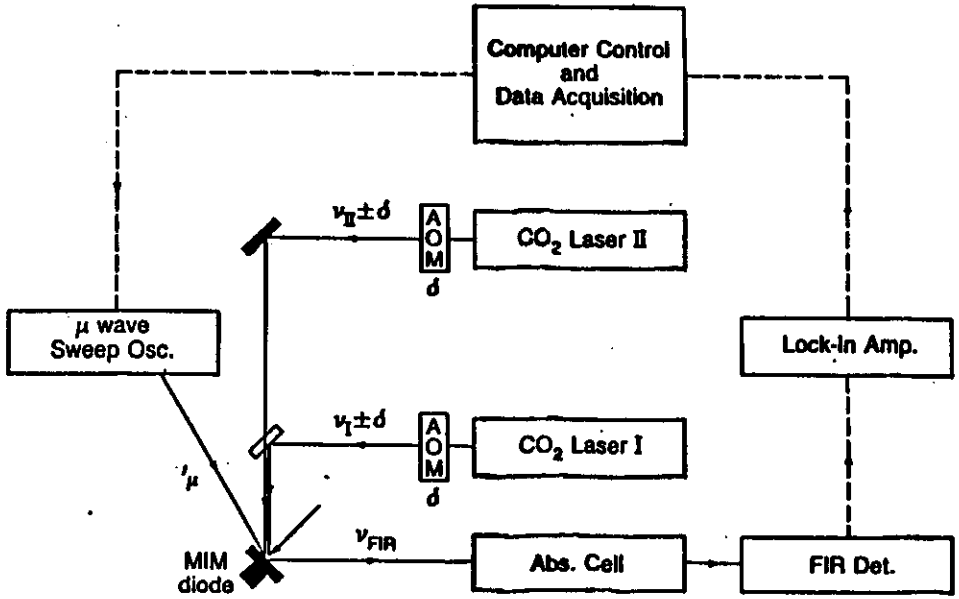


Figure 1. The electromagnetic spectrum showing oscillators, frequency and wavelength standards, and measurement regions. The extension of frequency measurements into the infrared has produced an overlap of the accurate ($< 4 \times 10^{-9}$) wavelength measurement region and the frequency measurement region for the first time. The frequency standard is the zero field hyperfine structure separation in the ground state of ^{133}Cs which is defined to be 9 192 631 770 Hz. The wavelength standard is the transition between the $2p_{10}$ and $5d_5$ levels of ^{86}Kr with the vacuum wavelength of this radiation defined to be 1/1 650 763.73 m.

3rd ORDER GENERATION



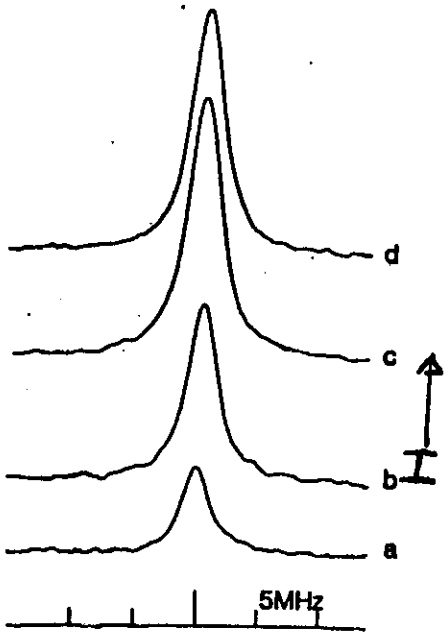
3rd ORDER
TuFIR SPECTROMETER
$\nu_{FIR} = (\nu_I - \nu_{II}) \pm \nu_\mu$

μ WAVE $\pm$ 20 GHz

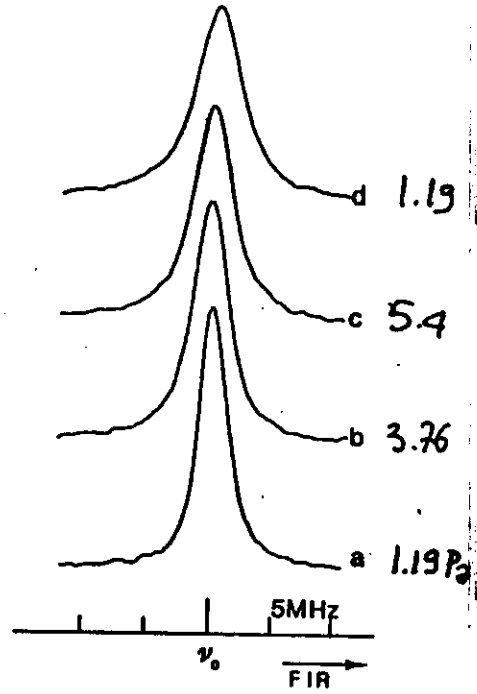
SPECTRAL COVERAGE COMPLETE BY MEANS OF ONLY 150 PAIRS

DOPPLER FREE SIGNAL

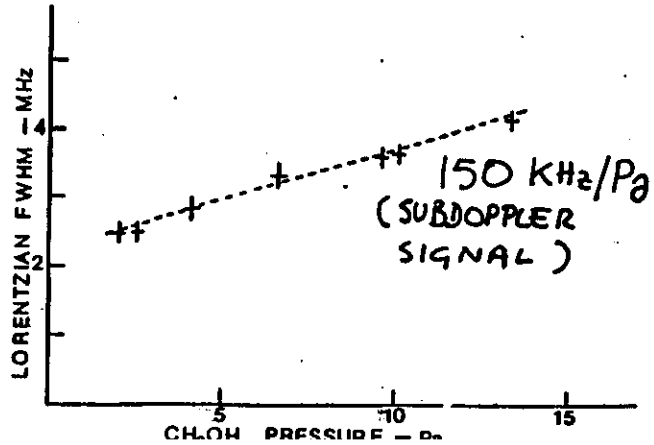
PUMP INTENSITY



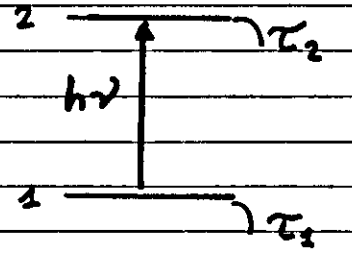
PRESSURE BROADENING



(DOPPLER BROADENED: 226)



SATURATION BROADENING



$$\gamma = 2\pi\left(\frac{1}{\tau_1} + \frac{1}{\tau_2}\right)$$

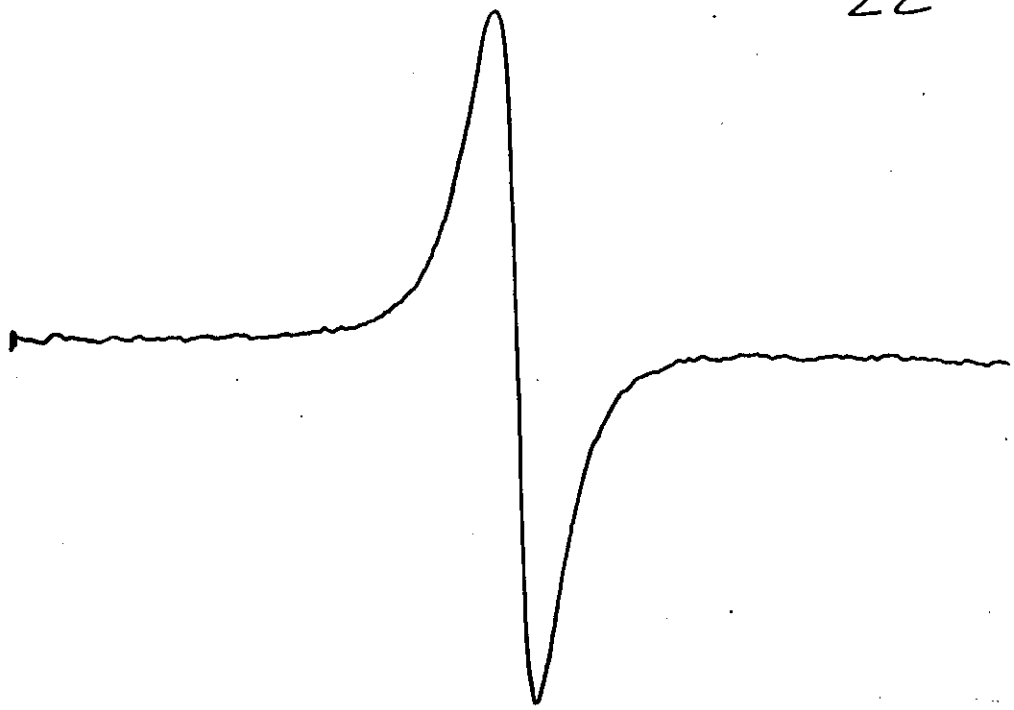
$$\Delta\nu_{hom} = \gamma\sqrt{1 + I/I_S}$$

