O dubleto de Autler-Townes

Colóquio da Pós-Graduação em Física Aplicada da UFRPE

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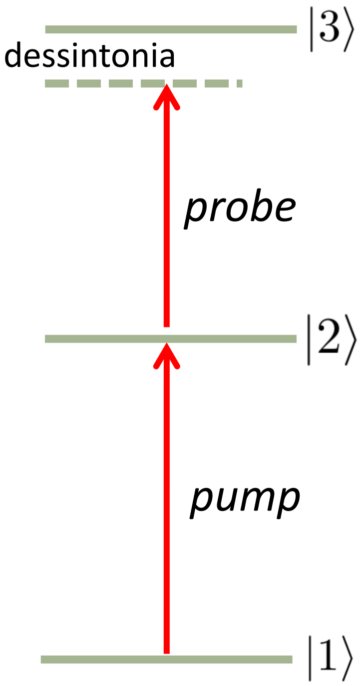
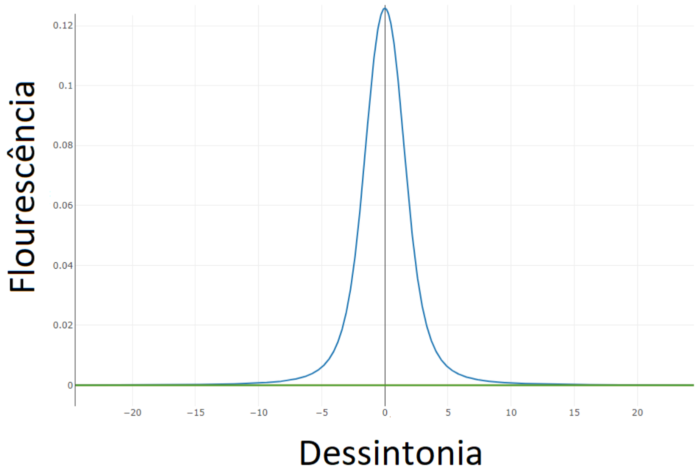
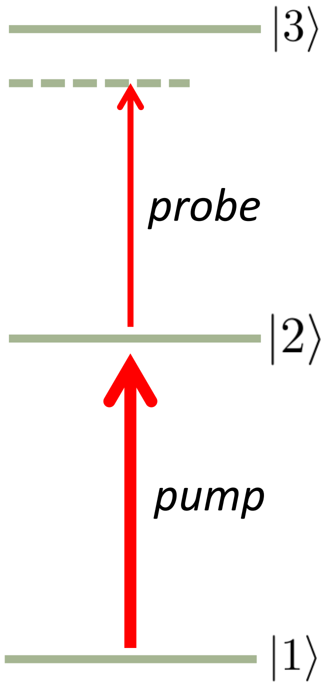
DEPARTAMENTO DE FÍSICA

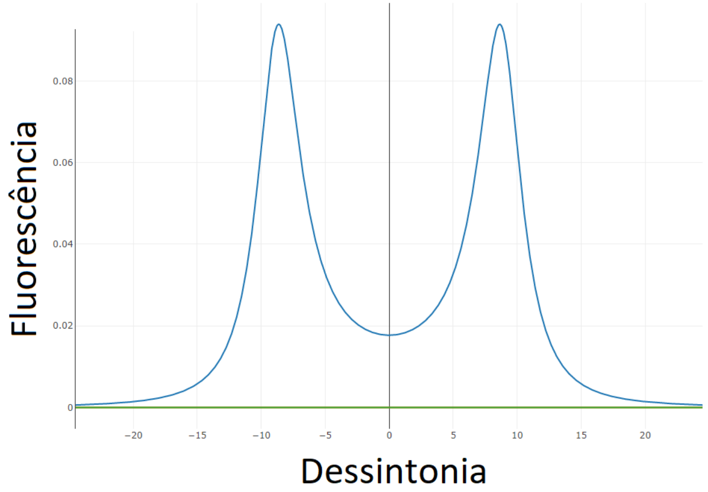
UNIVERSIDADE FEDERAL DE RONDÔNIA, CAMPUS JI-PARANÁ

