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SMR 1302 - 4

WINTER SCHOOL ON LASER SPECTROSCOPY AND APPLICATIONS

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COLD COLLISIONS IN THE PRESENCE OF LIGHT

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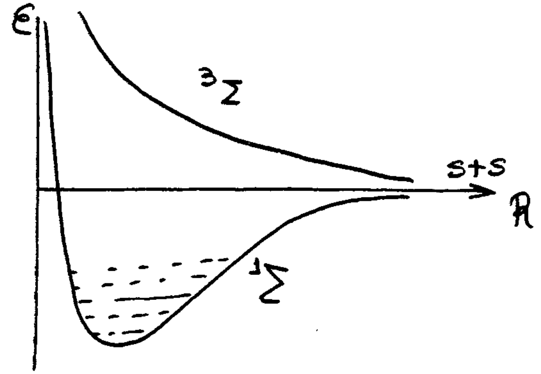
These are preliminary lecture notes, intended only for distribution to participants.

II- Cold Collisions in the Presence of light

* During approximation of two atoms

electronic states $\Longrightarrow$ Molecular potentials

Ex: H-H



* Molecular potential has long range part, normally not important

⟶ cold collision ⟶ long range is important and dominant

* conventional : $E_c \sim 1 eV$

* cold collision : $E_c \sim 10^{-8} - 10^{-10} eV$

Small details are important

* Time of collision

→ high temperature $\Delta t \sim 10^{-12} - 10^{-14}$ sec

→ Cold Collision $\Delta t \sim 10^{-7} - 10^{-9}$ sec

* In the case of excited state participation

time collision > lifetime state

$\Longrightarrow$ spontaneous emission is important

(prototype for an open dissipative system)

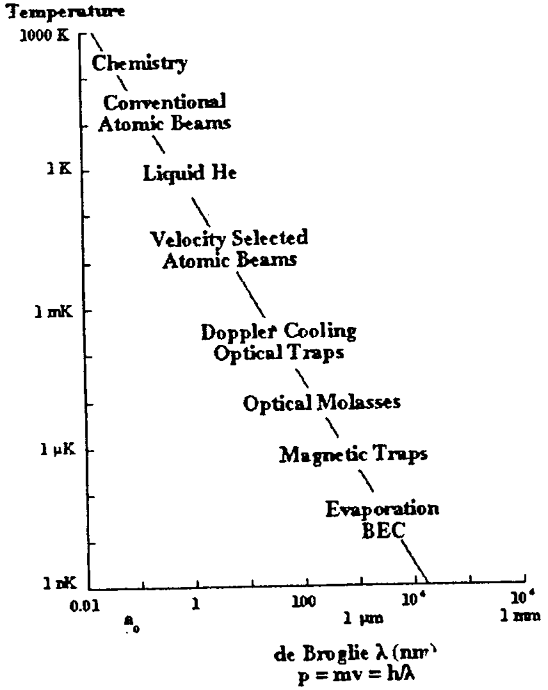
* Bound States

→ Low collisional energy allow to observe long range bound states

* Gas at quantum regime

— thermalization (evaporative cooling)

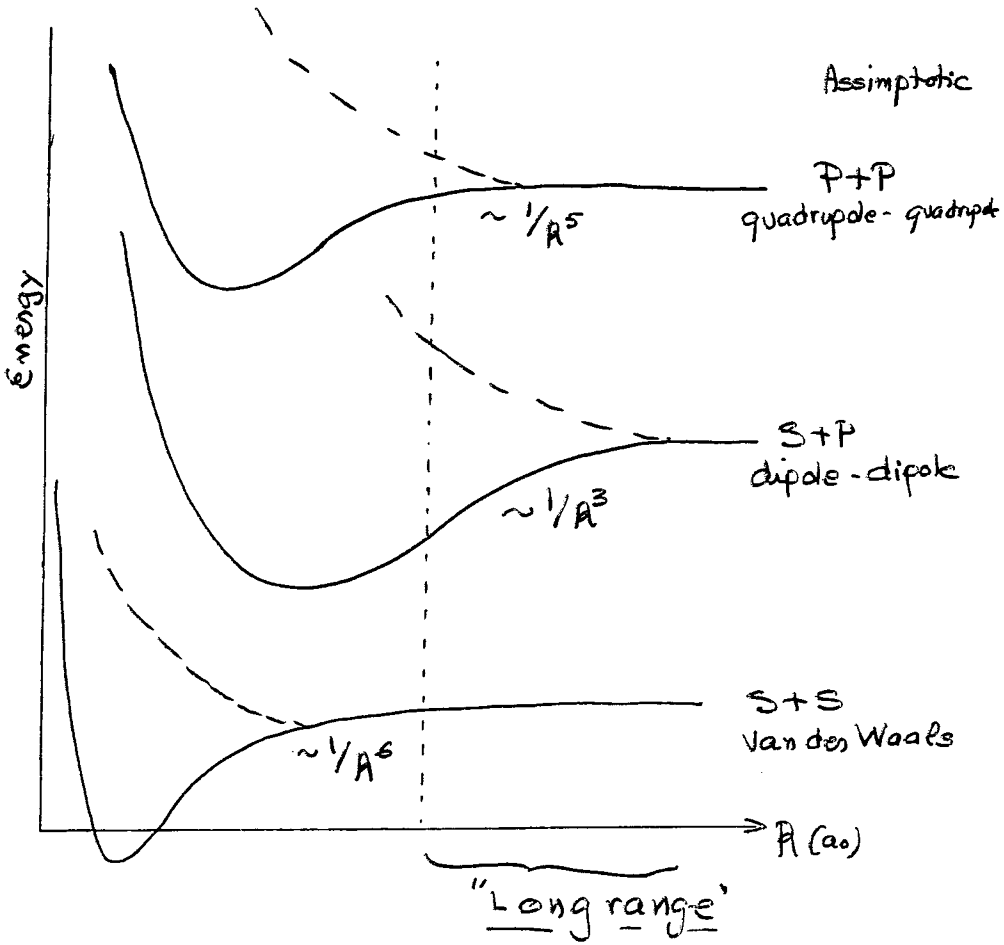
— Macroscopic properties depend on interaction



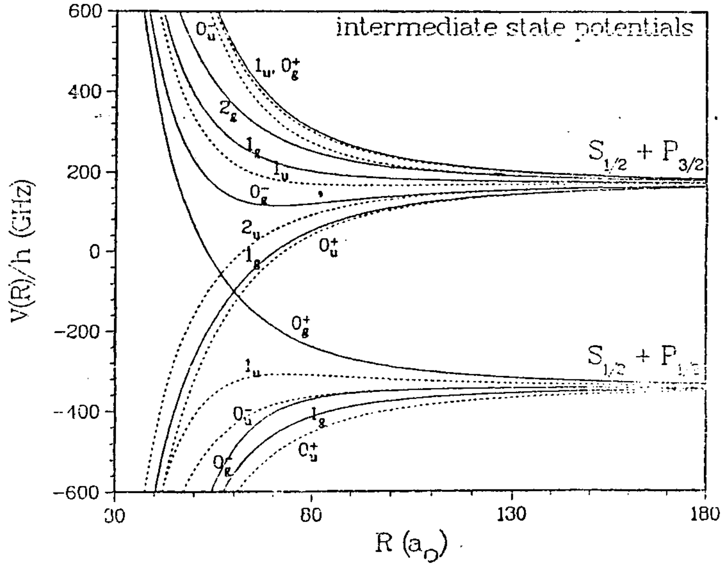
Possibilities for collisions

$$\begin{matrix}\text{Cold Atoms}\\ + \\ \text{photons}\end{matrix} \longrightarrow \begin{matrix}\text{Mixture}\\ |g\rangle \\ |e\rangle\end{matrix} \longrightarrow \begin{cases} |g\rangle + |g\rangle \\ |g\rangle + |e\rangle \\ |e\rangle + |e\rangle \end{cases}$$

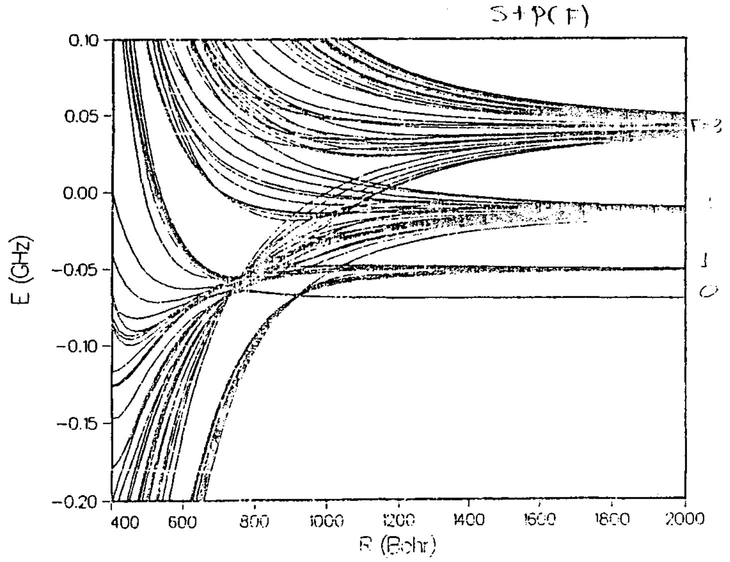
* Depending on the internal state of the atoms → different interaction



* Fine Structure in the atoms
⟹ several symmetries



* Hyperfine Structure → Each level several possibilitie



Ground - Ground state collision

* Ellastic process - collision is determined by the scattering length "a"

$$\sigma \sim 4\pi a^2$$

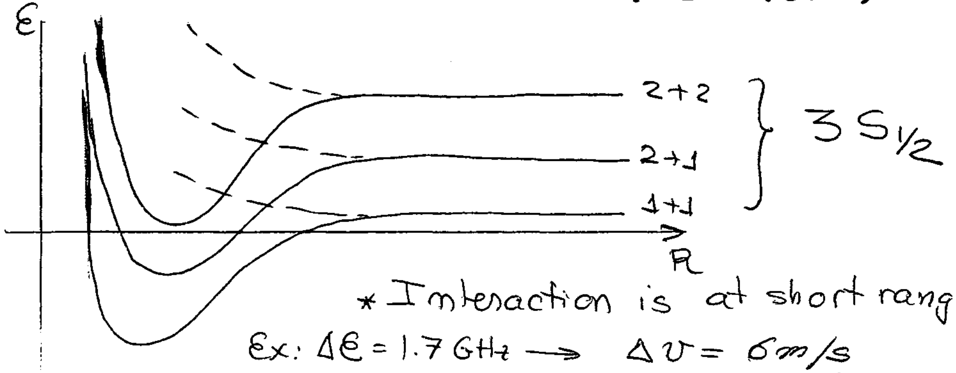
→ determination of a is by itself interesting collision problem

Important :
- evaporative cooling
- properties of a quantum gas
-

* Inelastic process : Hyperfine changing collision (HCC)

$$\mathrm{Na}\,(F=1) + \mathrm{Na}\,(F=2) \rightarrow 2\,\mathrm{Na}\,(F=1) + \Delta E$$

$$\mathrm{Na}\,(F=2) + \mathrm{Na}\,(F=2) \rightarrow \begin{cases} \mathrm{Na}\,(F=1) + \mathrm{Na}\,(F=2) + \Delta E \\ 2\,\mathrm{Na}\,(F=1) \quad + 2\Delta E \end{cases}$$



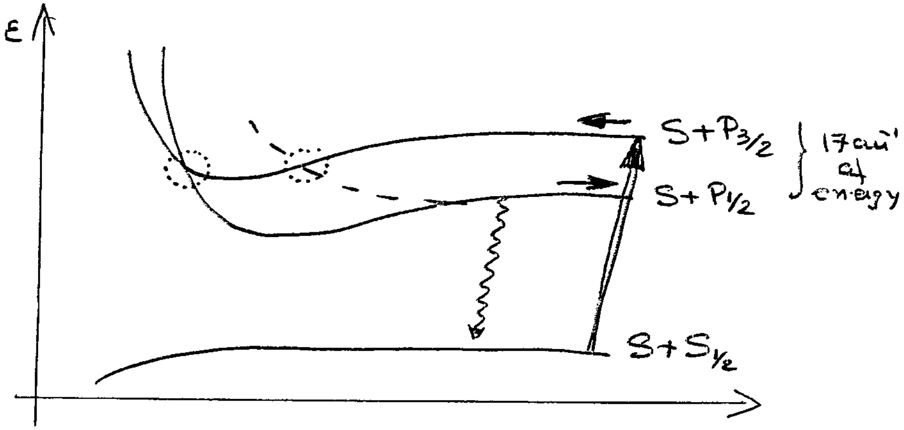
* Interaction is at short range

Ex: $\Delta E = 1.7$ GHz → $\Delta v = 6\,m/s$

Ground + Excited State

- Long range part of potentials become very important
- Processes where internal energy is converted in kinetic → $\boxed{\text{exoergic process}}$ and there are two main contribution