$$I_S = \frac{\varepsilon_0 c \hbar^2 \gamma A}{2|\mu_{12}|^2 \tau}$$

$$S = I/I_S$$

SAT. INTENSITY

SATURATION PARAMETER

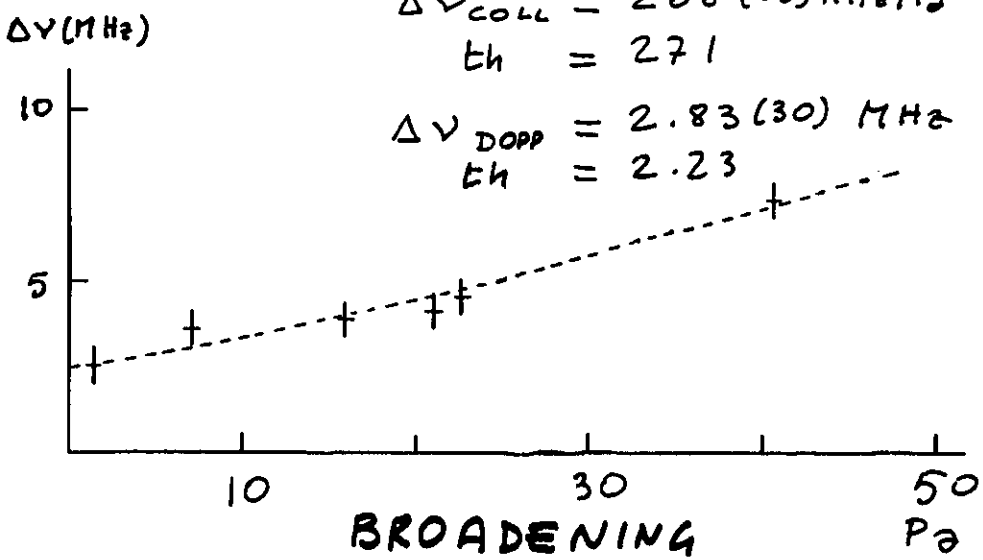


- 155 mTorr
- 400 ms T.C.
- ΔCO_2 = 10R(16) - 10R(38) (^{13}C)
  = 999 465.831 MHz
- ν = 999 416.100 (50) MHz

8. CH_3OH ground state

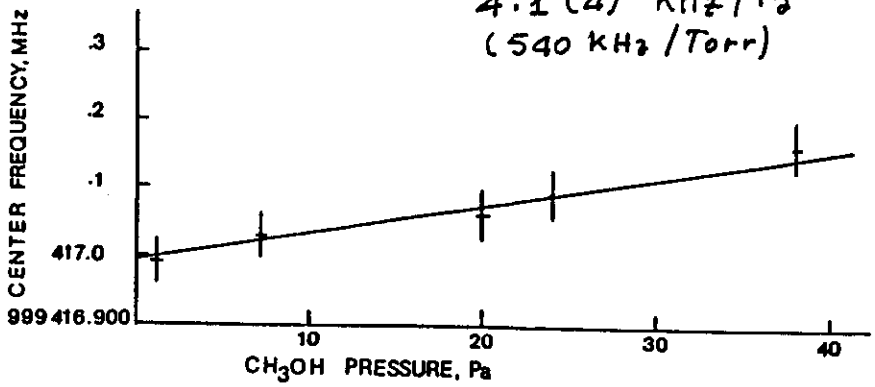
$\Delta\nu_{COLL}$ = 268 (23) KHz/Pa
th = 271

$\Delta\nu_{DOPP}$ = 2.83 (30) MHz
th = 2.23



BROADENING

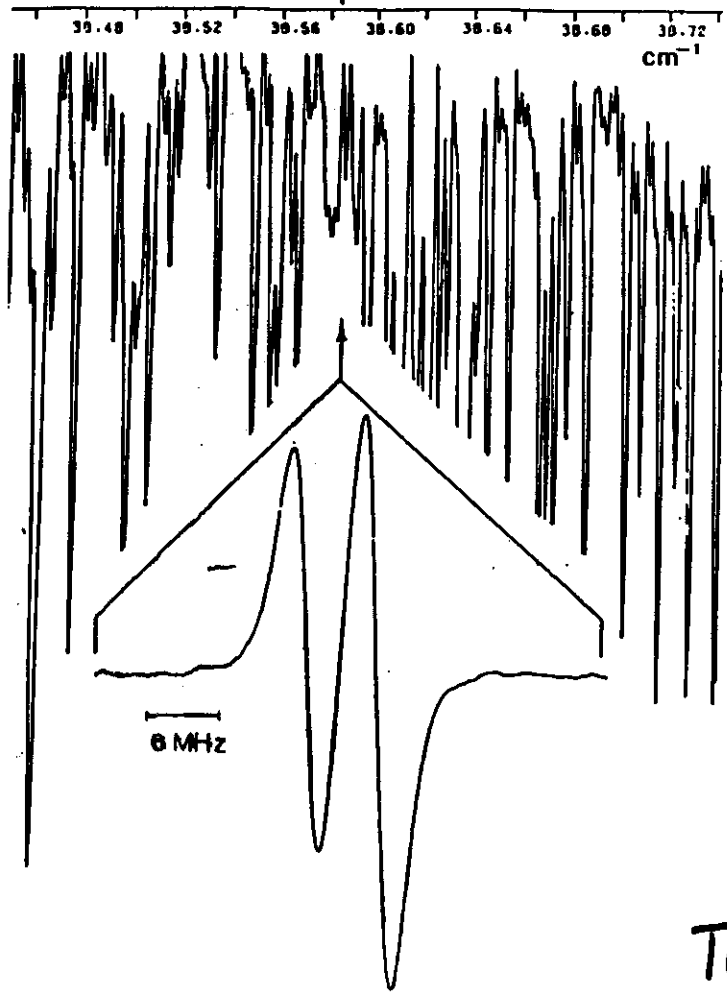
PRESSURE ↕ SHIFT



4.1 (4) KHz/Pa
(540 KHz/Torr)