O dubleto de Autler-Townes









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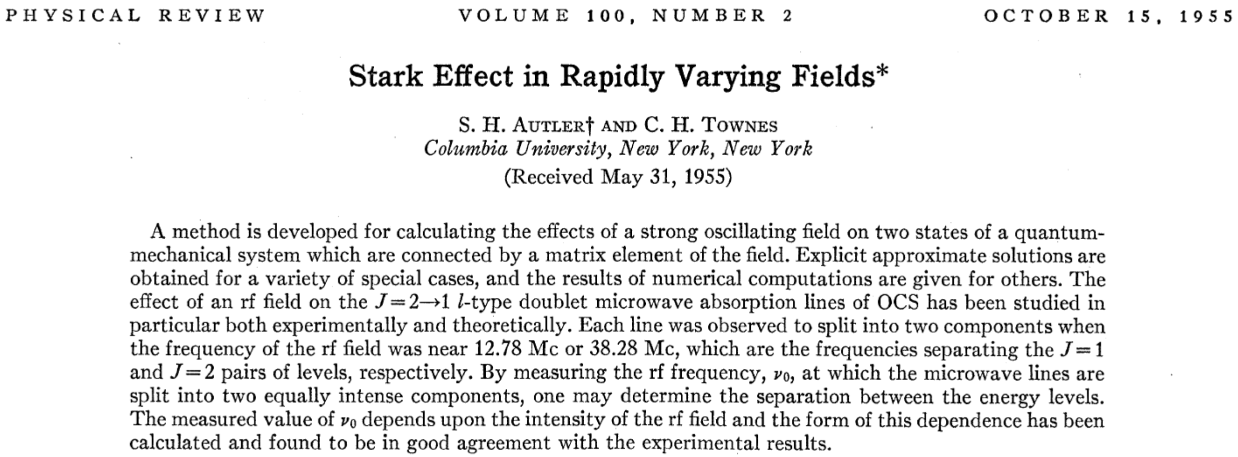
- Autler e Townes
- Teoria
- Aplicação
- O efeito Doppler
- A mistura de ondas
- Resultados recentes

Autler e Townes

Autler e Townes



PHYSICAL REVIEW VOLUME 100, NUMBER 2 OCTOBER 15, 1955

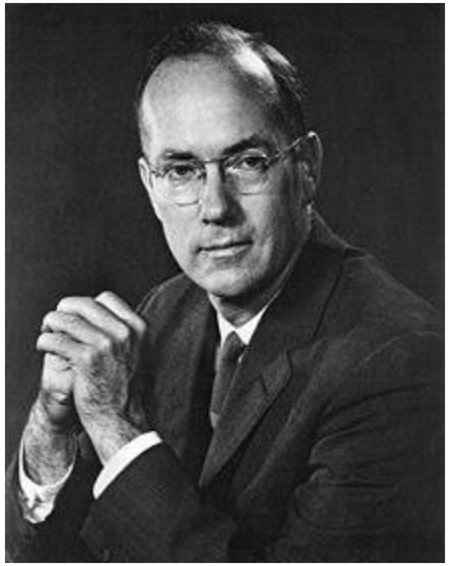
Stark Effect in Rapidly Varying Fields*

S. H. AUTLER† AND C. H. TOWNES
Columbia University, New York, New York

(Received May 31, 1955)

A method is developed for calculating the effects of a strong oscillating field on two states of a quantum-mechanical system which are connected by a matrix element of the field. Explicit approximate solutions are obtained for a variety of special cases, and the results of numerical computations are given for others. The effect of an rf field on the $J=2\rightarrow 1$ l-type doublet microwave absorption lines of OCS has been studied in particular both experimentally and theoretically. Each line was observed to split into two components when the frequency of the rf field was near 12.78 Mc or 38.28 Mc, which are the frequencies separating the $J=1$ and $J=2$ pairs of levels, respectively. By measuring the rf frequency, ν_0, at which the microwave lines are split into two equally intense components, one may determine the separation between the energy levels. The measured value of ν_0 depends upon the intensity of the rf field and the form of this dependence has been calculated and found to be in good agreement with the experimental results.