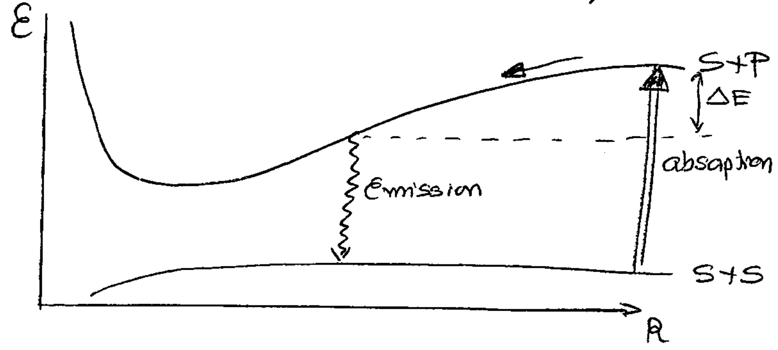
- Fine Structure Change (FSC)



Ex: $Na(P_{3/2}) + Na(S_{1/2}) \longrightarrow Na(S_{1/2}) + Na(P_{1/2}) + 17\,cm^{-1}$
→ 60 m/s for each atom

- Radiative Escape (RE)

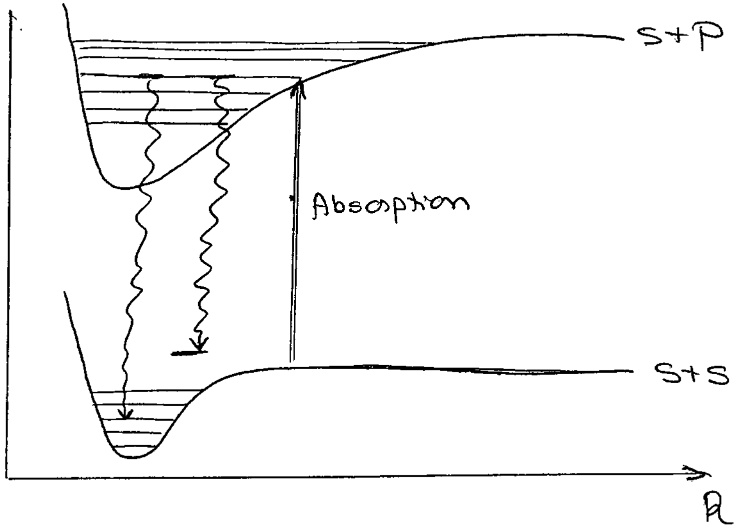
→ Atoms get excited at long range → gain kinetic energy → decay



Important points

- statistical nature of decay → velocity distribution
- Energy gainned depends on excitation point, potential slope
- Survival is important

Ground + Excited (Selective excitation)



* Absorption is selective (Franck-Condon factor)
(Free to bound)

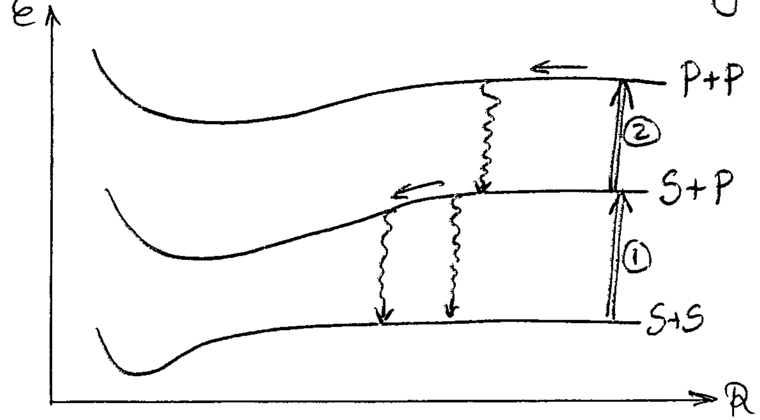
* Emission
⇒ bound → free (Kinetic energy)
⇒ bound → bound (Association)

absorption revels structure of bound states at long range (S+P)

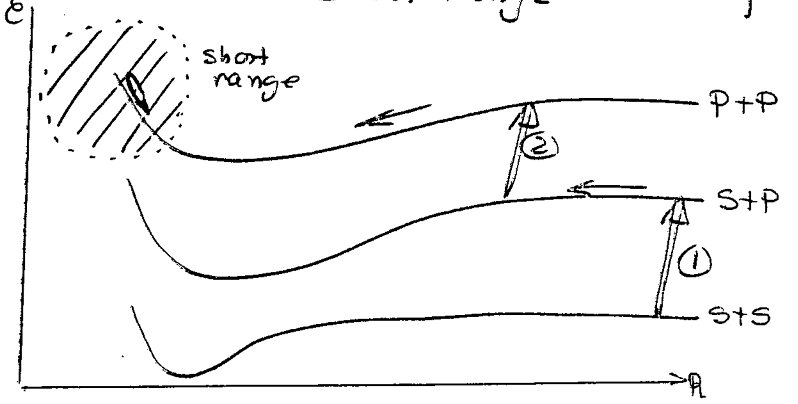
→ Both processes get atoms out of the trap.

Excite + Excite ~~state~~ collisions.

→ Starting with double excited states at long range → hard to survive to short range

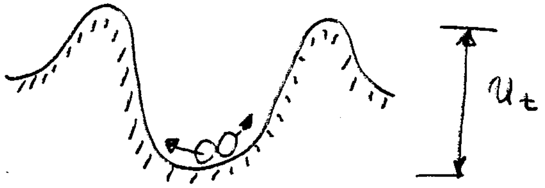


→ Starting at long range but getting motion before second excitation
→ better chances for survival
→ Collision channels at short range become possible



$\text{Exoergic collisions} \xrightarrow{\text{may}} \boxed{\text{Trap Loss}}$

Kinetic energy > trap depth.



$$\frac{1}{2}\mu v^2 > U_t$$

* Strong depending on U_t
→ trapping parameters
(Int., Δ, $\frac{dB}{dz}$, etc)

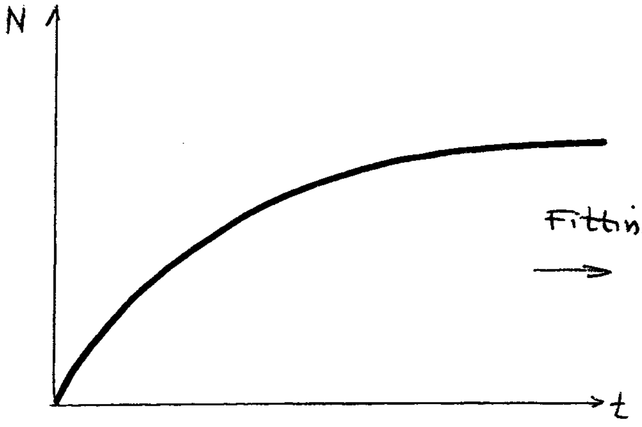
* Can be studied using variation of number of atoms in the trap

$$\frac{dN}{dt} = L - \gamma N - \beta \int_v M^2(r,t)\, d^3r$$

L = Loading rate
γ = background atoms rate
β = volumetric rate of collisions that takes to losses

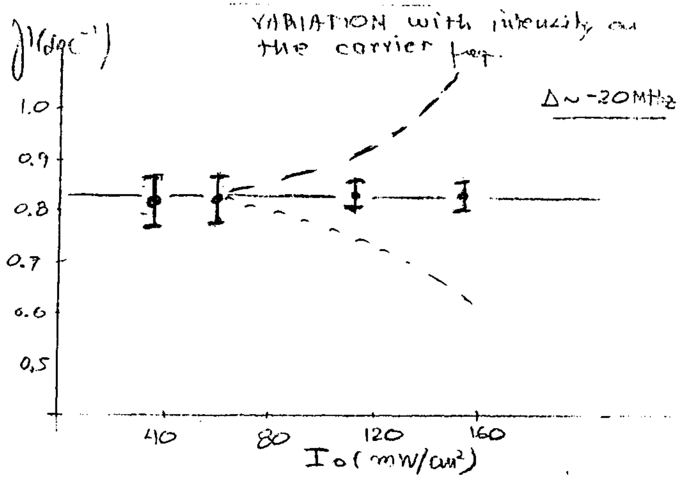
Having N atoms, each collide $n\sigma v$
→ total rate $\frac{1}{2} N n\sigma v$ → each collision loss of two atoms

$$\text{rate losses} = 2\frac{1}{2} N n\sigma v = \beta n N \Longrightarrow \boxed{\beta = \langle \sigma v \rangle}$$



Fitting
→ $\underline{\gamma}$ and $\underline{\beta}$

γ → depends on back ground



(intensity in the main laser freq.)

⇒ Important facts related with the analysis of transient behavior

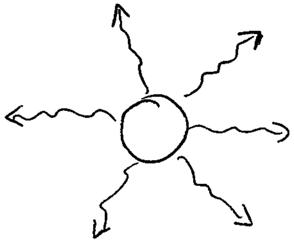
High number of atoms + high light intensity

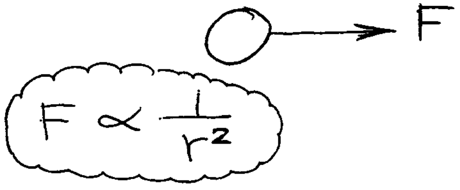
$$\Downarrow$$

radiation trapping

$$\Downarrow$$

positive pressure on atoms



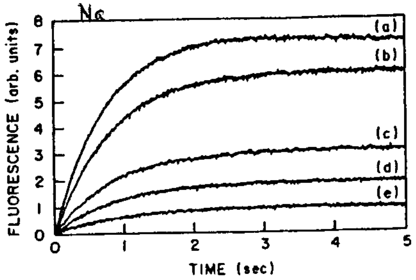


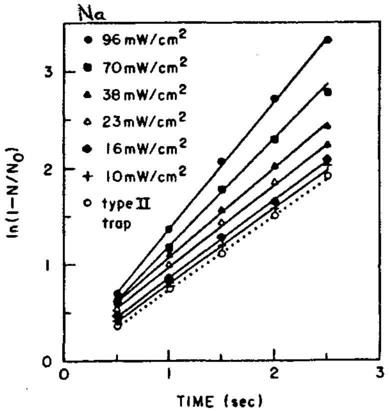
$$F \propto \frac{1}{r^2}$$

⇒ Due to positive pressure ⇒ atomic density is constant.

$$\frac{N}{V} = n_c$$

$$\rightarrow \quad \frac{dN}{dt} = L - (\gamma + n_c\beta)N$$





$$N = N_0\left[1 - \exp(-\gamma - n_c\beta)t\right]$$

- Independent measurement of γ
- Determine $\gamma + n_c\beta \longrightarrow$ obtain β

Atomic density with Gaussian Profile.

→ trapping forces more important

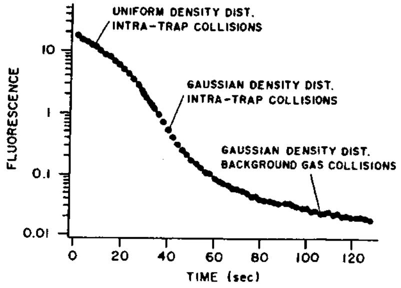
$$n(r,t) = n_0(t)\, e^{-r^2/w^2}$$

$$\boxed{\frac{dN}{dt} = L - \gamma N - \frac{\beta N^2}{(2\pi)^{3/2} w^3}}$$

Solution: $$N(t) = \frac{2L \sinh[\alpha t/2]}{\gamma \sinh(\alpha t/2) + \alpha \cosh(\alpha t/2)}$$

fitting ⇒ determine β

During unloading of a MOT → observation of several regimes



β depends
- Depth of trap
- Excited State population
- Collision channels (FSC, RE, HCC)

$$\boxed{\beta = \beta(I, \Delta, \text{atom})}$$

Besides loading and unloading

→ Sudden change of intensity

Load at high intensity → Change to low intensity

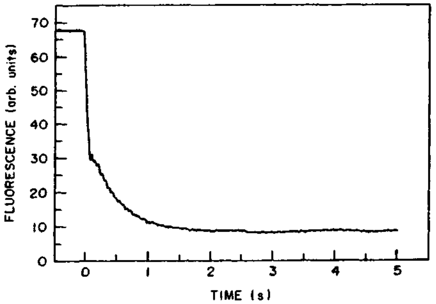


FIG. 26. Fluorescence-time spectrum. The abrupt drop at the initial moment is due to a change in light intensity without variation in the number of trapped atoms. From Santos *et al.* (1996).