RESOLUTION CAN BE MASKED BY COLLISIONS

259 μm

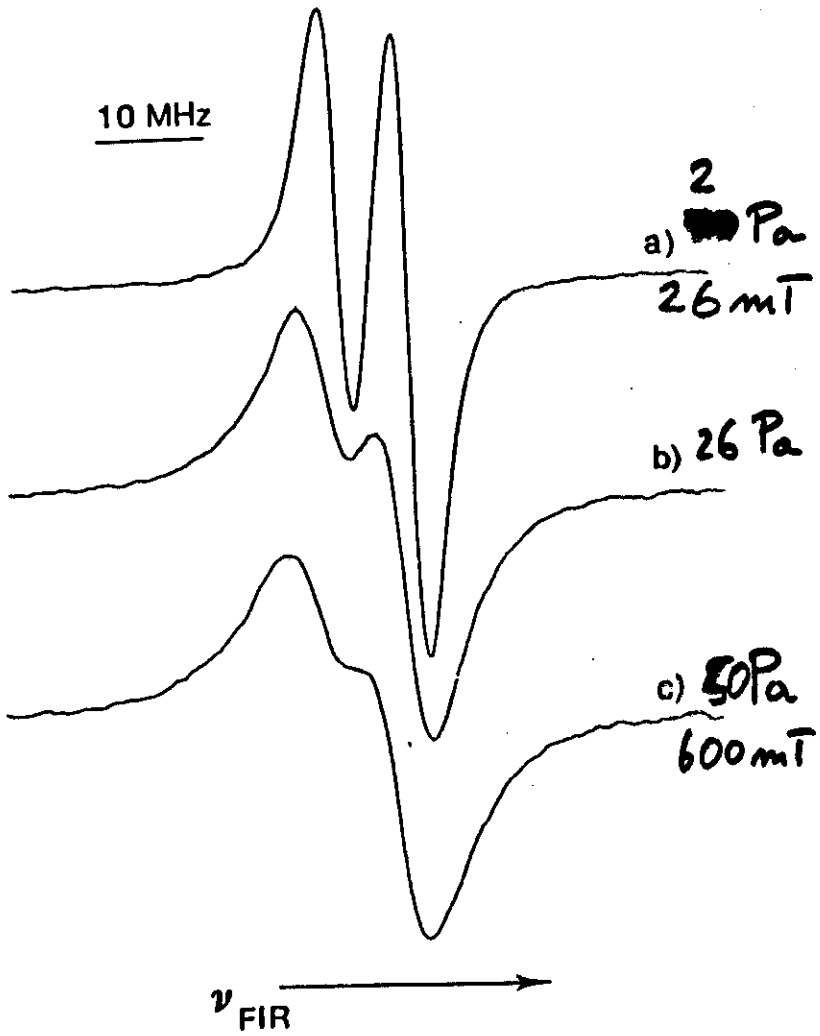


FTS

TuFIR

ZINK, EVENSON, JENNINGS, MORUZZI, INGUSCIO
J. MOL. SPECTROS (1982)

AND MATTER,, in HONOUR OF
A. GOZZINI, PISA SNS 1987



M. INGUSCIO – LECTURE n. 2

TECHNIQUES FOR HIGH RES. (SUBDOPPLER) SPECTROSCOPY

a) ATOMIC BEAMS

b) SATURATION SPECTROSCOPY

c) POLARIZATION SPECTR.

d) TWO-PHOTON

e) APPLICATIONS

HIGH RESOLUTION (SUBDOPPLER)

SPECTROSCOPY NECESSARY FOR:

1) OBSERVATION OF HOMOGENEOUS LINEWIDTHS (LIFETIMES, ATOMIC INTERACTIONS ...)

2) OBSERVATION OF STRUCTURES (SPLITTINGS) OF THE LEVELS (FINE, HYPERFINE, ISOTOPE ...)

A FUNDAMENTAL EXAMPLE (QUANTUM ELECTRODYNAMICS): LAMB SHIFT IN ATOMIC HYDROGEN

$2^2S_{1/2}$ ———) 1058 MHz L.S.

$2^2P_{1/2}$ ———

DOPPLER WIDTH OF BALMER α $\Delta\nu_D \sim 6000$ MHz

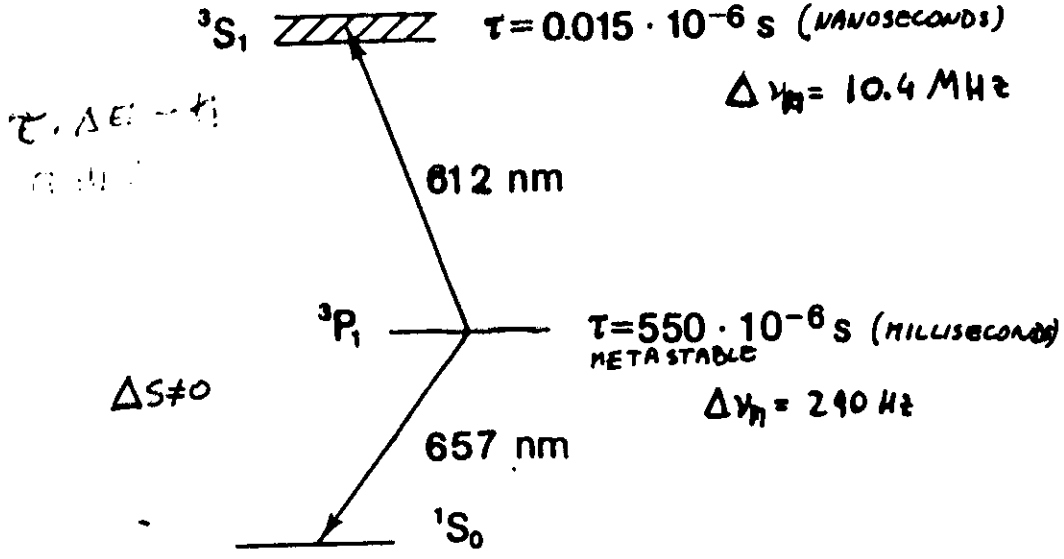
$1^2S_{1/2}$ ———

EARLIER APPROACHES

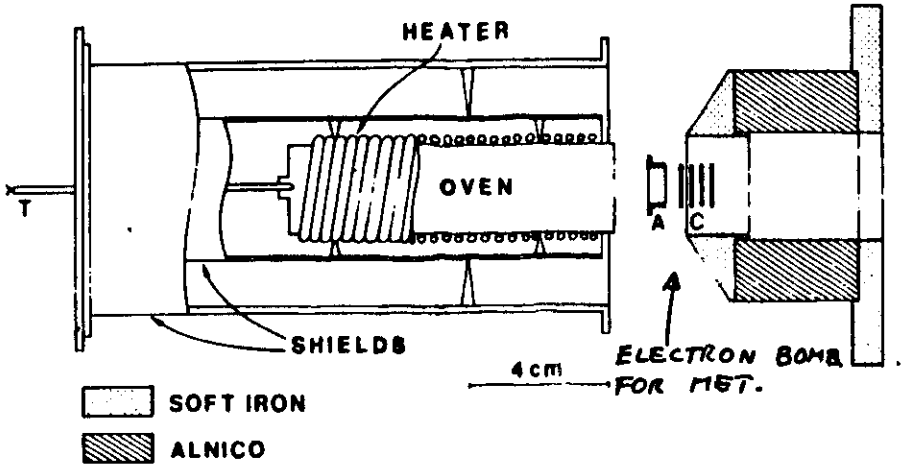
- LOWERING T (NOT VERY EFF. ($\sqrt{T}$) AND LIMITED TO SPECIES WITH ENOUGH DENSITY AT LOW TEMP.)

- ATOMIC COLLIMATED BEAMS + ORTHOGONAL OBSERVATION.

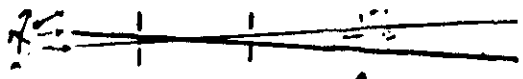
EXAMPLE: OBSERVATION OF THE TRANSITION AT 6122 Å IN AN ATOMIC BEAM OF METASTABLE CALCIUM

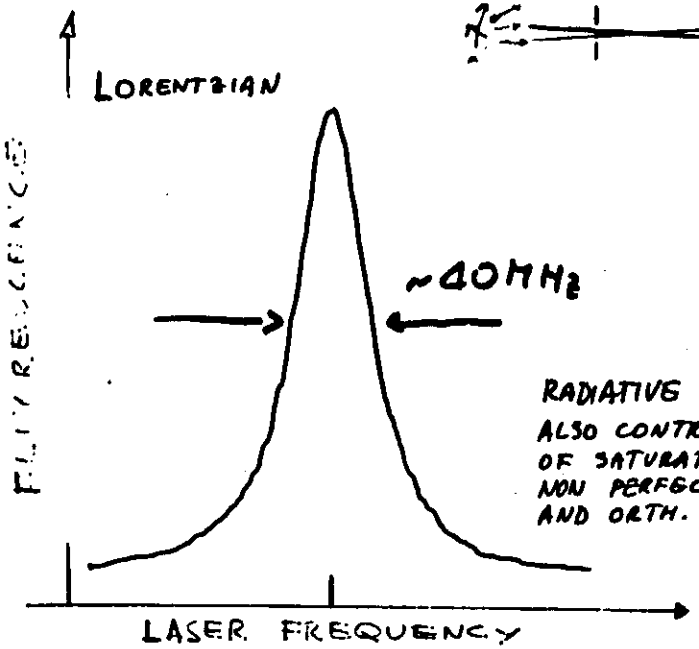


OVEN FOR THE PRODUCTION OF ATOMS (600 °C)