Stanley Autler (MIT)
(1922 – 1991)



Charles Hard Townes (UC Berkeley)
(1915-2015)

Prêmio Nobel de 1964
pela criação do maser

Teoria

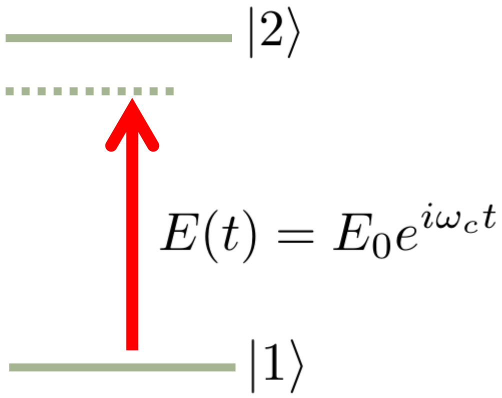
Teoria

Átomo livre

$$\hat{H} = \hat{H}_0$$

$$\hat{H}_0 |1\rangle = E_1 |1\rangle$$
$$\hat{H}_0 |2\rangle = E_2 |2\rangle$$

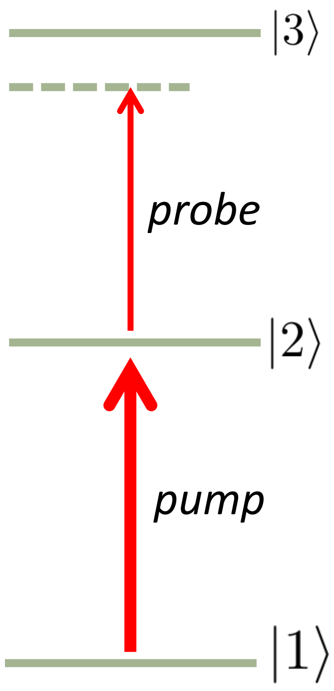
Átomo + campo



$$\hat{H} = \hat{H}_0 - \hat{\mu} E(t)$$

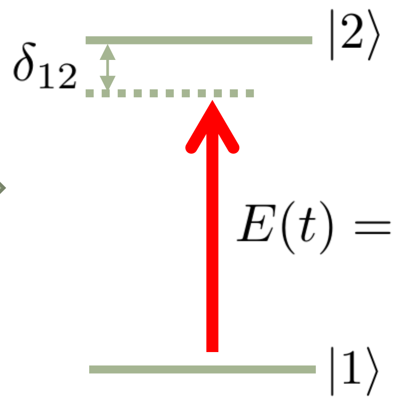
$$\hat{H} |1\rangle \neq E_1 |1\rangle$$
$$\hat{H} |2\rangle \neq E_2 |2\rangle$$

Teoria



$$\delta_{12} = \frac{E_2 - E_1}{\hbar} - \omega_c$$

$$\delta_{12} = \omega_{21} - \omega_c$$



$$E(t) = E_0 e^{i\omega_c t}$$

Átomo livre

$$\hat{H}_0 = \hbar\delta_{21}\begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$$

Átomo-campo

$$\hat{H}_1 = -\hbar\Omega_{12}\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$\hat{H} = \hbar\begin{pmatrix} 0 & -\Omega_{12} \\ -\Omega_{12} & \delta_{21} \end{pmatrix}$$

$$\begin{vmatrix} -\Delta E & -\hbar\Omega_{12} \\ -\hbar\Omega_{12} & \hbar\delta_{21} - \Delta E \end{vmatrix} = 0$$

$$\Delta E = \frac{\hbar\delta_{12}}{2} \pm \frac{\hbar}{2}\sqrt{4\Omega_{12}^2 + \delta_{12}^2}$$

$$\Omega_{12} = \frac{\mu_{12}E_0}{\hbar} = \frac{\langle 1|\, e\hat{r}\, |2\rangle\, E_0}{\hbar} = \frac{eE_0}{\hbar}\int \psi_1^* r \psi_2 d^3r$$

Teoria

$$\Delta E = \frac{\hbar \delta_{12}}{2} \pm \frac{\hbar}{2}\sqrt{4\Omega_{12}^2 + \delta_{12}^2}$$