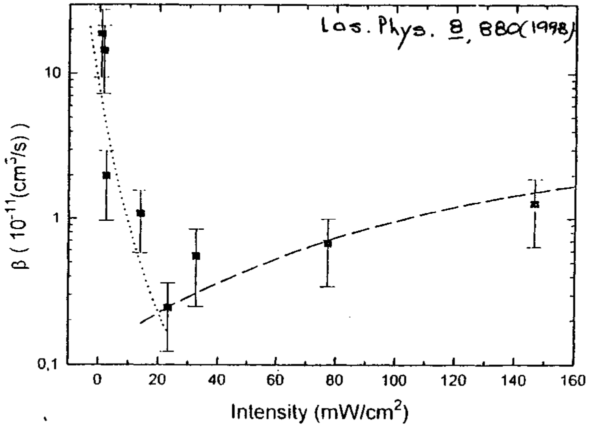
N_0 → number at I

N_0' → number at I'

$$N(t) = N_0' + (N_0 - N_0')\exp\left[-\gamma\left(1 + \frac{n_c\beta}{\gamma}\right)t\right]$$

→ Allow determination of β(I') down to very low intensity

Typical behavior of β(I) observe



Las. Phys. 8, 880 (1998)

Several regions (Interpretation)

High intensity ⟹ FSC + RE

Low intensity ⟹ HCC

Does anybody detected FSC?

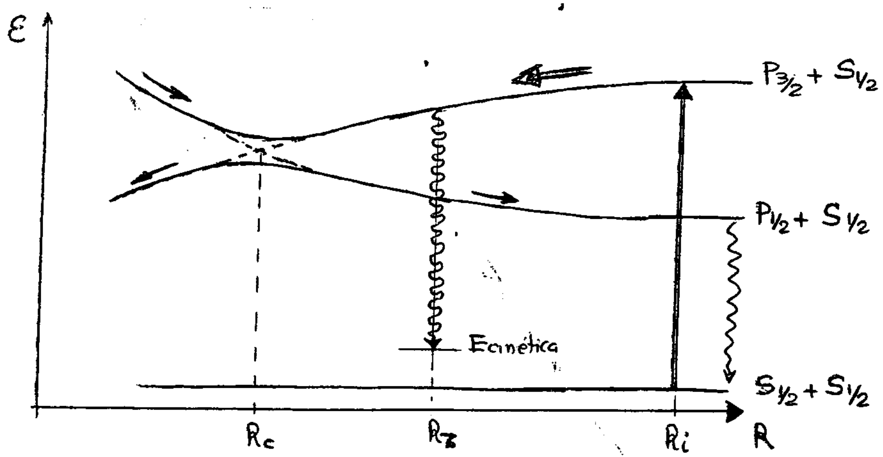
YES

Does anybody detected HCC?

NO

Main Model for $\beta \Rightarrow$ Gallager-Pritchard (GP)

- It is a semiclassical model considering FSC + RE



- A pair is excited at long range (R_i)
- $\Delta < 0$, probably attractive state is excited
- Number of excited pairs

$$(\text{Pairs})_{R_i} = \frac{M^2}{2} 4\pi R_i^2 \, dR_i$$

- Rate of excitation

$$\left(\frac{I}{\hbar\omega}\right) \frac{\lambda^2}{2\pi} \frac{\Gamma}{\Gamma^2 + 4\left(\Delta - \frac{C_3}{\hbar R^3}\right)^2}$$

- Once excited there will be decay (by spontaneous emission) at R_z (R_z is such that gainned energy is larger than U_t)

$$\boxed{P_{rad} \propto e^{-\Gamma t^*(R_i, R_z)}} \quad (RE)$$

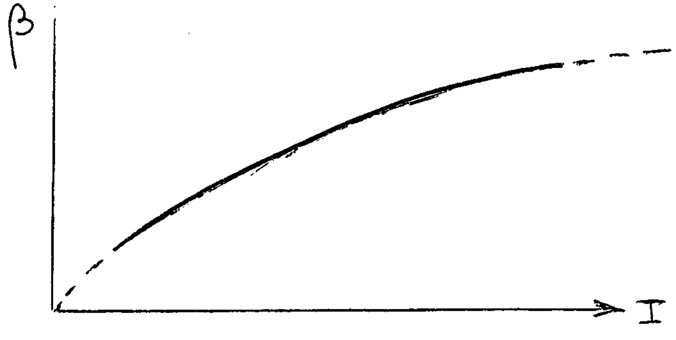
- At the anti-crossing may occur FSC (position R_e)

$$\boxed{P_{\Delta J}(R_i, R_e)} \quad (FSC)$$

$$\beta \propto \text{Rate of Collisions with loss} = \int_{R_i} \frac{M^2}{2} 4\pi R_i^2 \, dR_i \, B(I,\Delta) \left[P_{rad} + P_{\Delta J}\right]$$

B is a function on I, Δ, R_i .....

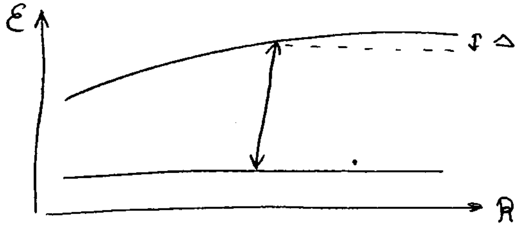
Obtained β(I)



"decreasing excitation"

$\beta(I) \rightarrow$ behavior of trap

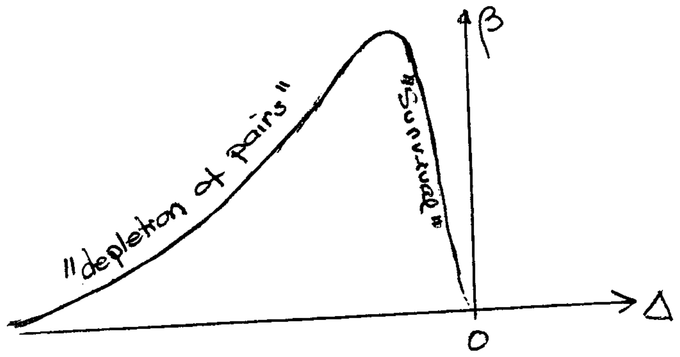
$\beta(\Delta) \rightarrow$ Potential and Survival



(Case $\Delta >> \Gamma$

$$\beta \propto \left\{ \Delta^2 \sinh\left(\frac{\Delta_\tau}{\Delta}\right)^{5/6} \right\}^{-1}$$

$\hbar\Delta_\tau$ = energy gainned by pair during a life-time (τ)



Investigation of $\beta(\Delta)$, normaly done using "catalises"

* Extra laser at Δ_c, introducing additional losses

$$\beta = \underbrace{\beta_t}_{\text{trap alone}} + \underbrace{\beta_c(\Delta_c)\,\frac{I_c(\Delta_c)}{I_{ref}}}_{\text{addition}}$$

* Measurement done by changing $I_c(\Delta_c)$, keeping total number constant

$$\beta_c(\Delta_0) \propto \frac{1}{I_c(\Delta_c)}$$

Typical results → Good understand

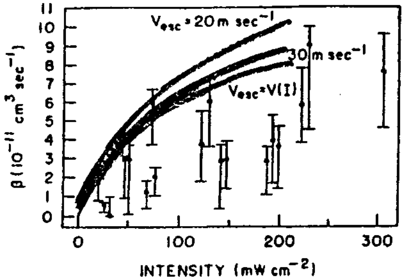


FIG. 28. Measurement of the trap loss rate constant as a function of MOT light intensity. The wider range of light intensity reveals an increase in β with MOT intensity. Dotted, full, and dot-dash curves are theory calculations using the optical-Bloch equation method of Band and Julienne (1992) with different assumptions about the maximum escape velocity of the MOT. The curve $V_{esc} = V(I)$ results from a simple model in which the escape velocity is a function of the MOT intensity. Data are from Marcassa *et al.* (1993).

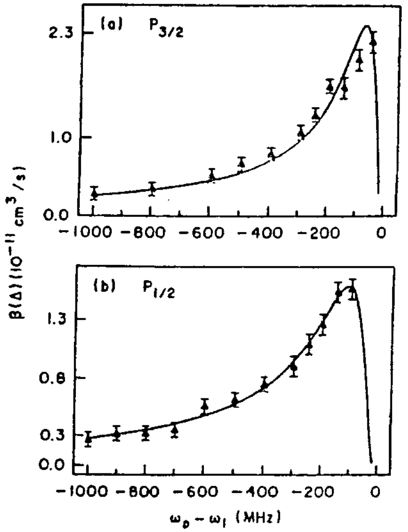


FIG. 29. Trap-loss spectrum in a Na MOT for catalysis laser detuned to the red from both atomic line-structure asymptotes. From Marcassa *et al.* (1997).

Rb

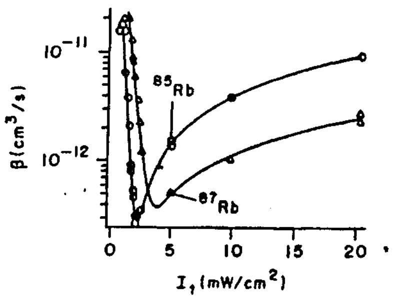
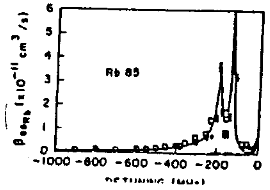


FIG. 32. Trap-loss spectrum for two isotopes of rubidium. Right-hand branch shows trap loss due FCC and RE. Left-hand branch shows trap loss due to HCC. From Wallace *et al.* (1992).



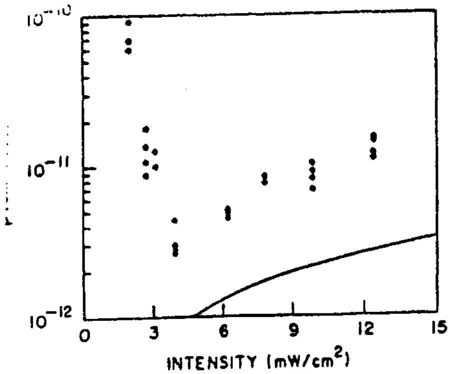
* Differences between isotopes

* $^{85}Rb \rightarrow \Delta E_{HF} \cong 3\,GHz$

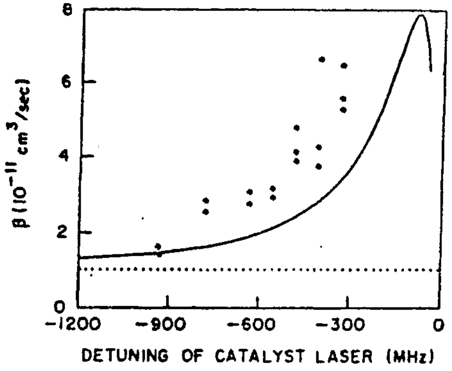
$^{87}Rb \rightarrow \Delta E_{HF} \cong 6\,GHz$

* Possible structure as function Δ

Cs



30. Trap-loss rate constant β as a function of MOT in-
ity for Cs collisions: comparison of experiment with GP
ry, from Sesko *et al.* (1989).



Li

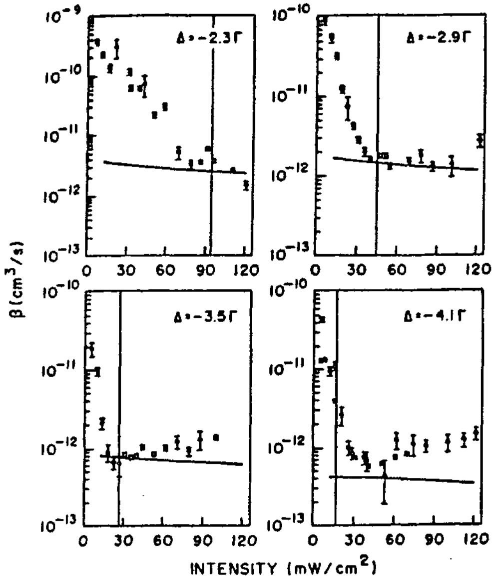
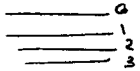


FIG. 40. Trap-loss rate constant β for four different detunings and a range of intensities in the Rice group's Li MOT. The vertical lines in each plot denote I_c the calculated critical intensity required to recapture an atom released in the shallowest direction. From Ritchie *et al.* (1995).