ATOMIC BEAM



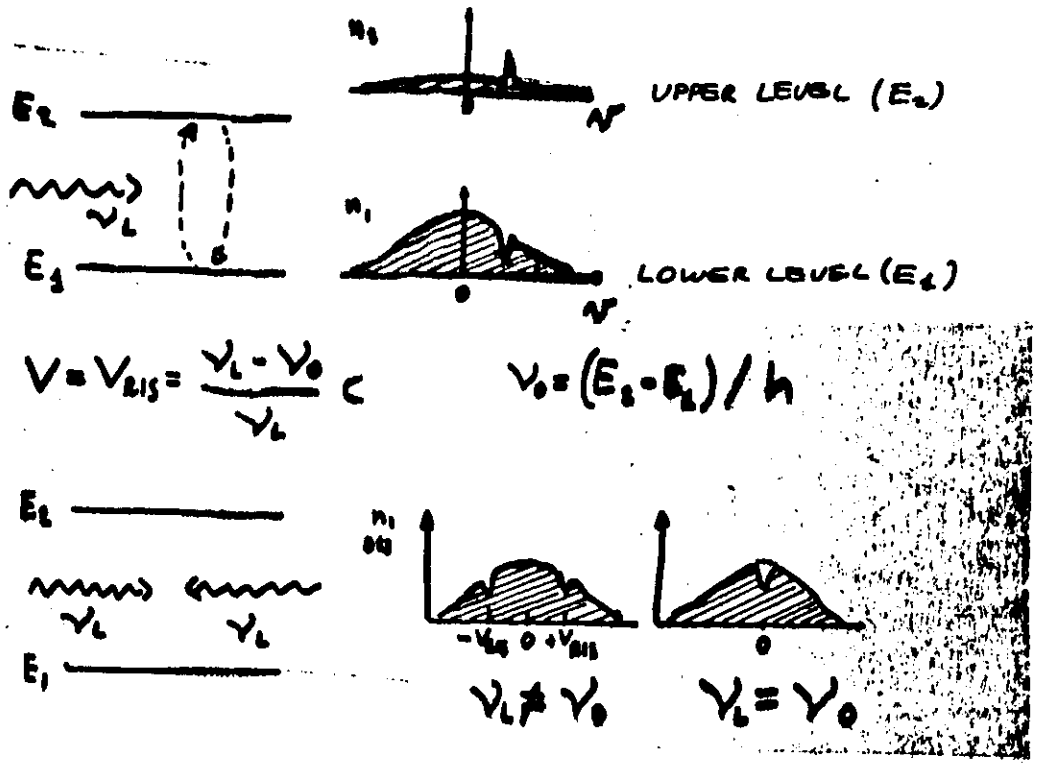


(DOPPLER WIDTH ~ 1500 MHz)

LASER SOURCE
- MONOCROMATIC ($\Delta\nu_{LAS} < \Delta\nu_{DOPPLER}$)
- DIRECTIONAL
- INTENSE (ENOUGH TO SATURATE)

SATURATION SPECTROSCOPY

(WE CHANGE THE EQUILIBRIUM ENERGY DISTR. BETWEEN THE LEVELS, SELECTIVE IN VELOCITY)



COUNTER PROPAGATING BEAMS: AT RESONANCE AT LINE CENTER WE HAVE A "DIP" WITH

2.3.

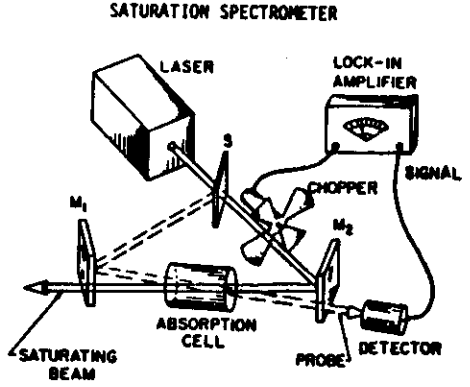


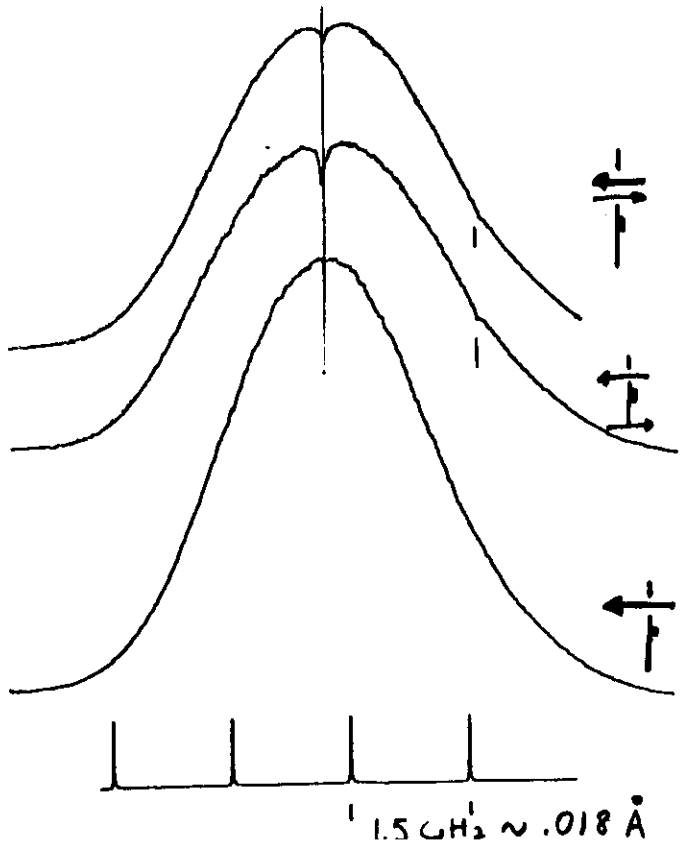
Fig. 1. Apparatus for Doppler-free saturated absorption spectroscopy of a gas sample.

EXPERIMENTAL APPARATUS

EXAMPLE ON A NEON TRANSITION

NeI $1s_5(\ldots - \ldots)2p_7$ . . 5944.5 Å

950 mTorr, 50 mA, I_L = 50 mW



2.4.

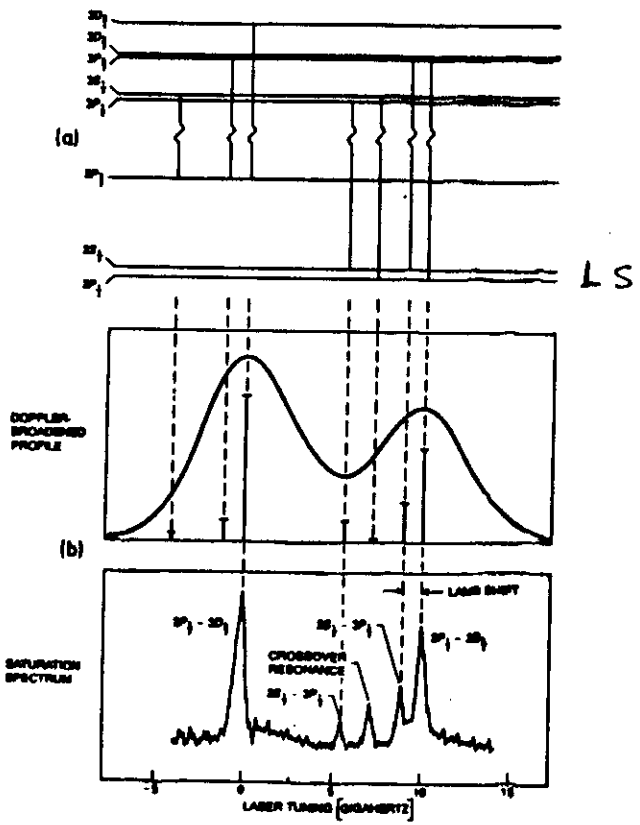


Fig.10.21a,b. Measurement of the Rydberg constant by saturation spectroscopy of the Hydrogen Balmer α transition. (a) Level scheme, (b) Doppler profile and saturation spectrum of the Balmer α line in a hydrogen discharge [10.31a]

SUB DOPPLER RESOLUTION OF HYDROGEN BALMER α, WITH OBSERVATION OF FINE STRUCTURE AND LAMB SHIFT.