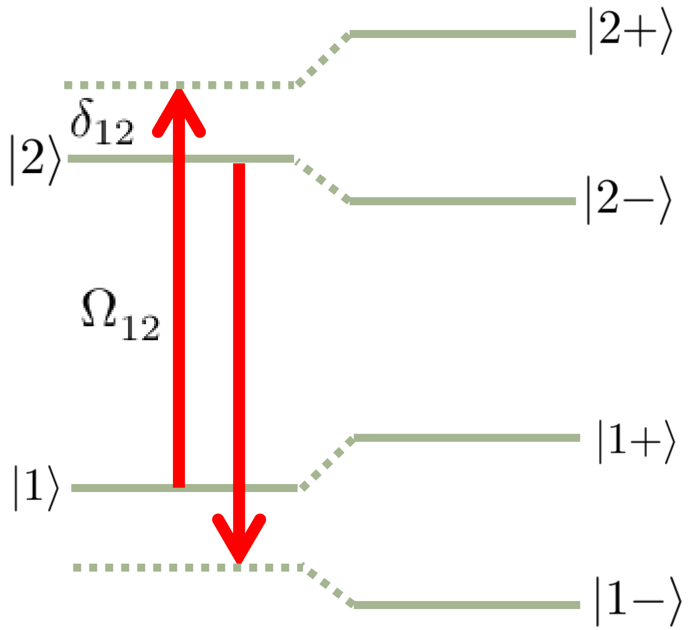
$$\Omega_{12} \ll \delta_{12}$$

$$\frac{\Delta E}{\hbar} = \frac{\delta_{12}}{2} \pm \frac{\delta_{12}}{2}\left(1 + \frac{2\Omega_{12}^2}{\delta^2}\right)$$

$$\frac{\Delta E}{\hbar} = \left\{\delta_{12} + \frac{\Omega_{12}^2}{\delta_{12}}, -\frac{\Omega_{12}^2}{\delta_{12}}\right\}$$

Light shift

AC Stark shift



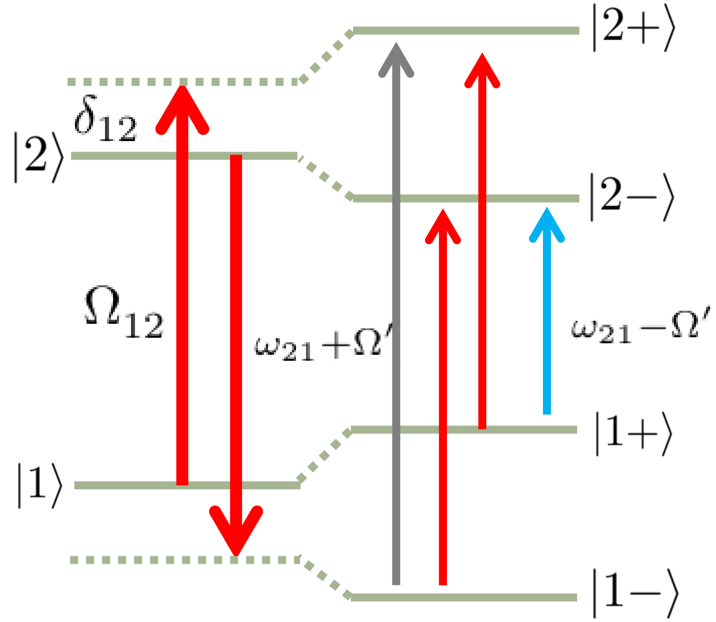
Dressed atom

(átomo vestido)

$$\omega_{2\pm} = +\frac{\delta_{12}}{2} \pm \frac{1}{2}\sqrt{4\Omega_{12}^2 + \delta_{12}^2}$$

$$\omega_{1\pm} = -\frac{\delta_{12}}{2} \pm \frac{1}{2}\sqrt{4\Omega_{12}^2 + \delta_{12}^2}$$

Teoria



$$\omega_{2\pm} = +\frac{\delta_{12}}{2} \pm \frac{1}{2}\sqrt{4\Omega_{12}^2 + \delta_{12}^2}$$