* Excite state with inverted hypestine



∴ Less influence of hypestine spasetti

* ΔE_{FSC} is small only became impostant at low intensity

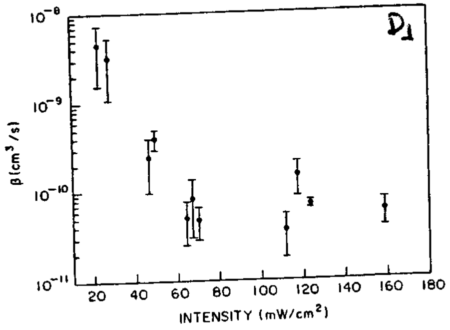
$\Delta E_{FSC} \sim 0.5\,K$

K

* It is possible to separete FSC aud RE ? (YES)

First Experiment using D_1 line

(trap at D_2, flip to D_1 observing decay)



* Absence FSC

* Larger values if compared with D_2 (D_1 trap much shallower)

* Equivalent low intensity behavior (but not value)

interesting point

⟹ Special experiments to measure β_{FSC}

* Pisa (Arimondo et al) → fluorescence in Cs

* Rochester (Bigelow et al) → fluorescence Cs

* Brasil → Fragment ionization in Rb

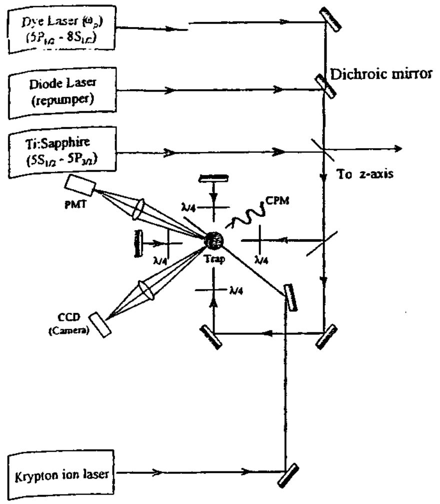


Fig. 1. Experimental setup. Rubidium is trapped in a MOT using a Ti:sapphire laser while a dye laser is tuned to the $5P_{1/2} \rightarrow 8S_{1/2}$ transition and the krypton laser ionizes atoms out of the $8S_{1/2}$ state. A channeltron particle multiplier detects the ions.

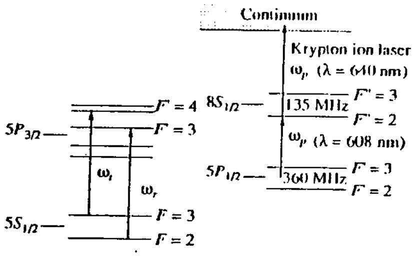
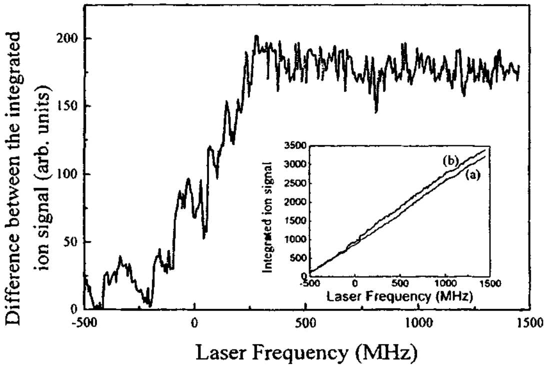


Fig. 2. Cw detection scheme. The produced $5P_{1/2}$ atoms generated from FSC collisions are excited to $8S_{1/2}$ state by a first photon from a dye laser (λ = 607 nm) and then ionized by a second photon (λ = 640 nm) provenient of a Krypton ion laser.

Problems: * atoms $P_{1/2}$ emerge with diff. velocities → difficults for selective laser.

* background ions

→ Integration.



From the produced ions

$$\boxed{\beta_{FSC} \lesssim 0.15\, \beta_{Total}}$$

RE is dominant

Measurement by Rochester's group (Cs)

J.P. Shaffer *et al.*: Cs radiative escape and fine structure changing collision rates 329

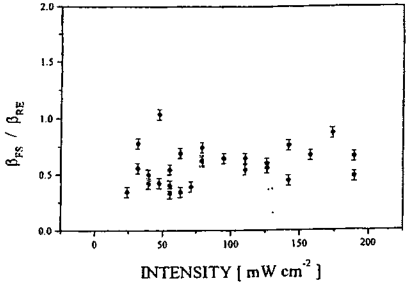
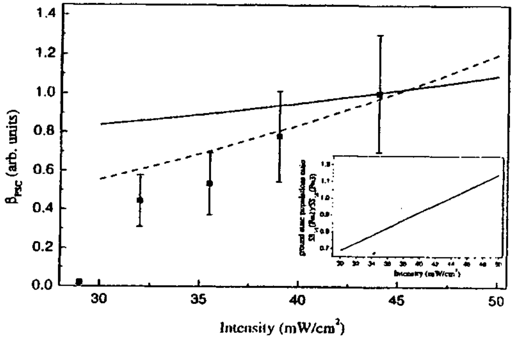


Fig. 6. The ratio β_{FS}/β_{RE} for a detuning of $\Delta = -1.4\Gamma$. The scatter in the plot gives a measure of the uncertainty in this value. The data points were fit to a constant to establish that $\beta_{FS}/\beta_{RE} = 0.58 \mp 0.03$.

About equal participation in Cs

Investigation of β_{FSC} with Δ



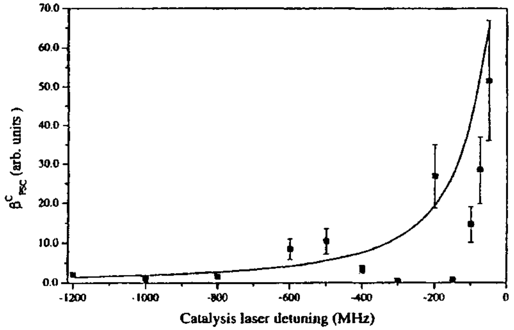
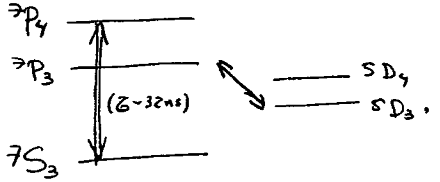


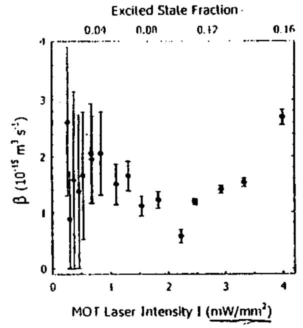
Fig. 3. Additional trap loss rate due to FSC introduced by the catalysis laser, β^c_{FSC}, as a function of catalysis laser detuning, operating below the transition $5S_{1/2}(F=3) \to 5P_{3/2}(F'=4)$; in the frequency range of -1200 MHz $\leq \Delta_c \leq -50$ MHz. The full line represents the theoretical prediction.

Interesting new results in trap loss

Mot of Cr atoms [Bradley et al PRA 61, 053407 (2000)]



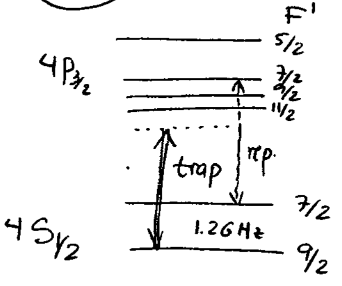
repumper ~ 660 nm
trap ~ 426 nm
I_s ~ 8.5 mW/cm^2



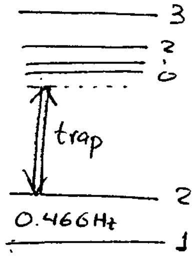
Clear minimum around 2 mW/mm^2

* Shows increase at low intensity, but HCC is not present.

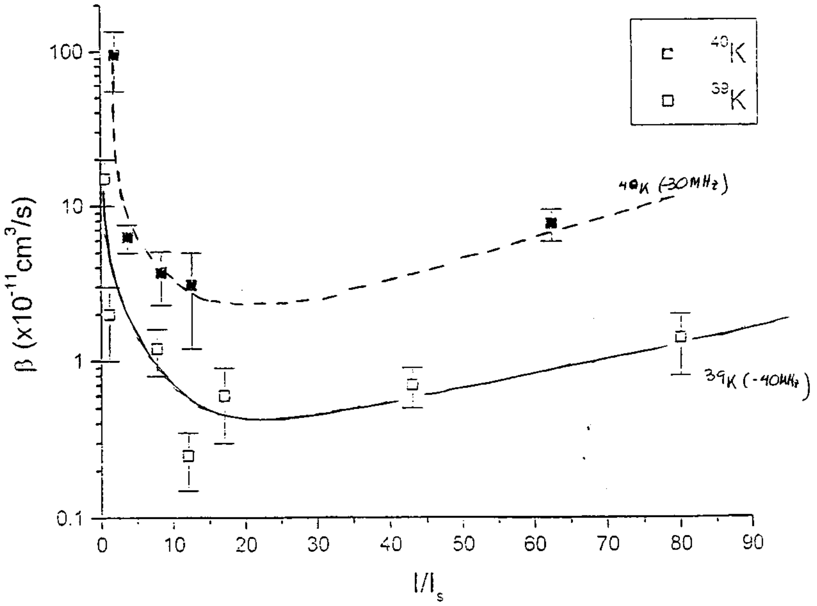
^{40}K (Florence)



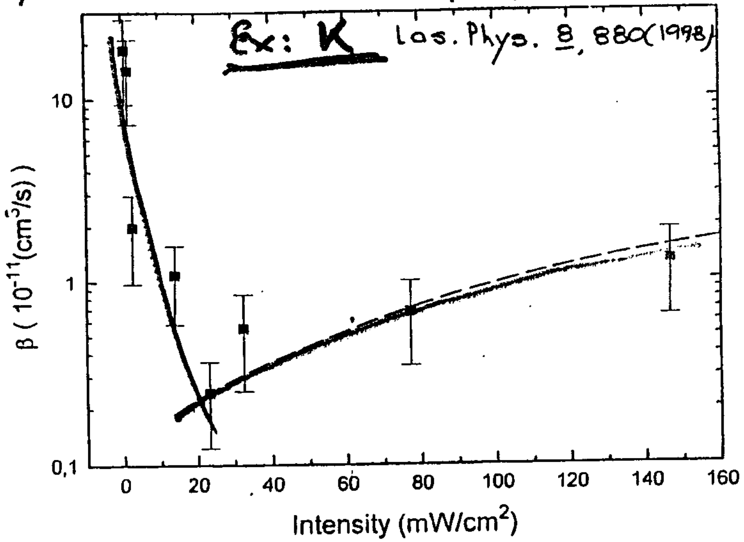
^{40}K
(trapping at low hyperfine)



^{39}K
(trapping at higher hyperfine)



- Typical behavior of β vs I



Region I → { Radiative Escape (RE) / Fine structure change (FSC) }

Region II → Hyperfine change (HCC)

Recently < FSC / RE

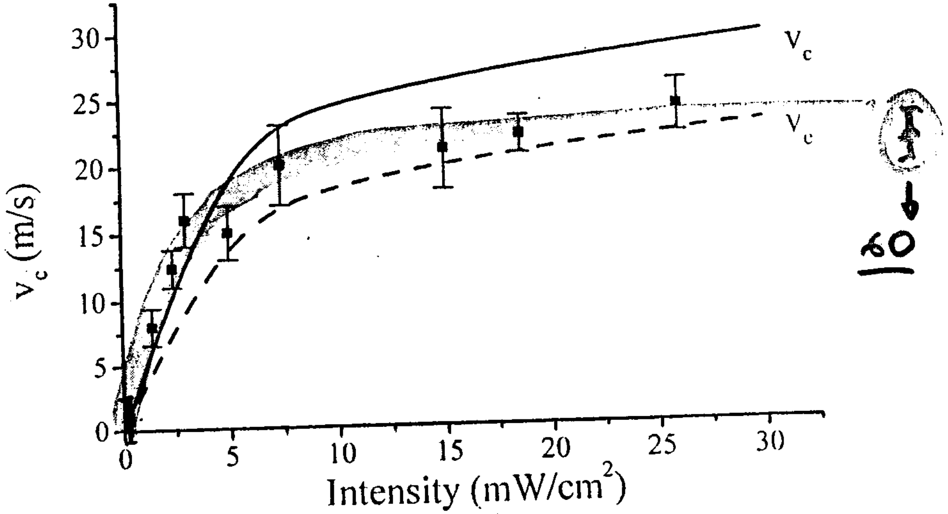
→ Trap loss is connected with Trap depth.