SOMETIME THE SENSITIVITY OF SATURATION SPECTR. NOT ENOUGH (DIP CONTRAST)

NEW TECHNIQUES

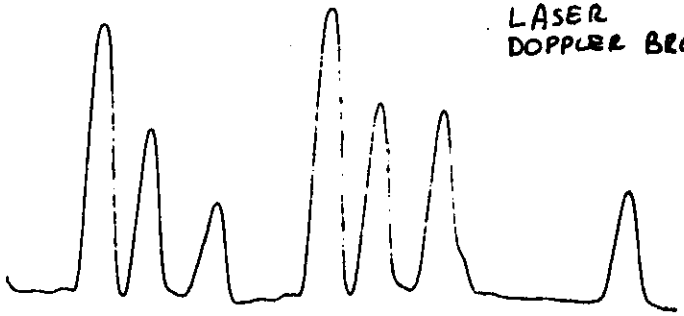
- POLARIZATION SPECTROSCOPY (ILLUSTRATED FOR THE HYPERFINE STRUCTURE OF MOLECULAR IODINE)

- INTERMODULATED SPECTR. (NEXT LECTURE COMBINED WITH OPTOGALVANIC DETECTION).

I_2 SPECTRUM (GOOD FOR λ CALIBRATION) 9

FOURIER TRANSFORM

LASER DOPPLER BROAD.



1939	16232.7893	2.1	36	1971	16238.4971	1.1	32	2003	16242.8937	.7	51	2035	16247.8549	.7	42
1940	16232.9959	.8	32	1972	16238.5946	.8	31	2004	16243.2730	.6	53	2036	16247.4458	1.7	17
1941	16233.0872	.7	33	1973	16238.7126	.8	30	2005	16243.3429	.9	17	2037	16247.6548	.5	44
1942	16233.1332	.4	43	1974	16239.1054	.6	28	2006	16243.3662	.8	30	2038	16247.8851	0.6	17
1943	16233.2791	2.4	15	1975	16239.1984	.6	25	2007	16243.6739	.7	39	2039	16247.9973	.7	30
1944	16233.4513	1.8	20	1976	16239.2976	.5	47	2008	16243.7898	.8	38	2040	16248.2979	.6	63
1945	16233.7256	2.3	45	1977	16239.4886	1.0	16	2009	16243.7776	1.8	21	2041	16248.4641	.6	27
1946	16233.7472	.9	48	1978	16239.6225	.6	63	2010	16244.0880	1.8	26	2042	16248.5208	.5	46
1947	16233.8916	.7	28	1979	16239.6932	.7	31	2011	16244.1068	1.3	46	2043	16248.6767	.8	21
1948	16234.1210	.5	48	1980	16239.7828	.7	27	2012	16244.1982	.7	18	2044	16248.8810	.6	37
1949	16234.4863	.6	31	1981	16240.1895	.6	48	2013	16244.4252	.6	42	2045	16249.1452	.5	33
1950	16234.5702	.6	38	1982	16240.2874	.8	21	2014	16244.4884	1.1	18	2046	16249.3674	.9	26

$\pm .002\ cm^{-1}$

$\pm$ 60 MHz

Fig. 15 Registrazione in fluorescenza stimolata di una regione dello spettro della molecola di I_2 e confronto con le righe tabulate .

DOPPLER + HYPERFINE 10

1.5 comp. J' ...

2.1 comp. J' ...

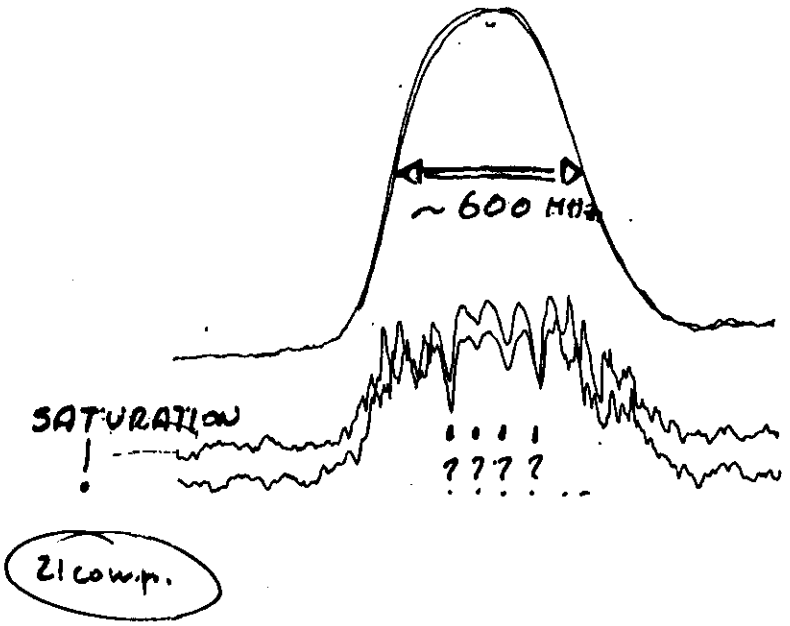


Fig. 22 Struttura iperfina della molecola di Iodio .
Profilo di assorbimento con fascio opposto saturante .

POLARIZATION SPECTR

(SATURATION COMBINED WITH OPTICAL PUMPING).

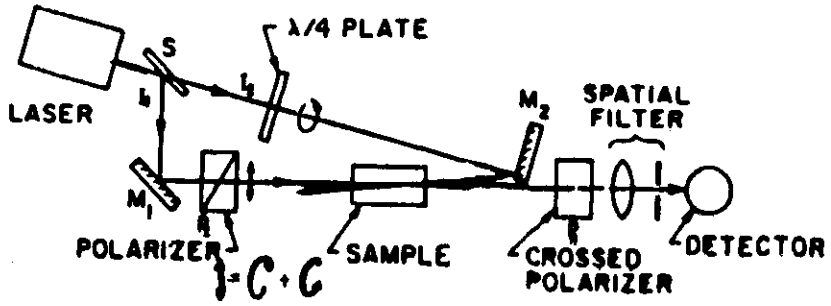
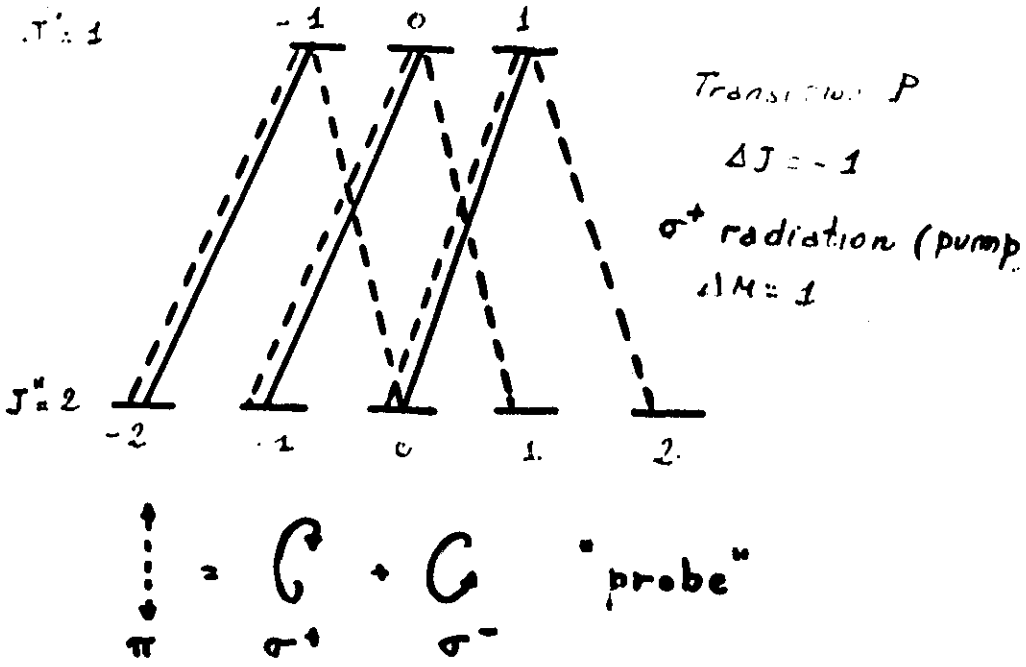