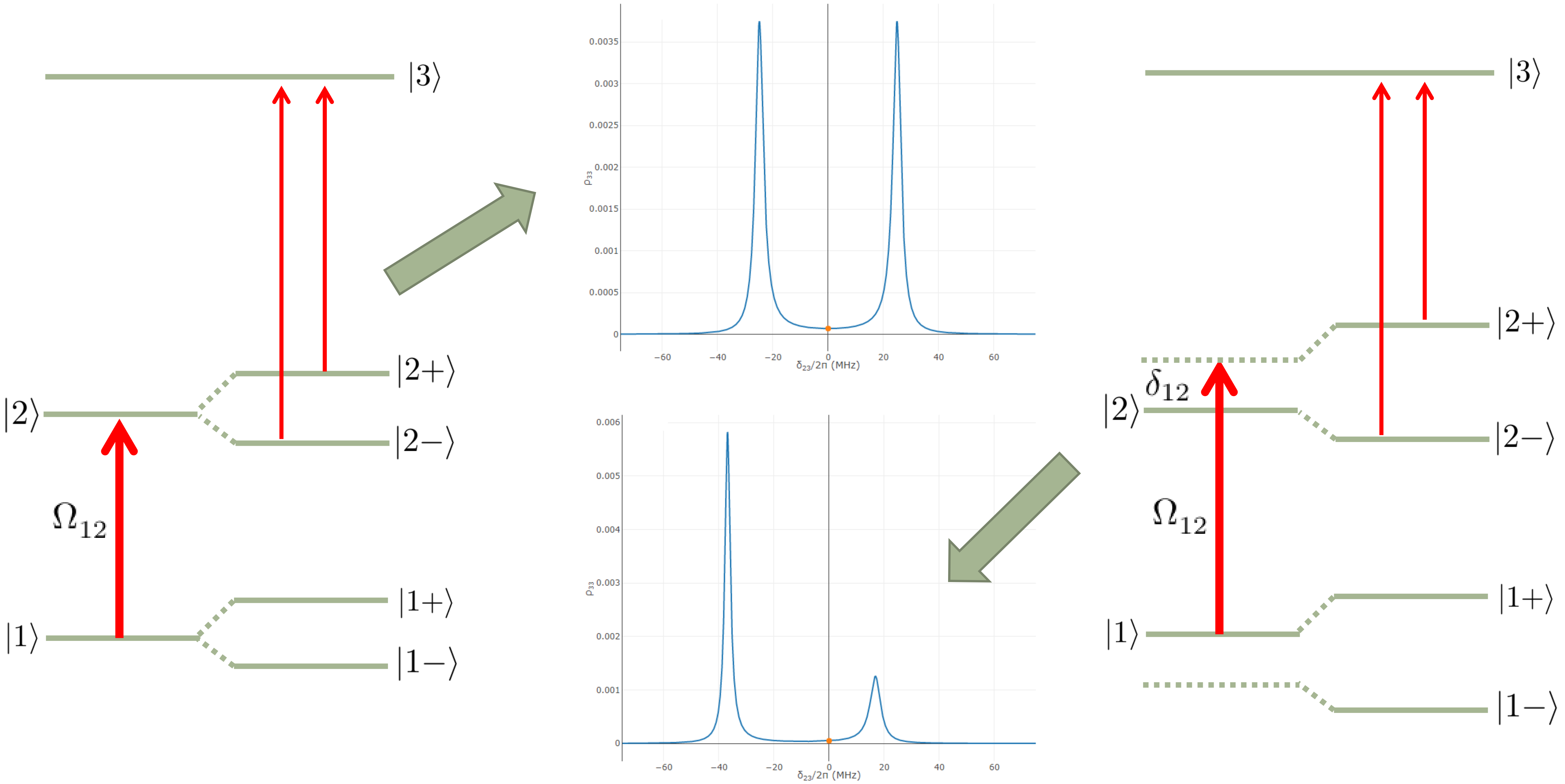
$$\omega_{1\pm} = -\frac{\delta_{12}}{2} \pm \frac{1}{2}\sqrt{4\Omega_{12}^2 + \delta_{12}^2}$$