→ Trap depth is connected with escape velocity (Ve)

Knowledge of Ve is important in the interpretation of β

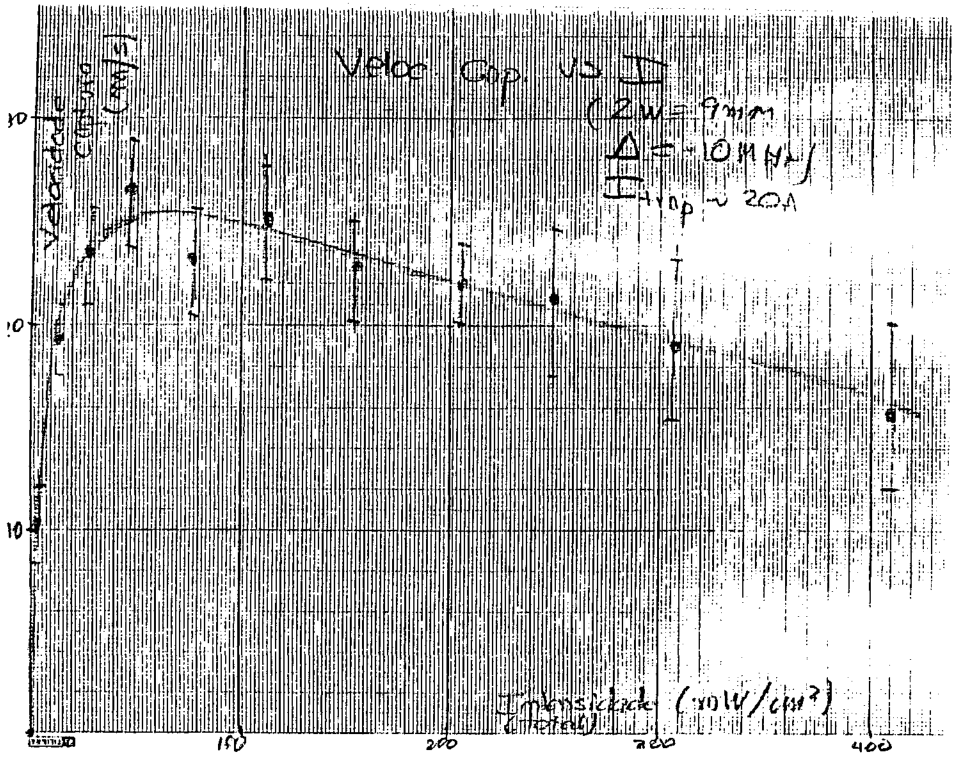
II - Recently done experiments by our group:

- Measurement of capture velocity (Vc) (Na) [Phys. Rev. A 62, 13404(2000)]



Observations

- How is Vc measured?
- Dependence with $\frac{dB}{dz}$ and Capture Volu (to be published)
- Normal operation W ~ .5 cm → damping force dominant to Vc



(January - 2001)

* Overlapping ^{87}Rb - BECs

[Myatt et al - Phys. Rev. Lett. 78, 586 (1997)]

Overlapping BECs of mixed spin states $|2,2\rangle$ and $|1,-1\rangle$ shows very small spin exchange rate

$$\beta_{eq} \sim 2\ 10^{-14}\ cm^3/s$$

compared to values from MOTs

$$\beta \sim 10^{-11}\ cm^3/s$$

* Counting Cold Collisions

(Cs) [Ueberholz, Kuhr, Frese, Meschede, Gomer
Un. Bonn - 1999]

- * trapping small number
- * directly observe two-body collisions
- * Observation of low rate for HCC attributed to suppresion due to repumper

* HCC in ^{87}Rb

[Nesnidal and Walker
Phys. Rev. A 62, 030701 (2000)]

* Detailed measurement at low intensity where HCC is dominant

$$F=2+F=2 \to F=1+F=1$$
$$F=2+F=2 \to F=1+F=2$$

RENÉE C. NESNIDAL AND THAD G. WALKER

PHYSICAL REVIEW A 62 030701(R)

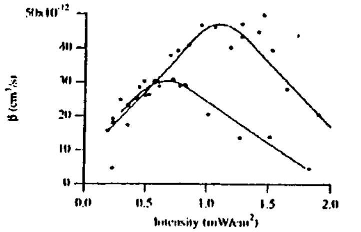


FIG. 1. Loss rates due to ultracold collisions as a function of total trap laser intensity with a detuning of $\Delta = -1\Gamma$. The circles and squares indicate data taken with a magnetic-field gradient of 10 and 18 G/cm, respectively. The solid lines have been included to guide the eye.

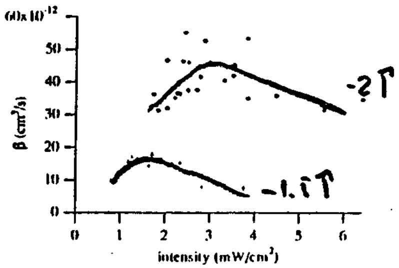


FIG. 2. Loss rates as a function of total trap laser intensity for larger laser detunings. The +'s and circles indicate data taken at $\Delta = -1.5\Gamma$ and -2Γ, respectively.

* Explanation :→ spin-exchange in a hyperfine excite-state

$$5S(F=2) + 5P_{3/2} \longrightarrow 5S(F=1) + 5P_{3/2}$$

→ Light modification of HCC (?)

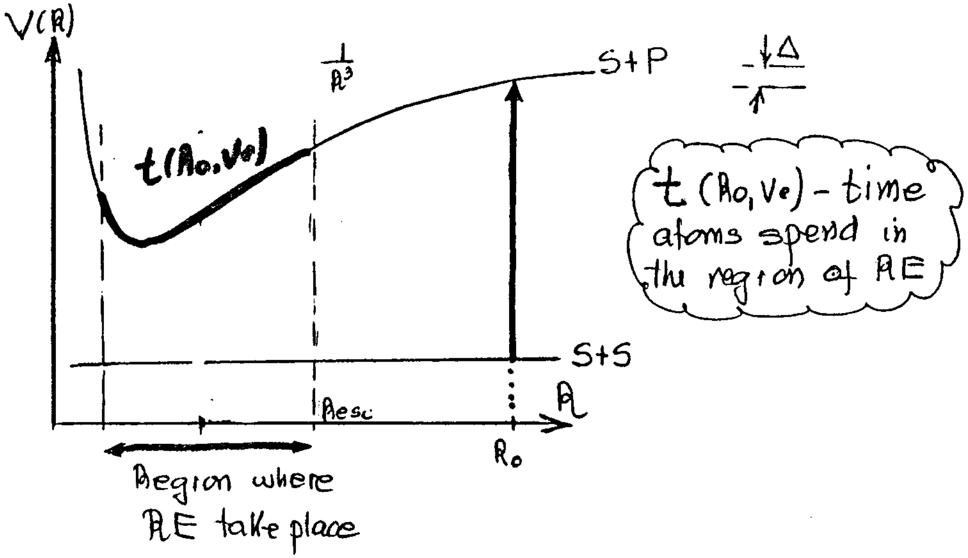
* turning down β at low I.

IV- Our new model

* Gallagher-Pritchard (GP)
* V_e (I) inferred from our previous experiment
* (we will apply to ^{85}Rb)

⟹ Important to have the correct variation of V_e with intensity.

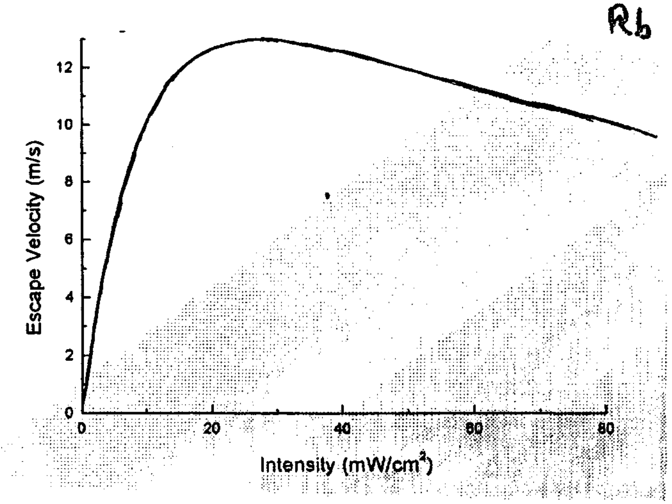
* Consider RE as dominant (based on previously done experiments)



$t(R_0, V_e)$ - time atoms spend in the region of RE

Important terms for the model

* **Escape Velocity (Ve)**



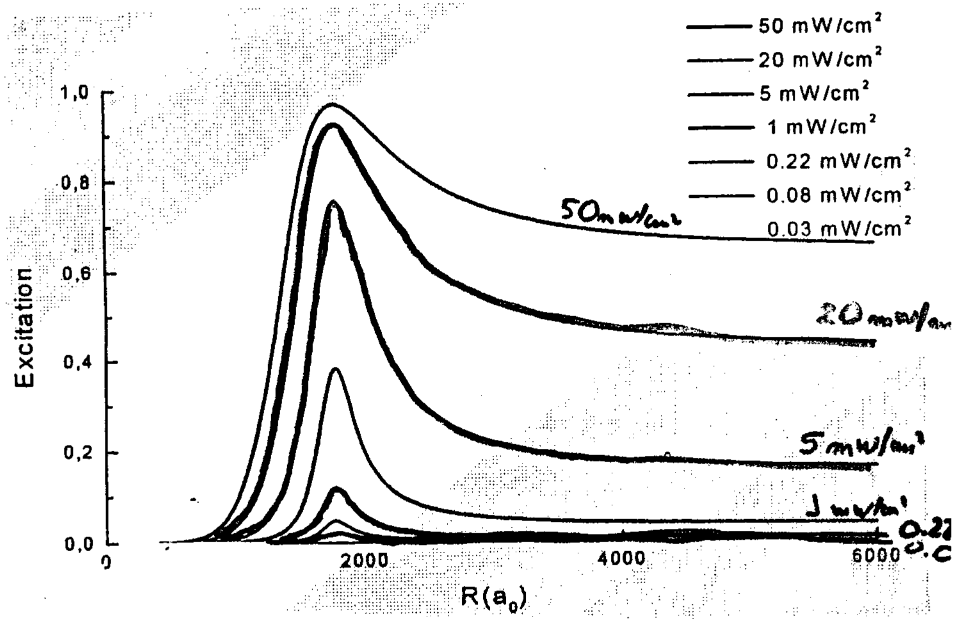
* Best fitting with experimental determination of (Vc) $\Longrightarrow$ damping as dominant process.

* Existence of maximum

$$\beta \propto \int_0^\infty 4\pi R_0^2 \, \epsilon(R_0, \omega_L, \underset{\nearrow}{I}) \, P_{RE}(R_0, \underset{\nearrow}{V_e}) \, dR_0$$