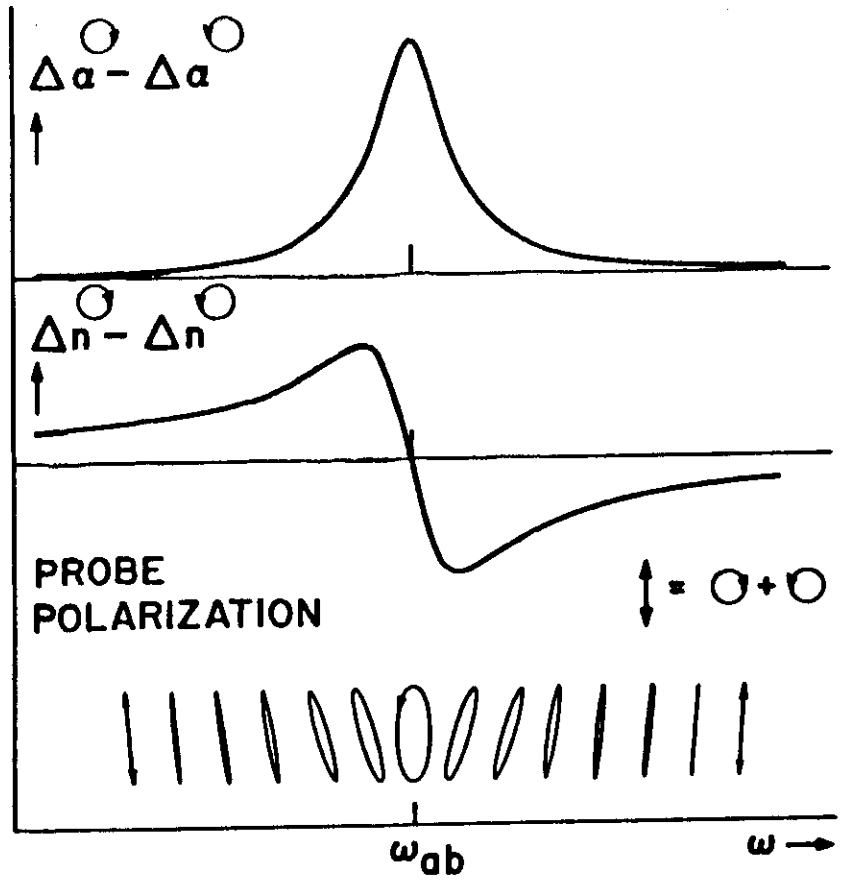
Fig.10.34. Schematic experimental arrangement for polarization spectra



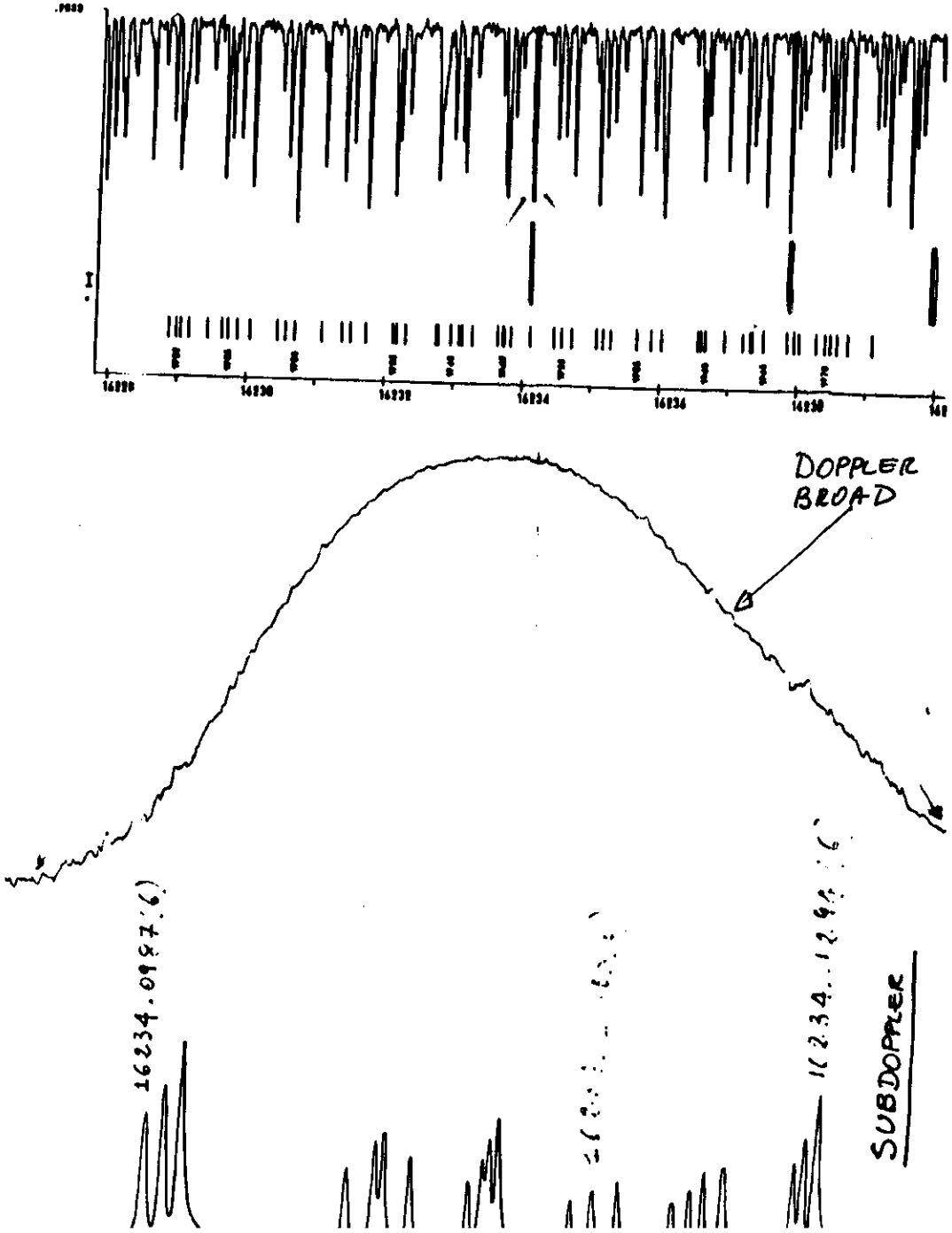
$$I_T = I_0 \left[\frac{1}{2} \left(\Delta\alpha_0 L \right)^2 \right]$$

INDUCED BIREFRINGENCY

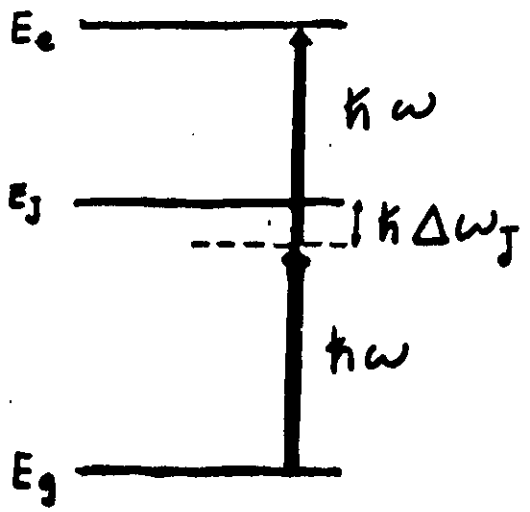
DOPPLER FREE LASER POLARIZATION SPECTROSCOPY



SPECTRE MOLECULAIRE DE L'IODE LAB. AIME COTTON ORSAY-FRANCE



2 PHOTON TRANSITIONS



e, g SAME PARITY

J OPPOSITE

ONLY REQUIREMENT : ENERGY CONSERVATION AT THE END OF THE PROCESS.

$$E_e - E_g = 2\hbar\omega$$

(POSSIBLE IMPORTANCE OF A NEARBY RES. INTERMEDIATE LEVEL).