$$\Omega'_{12} = \sqrt{4\Omega_{21}^2 + \delta_{12}^2}$$

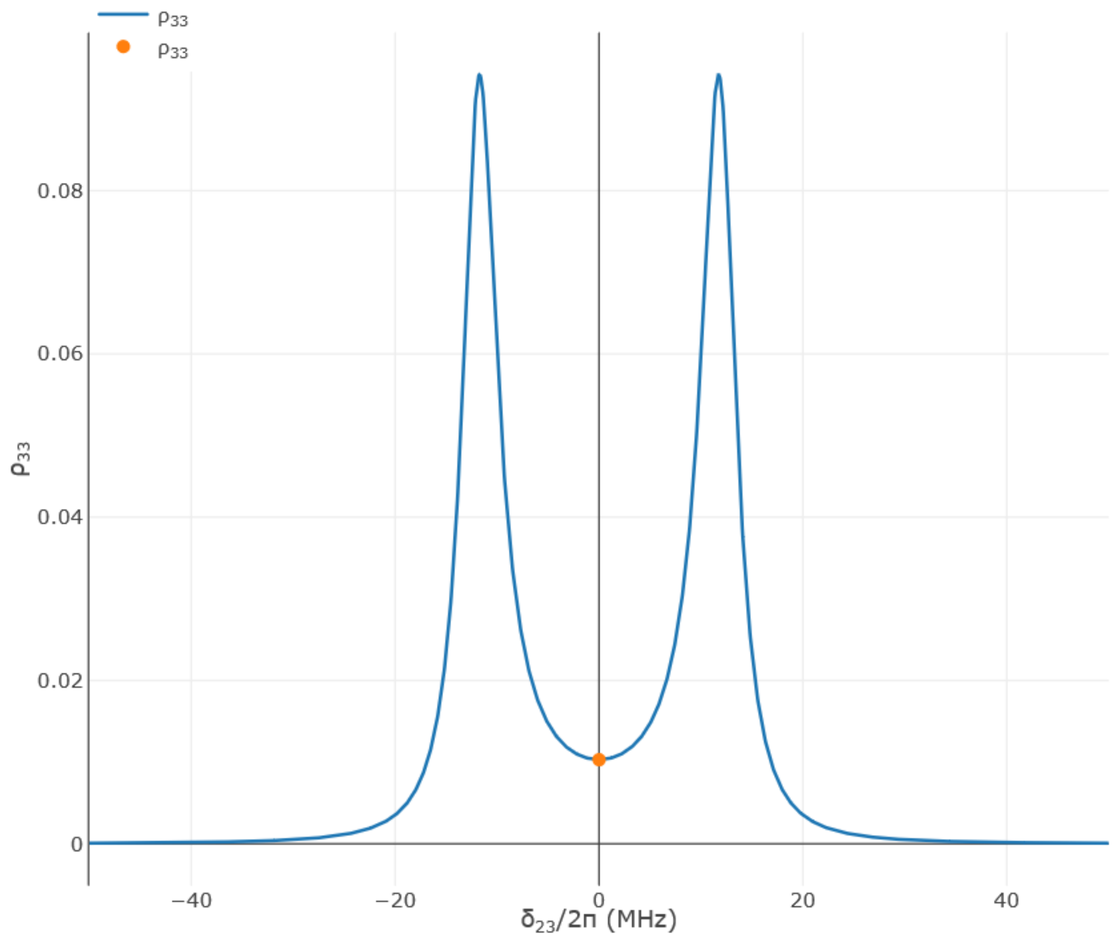
$$\langle\hat{\mu}\rangle = \mu_{12}\frac{\Omega}{\Omega'}\left[-\frac{\delta}{2\Omega'}e^{-i\omega_{21}t} + \frac{1}{4}\left(\frac{\delta}{\Omega'} - 1\right)e^{-i(\omega_{21}+\Omega')t} + \frac{1}{4}\left(\frac{\delta}{\Omega'} + 1\right)e^{-i(\omega_{21}-\Omega')t}\right] + c.c$$

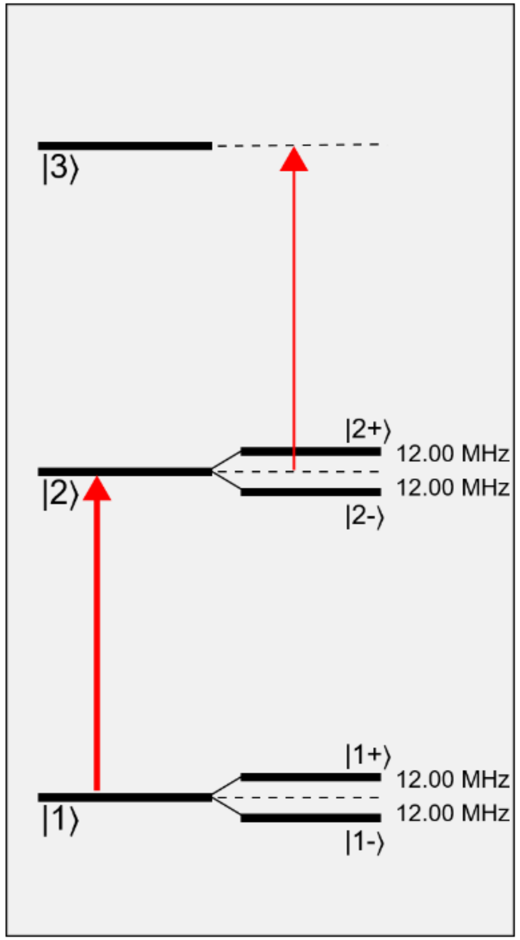
R. Boyd, *Nonlinear Optics* (Academic Press, 2008)

Teoria



|3⟩
|2+⟩
|2⟩
|2−⟩
Ω12
|1+⟩
|1⟩
|1−⟩
ρ33
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
−60
−40
−20
0
20
40
60
δ23/2π (MHz)
0.006
0.005
0.004
0.003
0.002
0.001
δ12