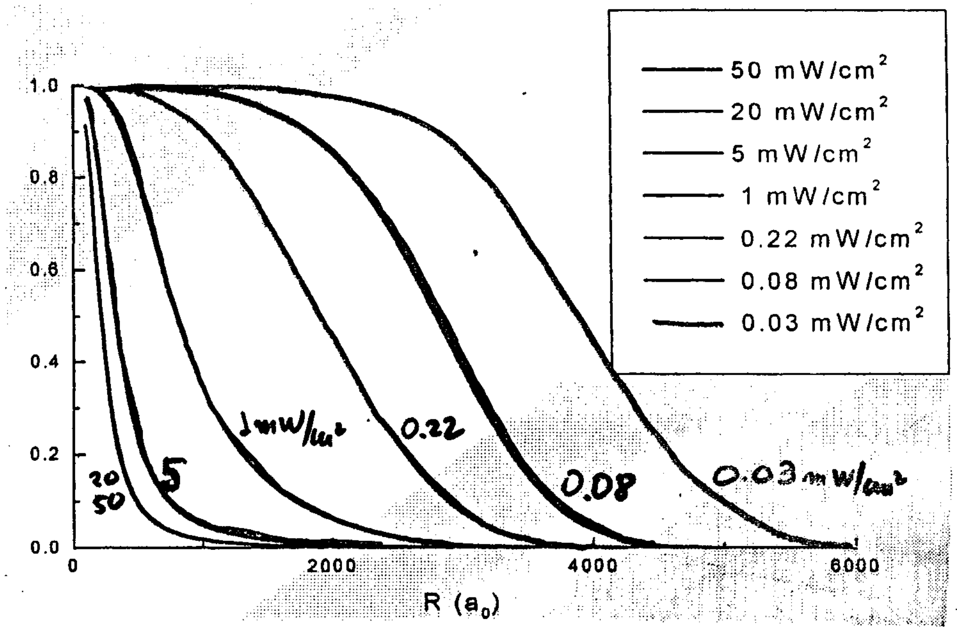
Let's observe each term

* $\boxed{\text{excitation rate } \epsilon(R_0, \omega_L, I)}$



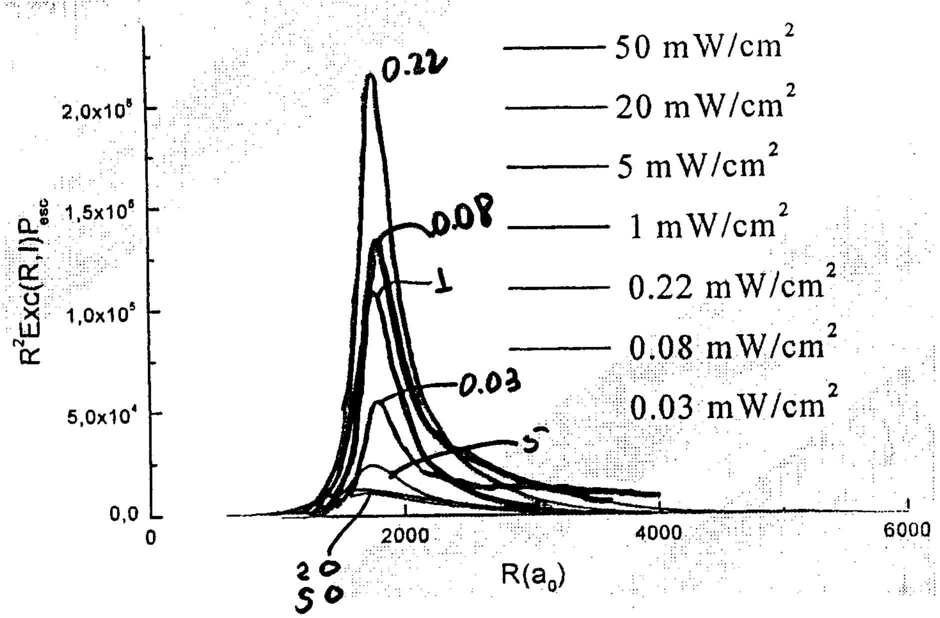
* ϵ is monotonic with I
* assymetry ⟶ potential

* Radiative Escape Probability (PRE)



- * P_{RE} always decreases with R (Large R smaller chance to survive)
- * Higher intensity → increase Ve atoms must survive to short range
- * Intense variation at lower intensity (more pronounced than at higher intensities)

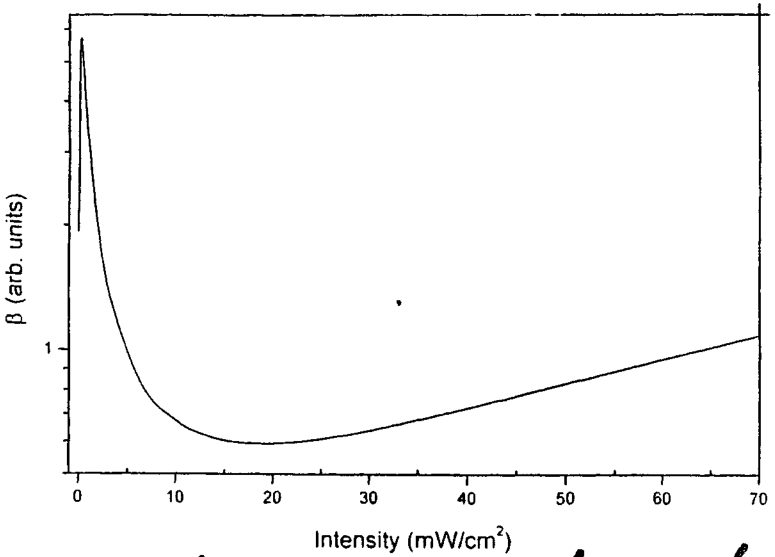
* Overal product / (integrand)



- * Is not monotonic with intensity
- * Interesting consequences in β.

$$\beta \propto \text{Integral (area)}$$

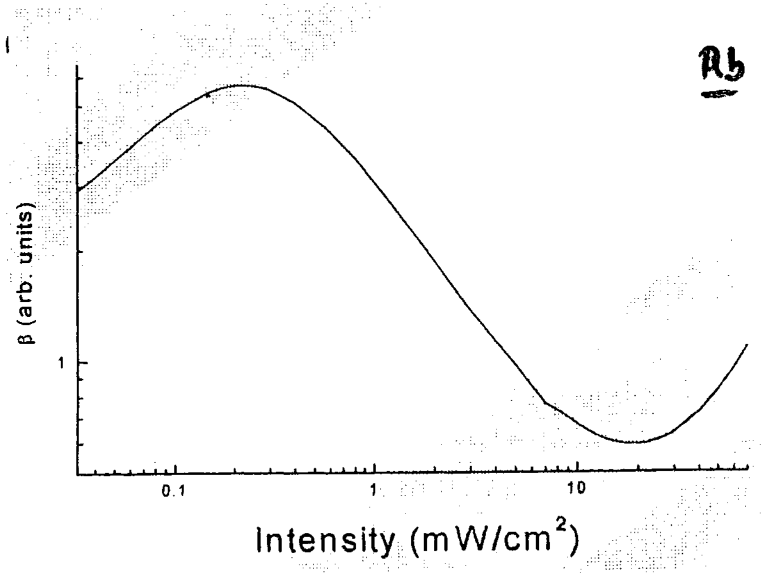
* Overal behavior of β(I)



→ can fit well most part of existent β vs I

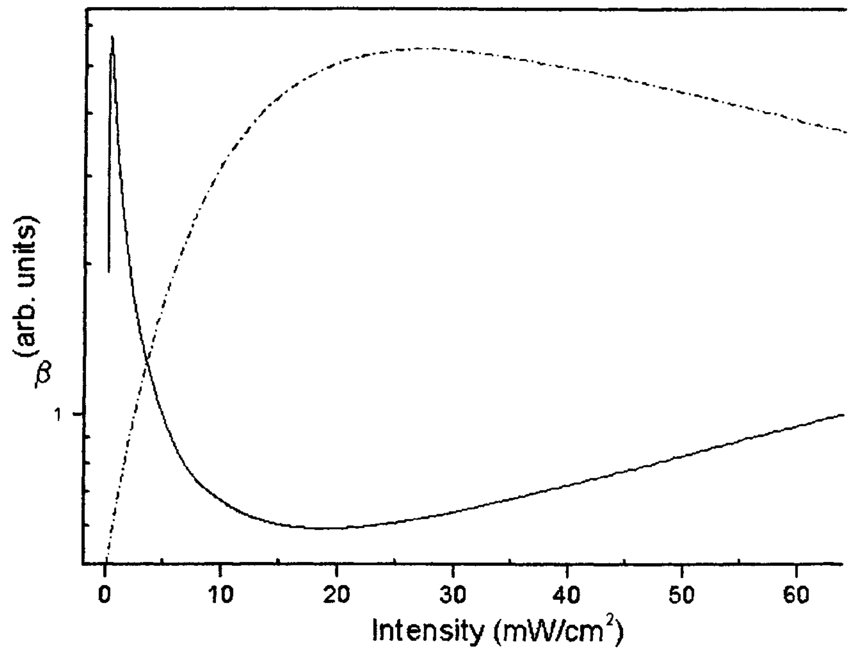
* At low intensity:

Rb



β → 0
I → 0

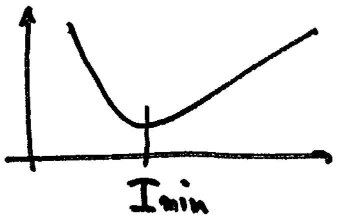
Fig.1: G.D. Telles *et al.*, Alternative Interpretation for the Magneto Optical Trap Losses at Low Light Intensi

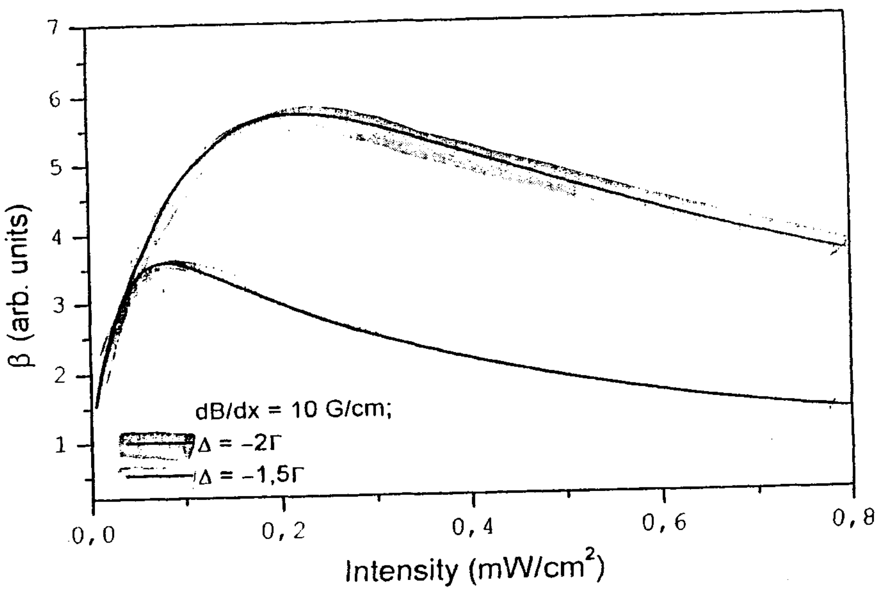


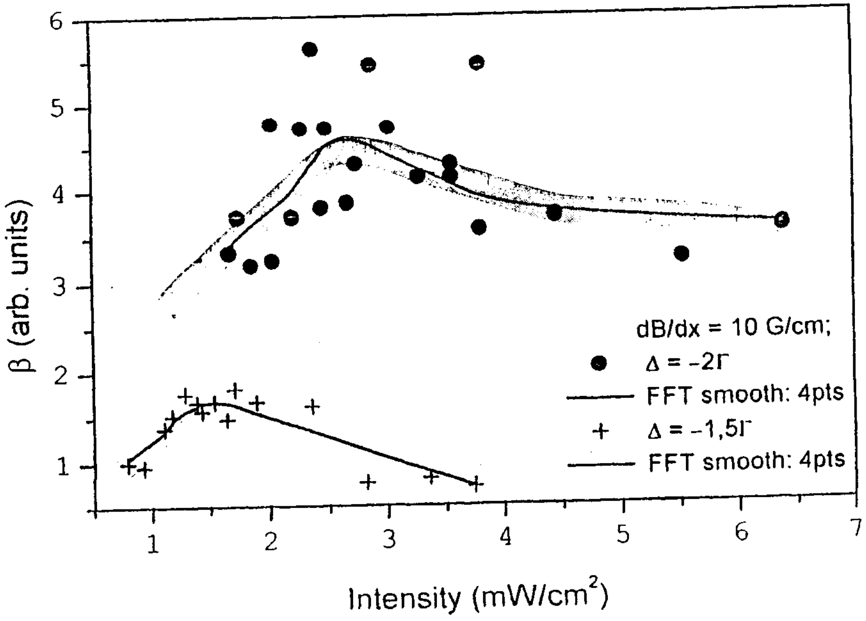
- Is HCC necessary to explain trap loss?
- What is the real level of participation of HCC in trap loss at low intensity?