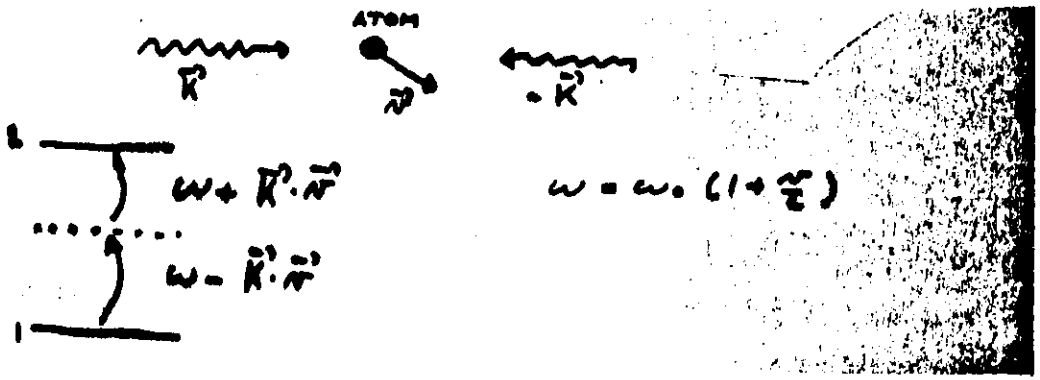
FIRST OBS. MICROWAVES (KASTLER)

INTEREST IN ATOMIC AND MOLECULAR SPECTROSCOPY

1) DIFFERENT SELECTION RULES FROM SINGLE PHOTON (PARITY)

2) TWO PHOTON EXCITATION ALLOWS TO USE VISIBLE OR NEAR UV RAD. FOR ENERGY JUMPS CORRESPONDING TO SHORTER WAVELENGTHS

3) ELIMINATION OF 1st ORDER DOPPLER WHEN PHOTONS ARE ABSORBED FROM COUNTER-PROP. BEAMS.



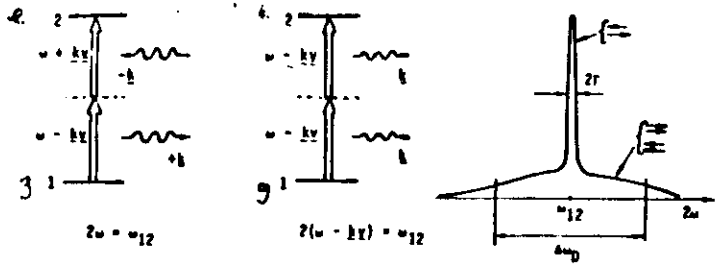
ENERGY CONSERVATION

$$E_2 - E_1 = \hbar(\omega + \vec{k}\cdot\vec{v}) + \hbar(\omega - \vec{k}\cdot\vec{v}) = 2\hbar\omega$$

At resonance satisfied by all atoms independently

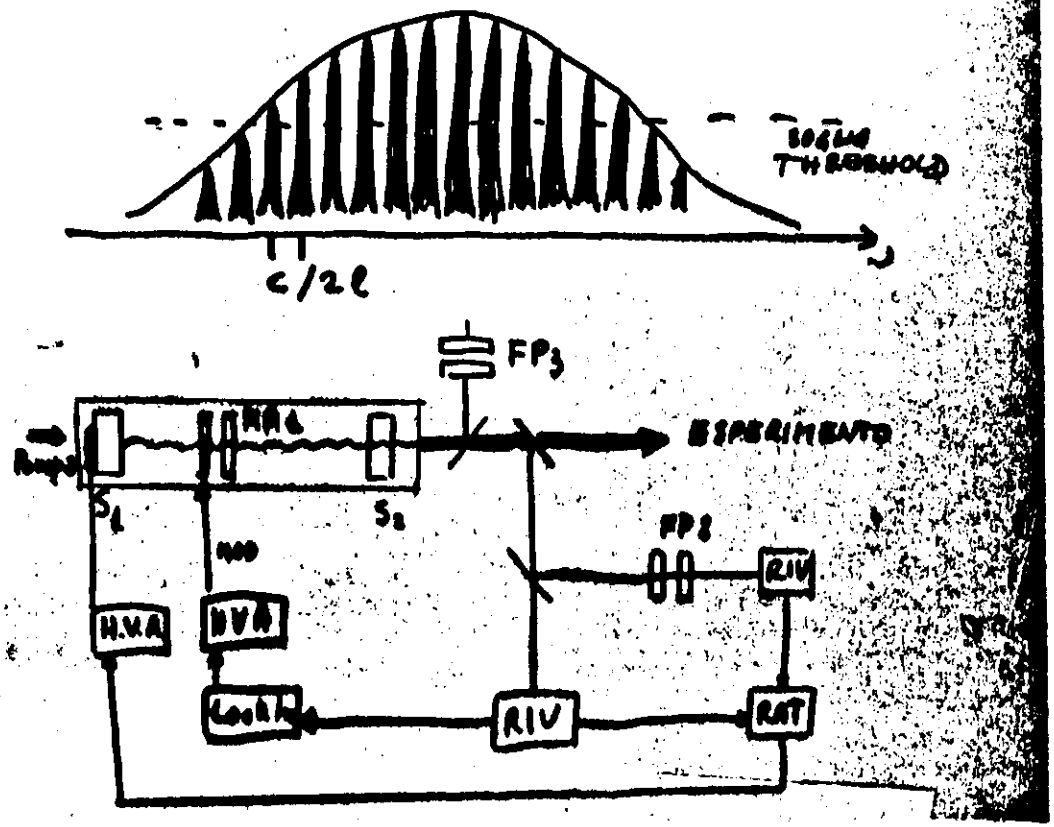
FIGURE

LINE SHAPE

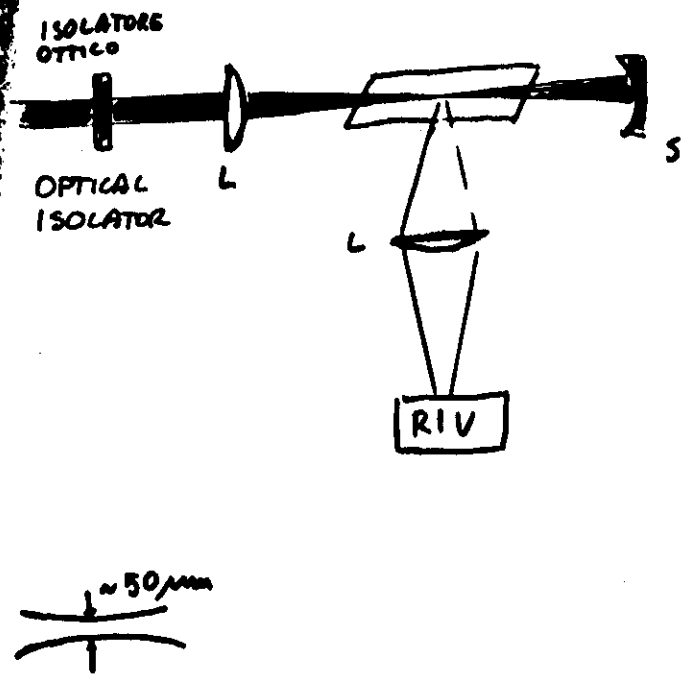


LORENTZIAN OVER A

APPARATO SPERIMENTALE : IL LASER
APPARATUS EXPERIMENTAL (DYE LASER)



HIGH ENERGY DENSITY
(STRONG FOCUSING)



FP1 MODE SELECTION

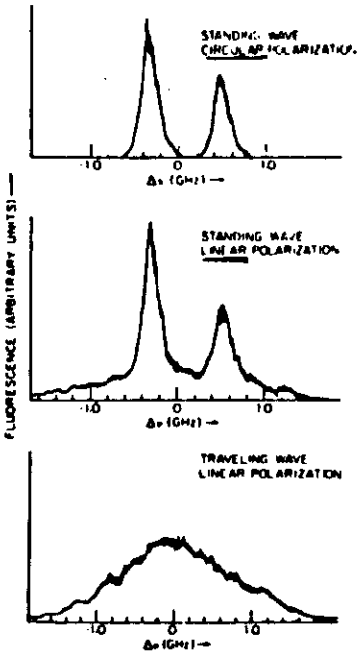
FP2 CONTROL OF FREQUENCY

FP3 CALIBRATION OF FREQ SCALE

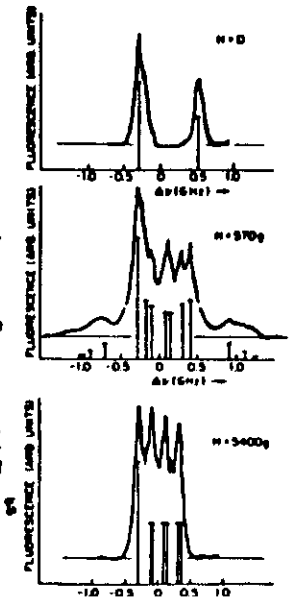
$\Delta\nu_{min} \sim 1\,MHz \sim 10^{-5}\,\text{Å}$ in the VISIBLE