$\Omega_{12}/2\pi$ = **12** MHz

$\Omega_{23}/2\pi$ = **0.6** MHz

$\delta_{12}/2\pi$ = **0** MHz

$\delta_{23}/2\pi$ = **0** MHz

v = **0** m/s

λ_{12} = **780** nm

λ_{23} = **776** nm

$\gamma_{22}/2\pi$ = **6** MHz

$\gamma_{33}/2\pi$ = **0.66** MHz

$\Gamma/2\pi$ = **0.1** MHz

Variando:

- δ_{12}
- δ_{23}

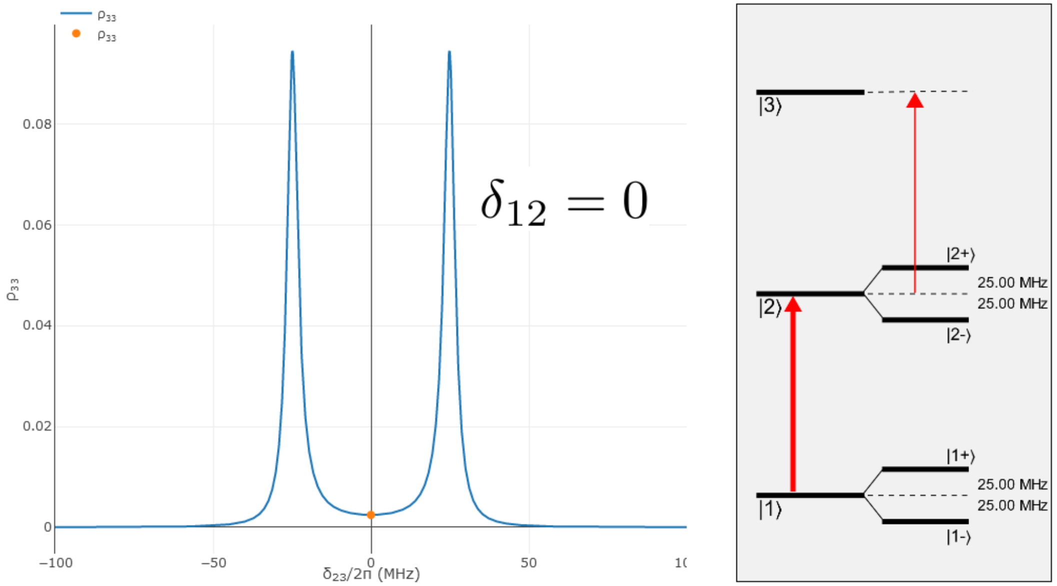
Configuração

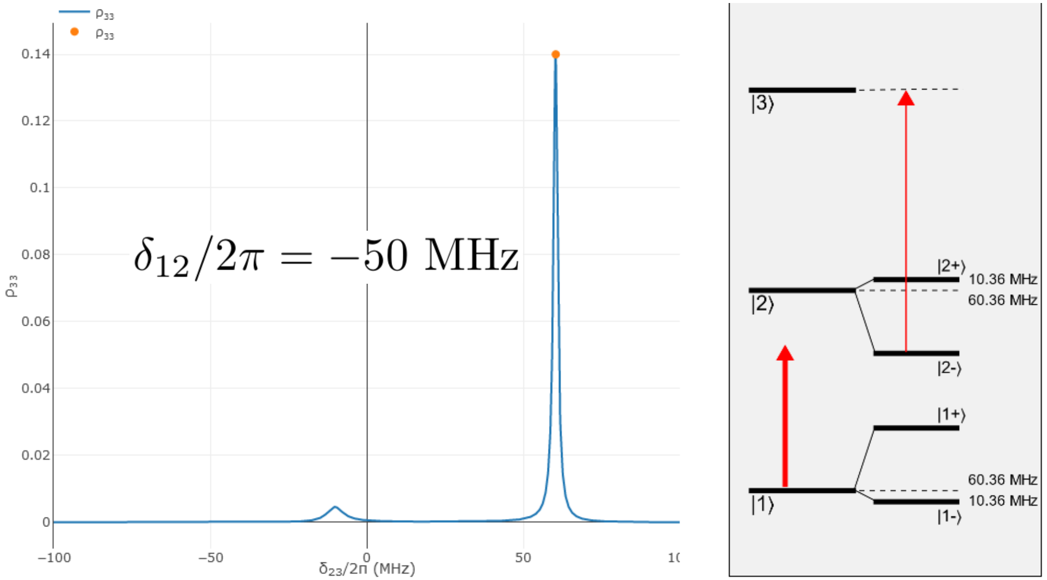
- **Copropagante**
- **Contrapropagante**