- Comparison with experimental data → **position of minimum**

Species	Δ (Γ)	I_{exp}(mW/cm^2)	I_{mod}(mW/cm^2)	Reference
Li	-3.5	28	25	N.W.M. Ritchie et al PRA 51, R890 (95)
Na	-1	5	7.9	S.R. Muniz et al, PRA 55, 4407 (97)
K	-7	80	81	L.G. Marcassa et al, accepted PRA (00)
Rb	-1	3	2.5	C.D. Wallace et al, PRL 69, 897 (92)
Cs	-1	4	1.4	Sesko et al, PRL 63, 961 (89)

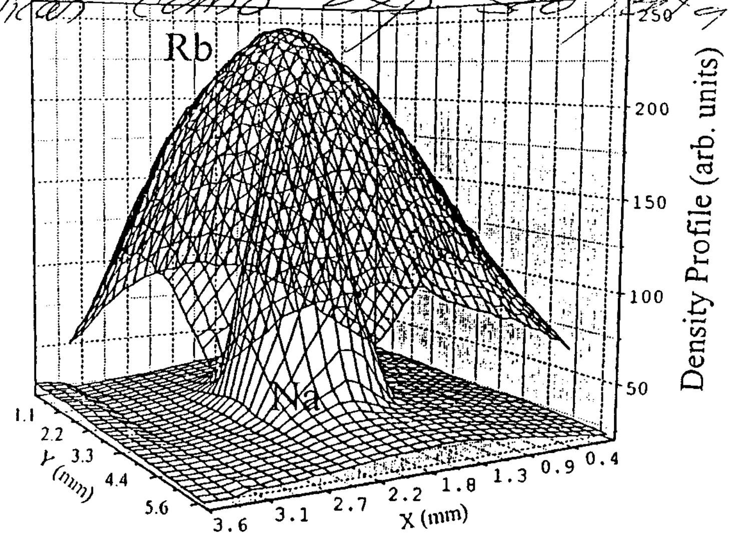






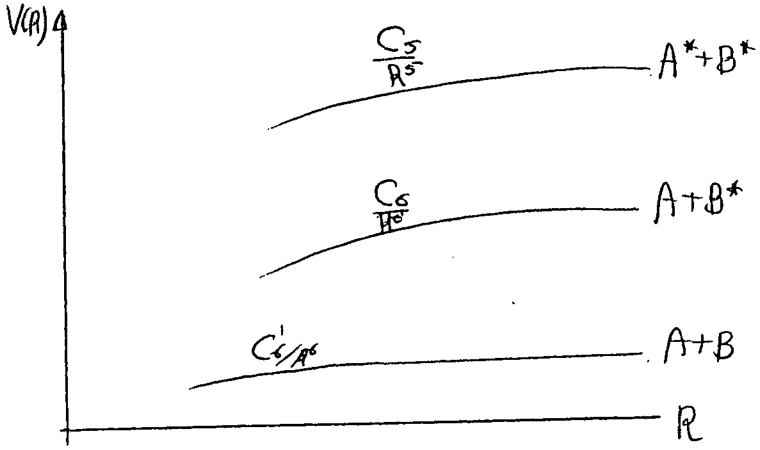
Heteronuclear Systems

~~explicar como exp [illegible]~~



ow we measure trap loss?

$\beta_{A/B}$ (loss of A in the presence of B)



- Mechanisms of loss
  RE, FSC (HCC)

* $\boxed{\beta_{A/B} \text{ as a function of } I_A}$

As I_A increases: * Ve varies (increases)
* Population A^* increases

* the behavior of $\beta_{A/B}$ vs I_A will depend on :

* Competition between Ve, A^*

* what mechanism is involved: $A+B^*$; A^*+B ; A^*+B^*

* Relative C_6 or C_5 coeff.

*

* • Mass ratio $\frac{m_A}{m_B}$ is important

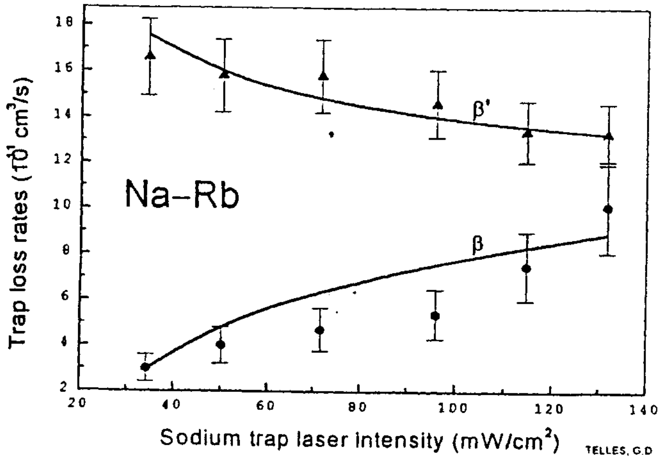
* • Detuning

* • Each system ⟹ peculiarities

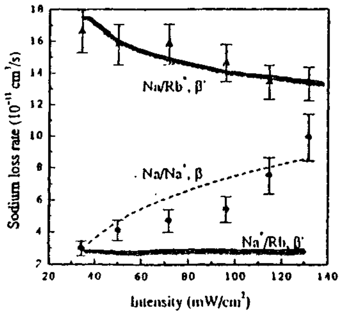
$$\boxed{\frac{dN_A}{dt} = -\gamma N_A - \beta \int n_A^2 d^3r - \beta' \int n_A n_B d^3r}$$

change A ↔ B.
⟶ change β'

Na/Rb Phys. Rev. A 59, R23 (1999)



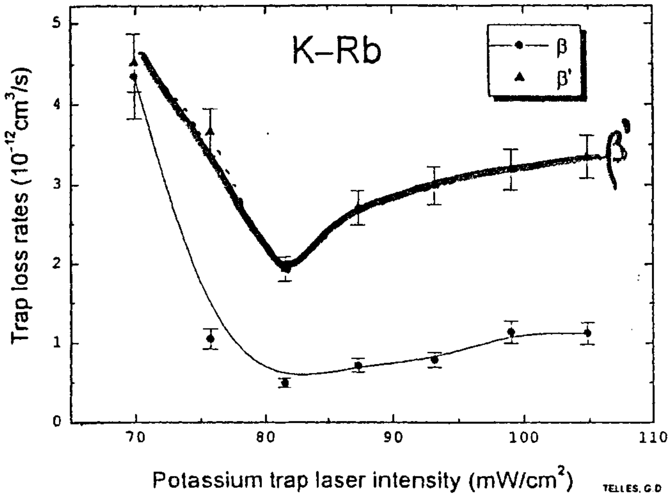
- * β' and β ⟶ aposite behavior
- * Model GP-like using RE
- * Two possibilities $\begin{cases} Na/Rb^* \\ Na^*/Rb \end{cases}$



$C_6(Na/Rb^*) \sim 10\, C_6(Na^*/Rb)$

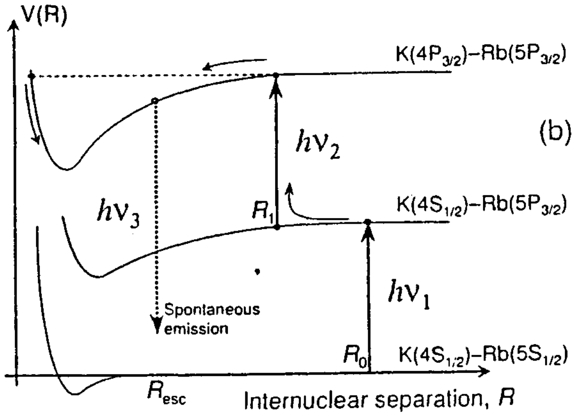
Na/Rb* ⟶ dominant

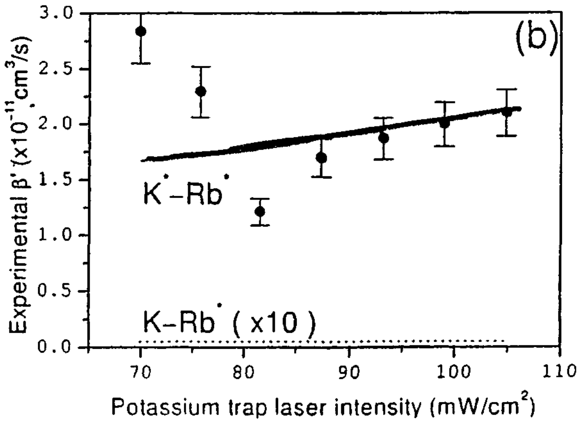
K/Rb Phys. Rev. A - Accepted (2000)
Δ ~ -40MHz



- * K*-Rb channel ⟶ All repulsive
- * Only K-Rb* ⟹ does not explain relative value
- * Possibility of K*-Rb*
- * Low intensity we have interpreted in the paper as HCC (?)
  (New analyses)

Double excited participation:





$\Longrightarrow$ K*- Rb* dominant

---

* Reciprocity

$$\boxed{\beta'_{Rb/K} \ll \beta_{K/Rb}}$$ at (70-100 mW/cm^2)

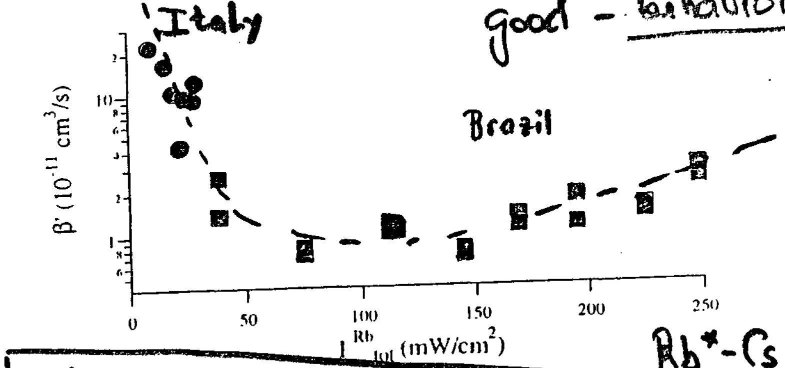
* FSC release ~ 100K ⟶ enought to eject both atoms

$\Longrightarrow$ $\boxed{\text{RE must be dominant}}$

* $\dfrac{\beta'_{K/Rb}}{\beta_{K/K}} \sim 3$ (model OK)
  - mass ratio
  - survival probability
  - HCC (?)

Rb/Cs Brazil + Pisa [Phys. Rev. A (2001)? (process)]

good - behavior !!!

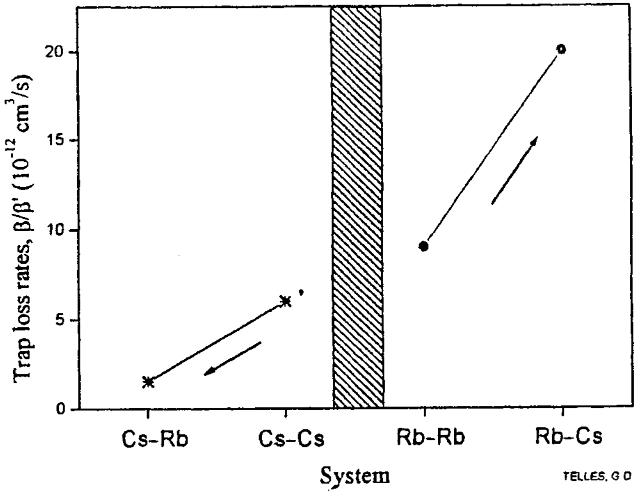


$$\boxed{\beta'_{Rb/Cs} \sim 20\,\beta'_{Cs/Rb}}$$

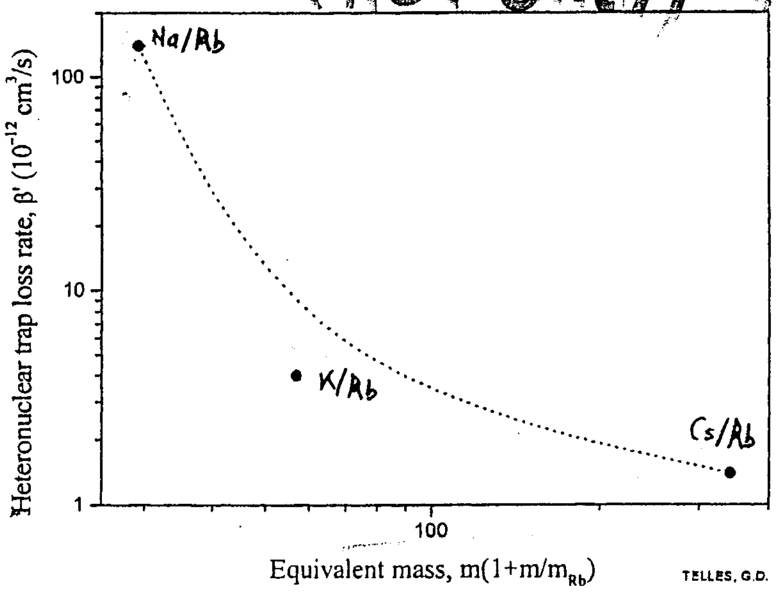
Rb*-Cs ⇒ repulsive

Rb-Cs* (main channel)