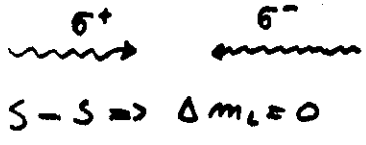
SOME APPLICATIONS (5)

HYPERFINE STRUCTURE



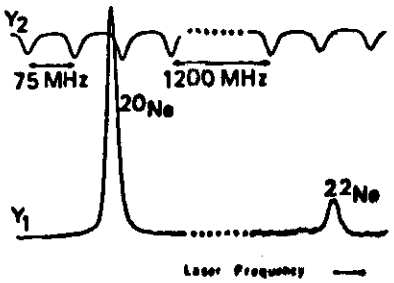
ZEEMAN EFFECT



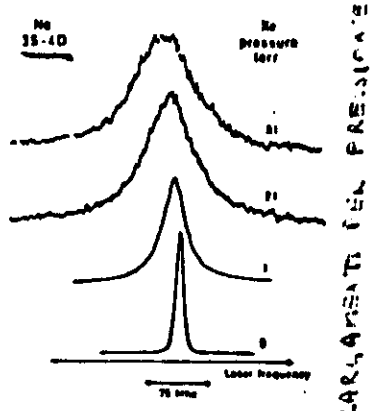


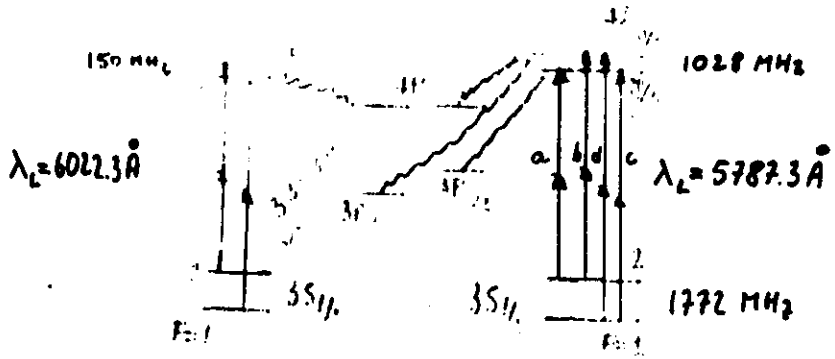
S − S ⇒ $\Delta m_L = 0$

ISOTOPE SHIFT

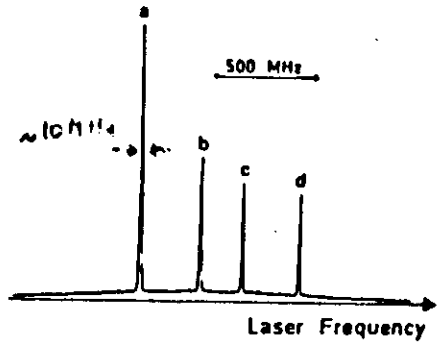


PRESSURE BROADENING AND SHIFT



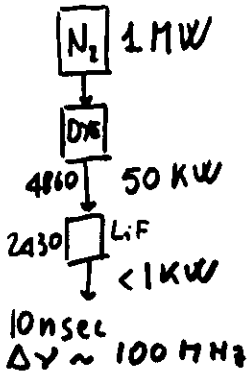


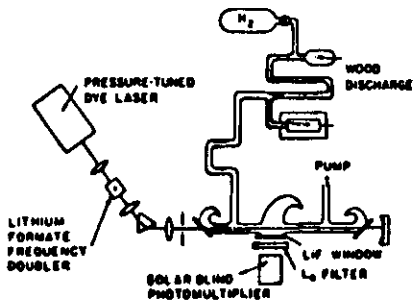
$\Delta\omega_J / \omega \sim 1/\ldots$



$\Delta\nu_D \sim 2.000$ MHz

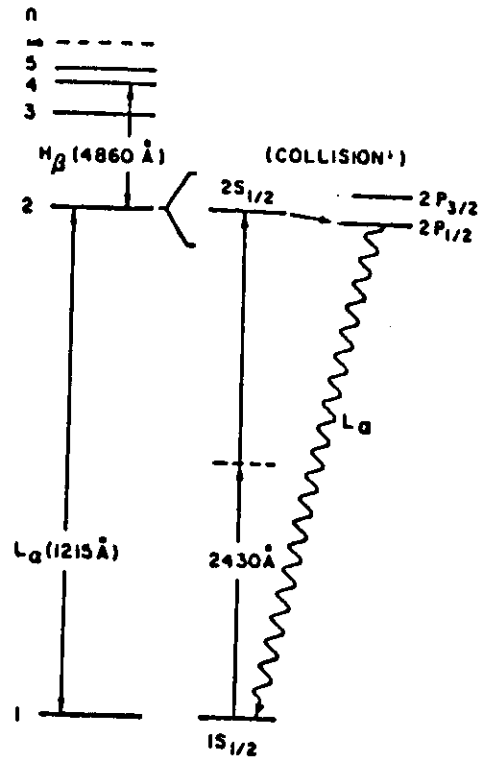
HYDROGEN





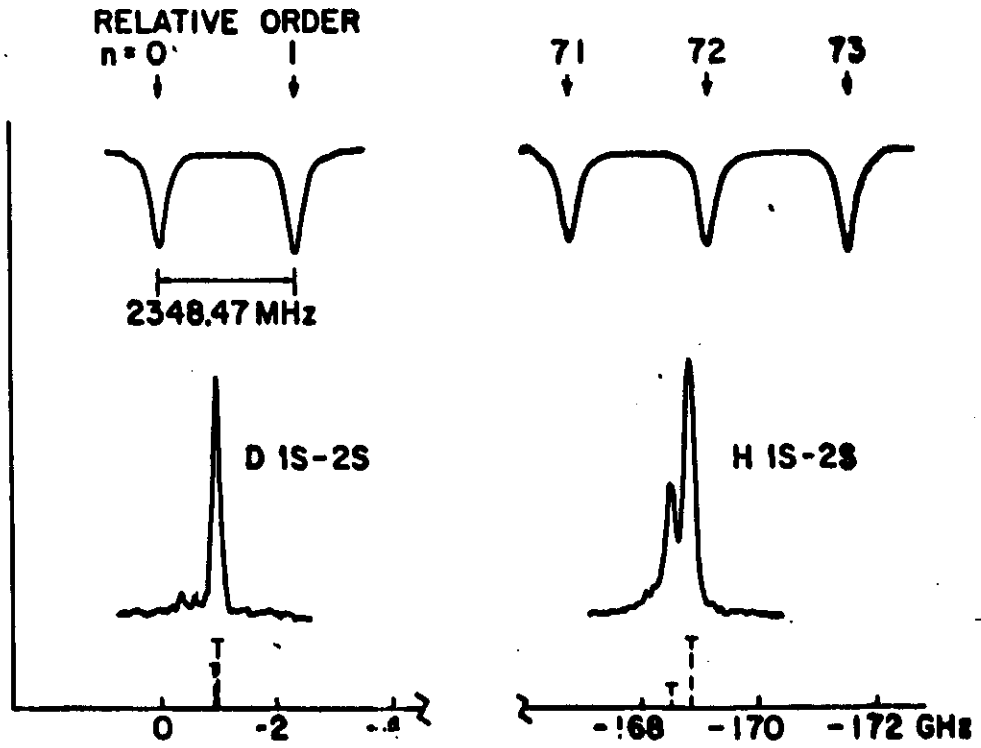
Hänsch et al 1975

7.3.



1215 x 2 = 2430 x 2 = 4860

ISOTOPE SHIFT OF HYDROGEN 1S - 2S



DYE LASER FEQUENCY DETUNING (−ν)

Δν < 2% Δν DOPPLER

7.4.