Homo vs Hetero

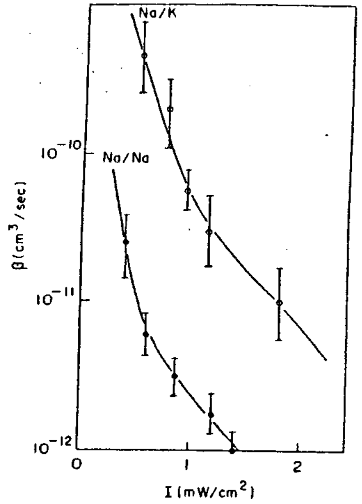


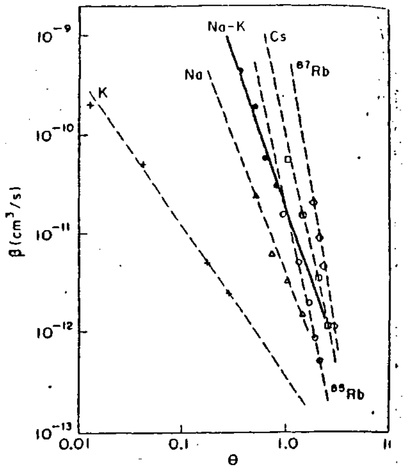
* Importance of mass ratio (NOT ONLY)



Na/K

Phys. Rev. A 52, R4340 (1995)
Phys. Rev. A 60, 3892 (1999)





$$\boxed{\Theta \sim \frac{1}{\lambda^2}\frac{\Gamma^3}{\Delta^3}\frac{I}{I_{sat}}\frac{\omega}{m}}$$

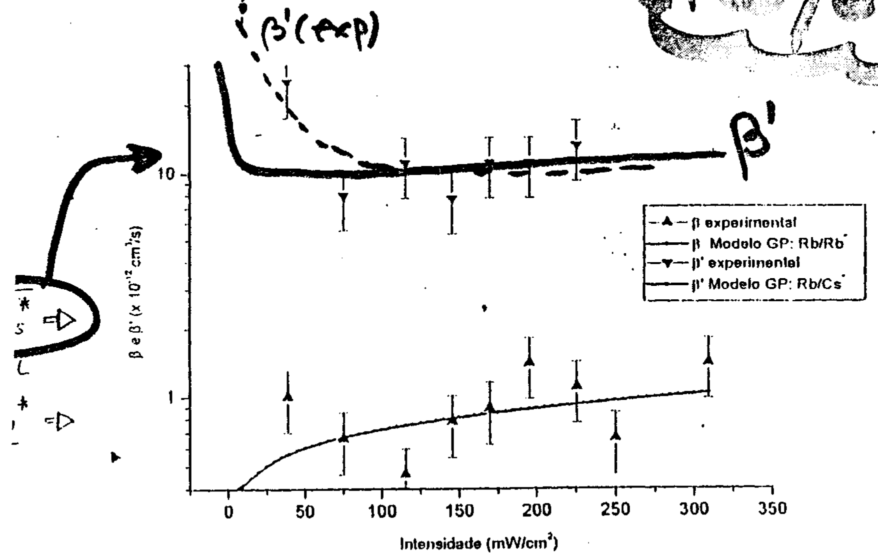
Rev. Mod. Phys. 71, 1 (1999)

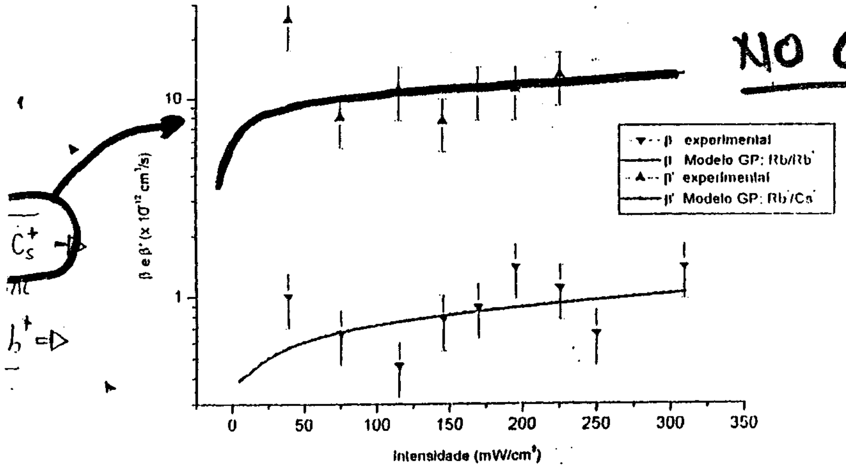
VS

Sistema : Rb/Cs

Rb/Cs

II-49





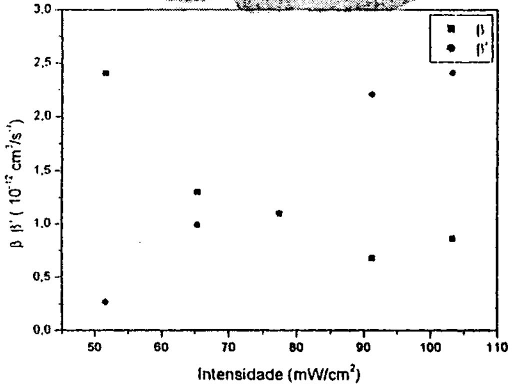
NO GOOD!

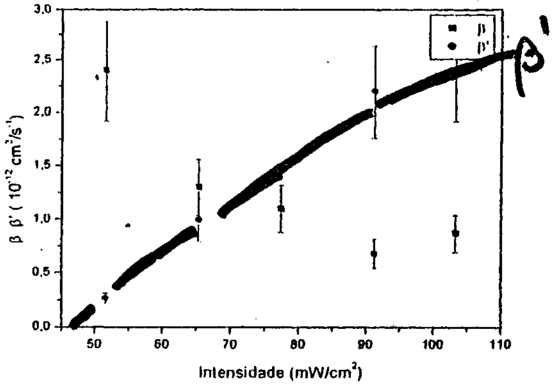
Cs/K

II-50

~~K/Cs~~

Cs/K

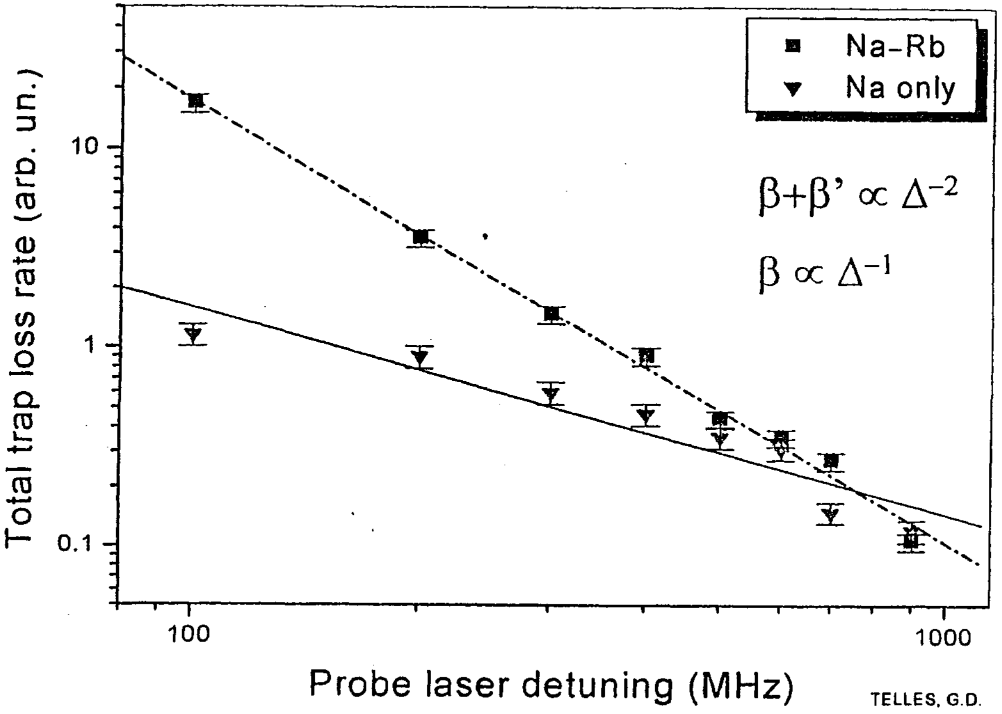




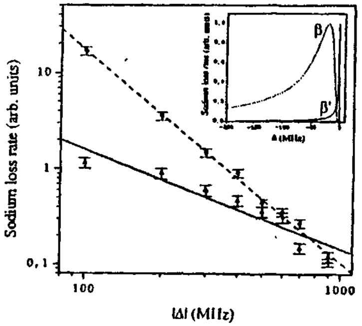
Δ = -5 MHz

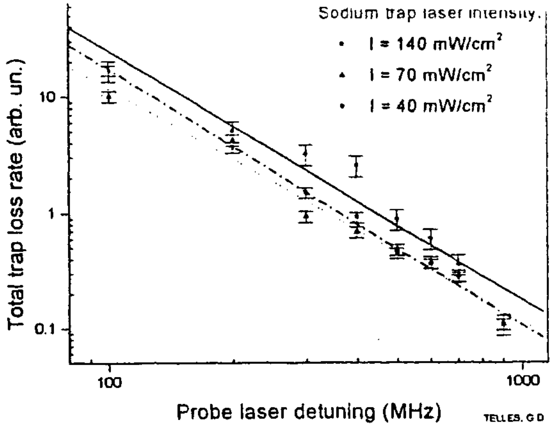
Detuning Dependence

* Extra laser ⇒

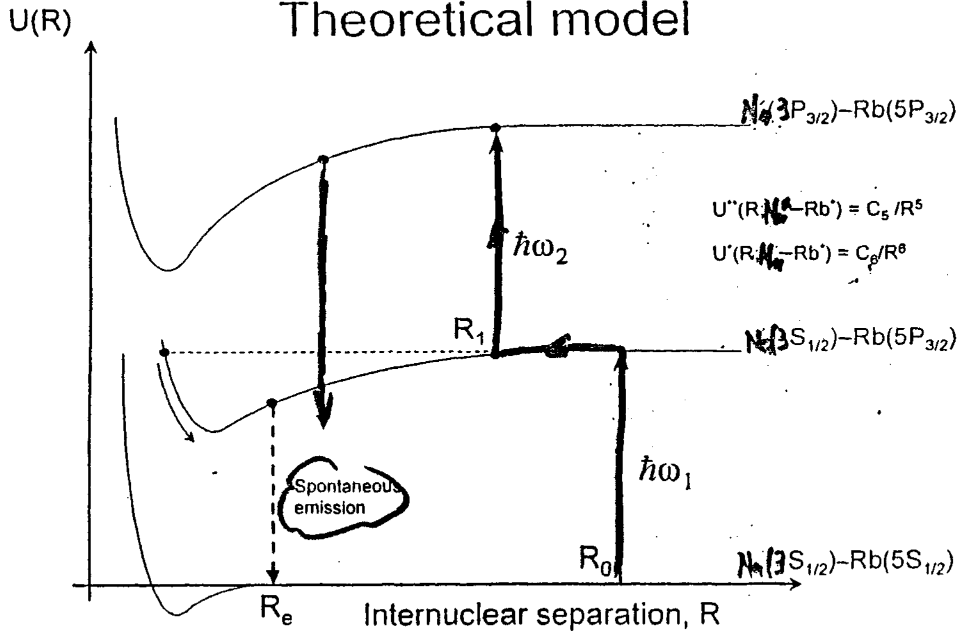


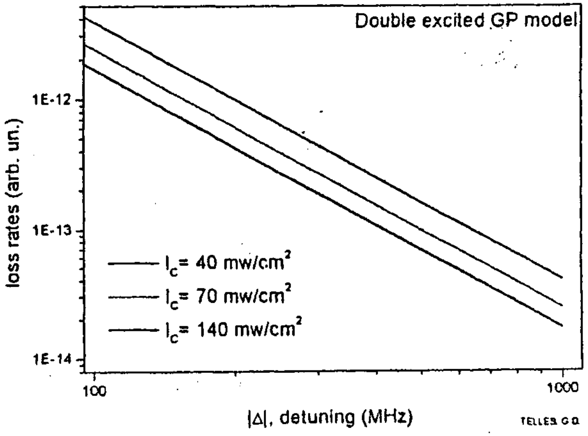
* extra laser to excite Rb
⟶ no variation





Theoretical model





Lista publicaçõs pelo grupo sao Carlos em colisõs frios

- Marcassa et al - Phys. Rev. A, R4563 (1993)
- Santos et al - Phys. Rev. A, 52, R4340 (1995)
- Bagnato et al - Las. Phys. 4, 1062 (1994)
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- S. Miranda et al - Phys. Rev. A 59, 882 (1999)
- G. Telles et al - Phys. Rev. A 59, R23 (1999)
- Weiner, Bagnato, Zilio, Julienne - Rev. Mod. Phys. 71, 1 (1999)
- Marcassa et al - Eur. J. Phys. D 7, 317 (1999)