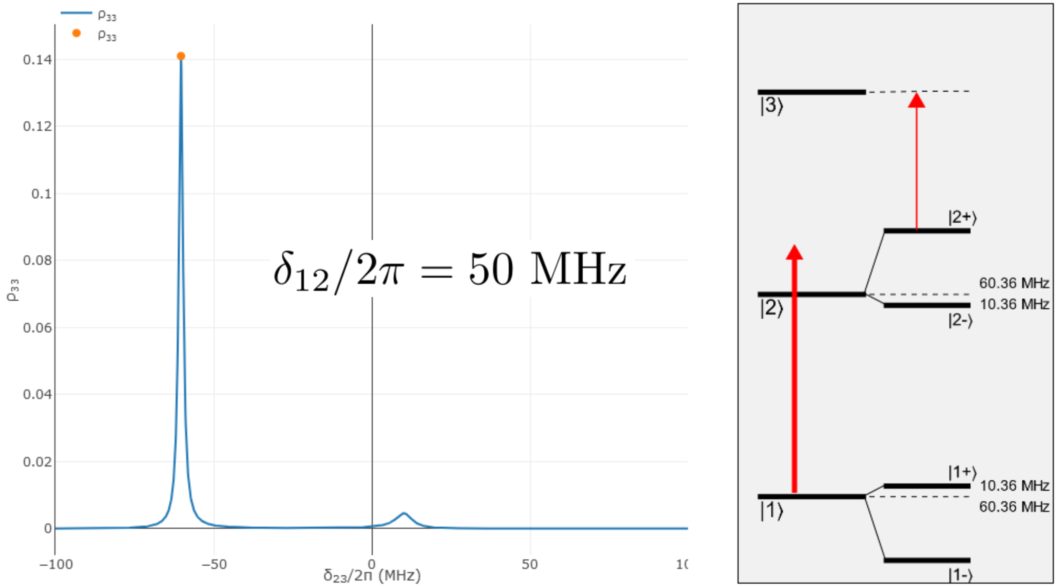
Varrendo a dessintonia do laser *probe*

$$\delta_{23}$$

$$\Omega_{12}/2\pi = 25\ \text{MHz}$$





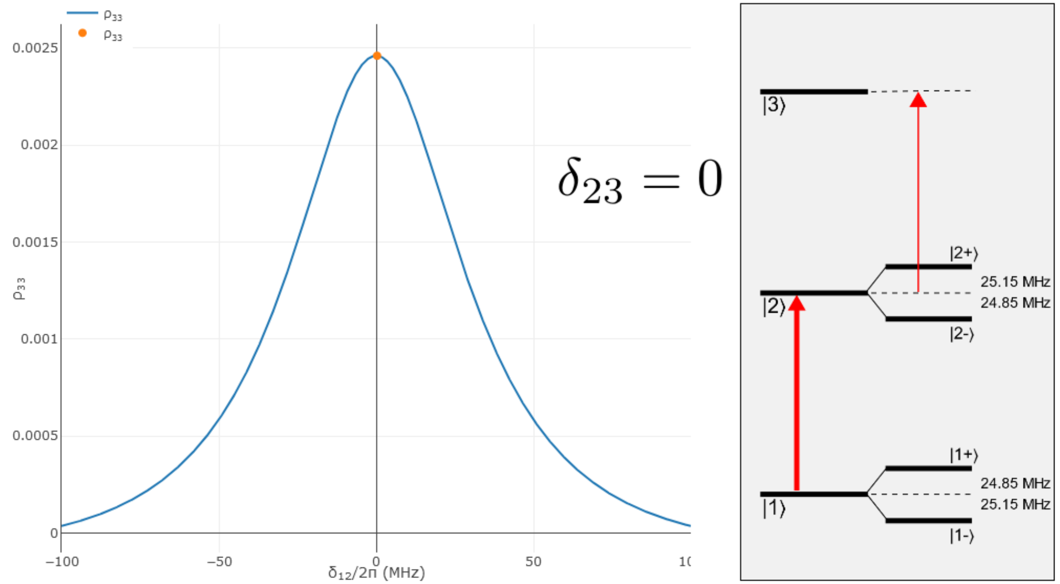


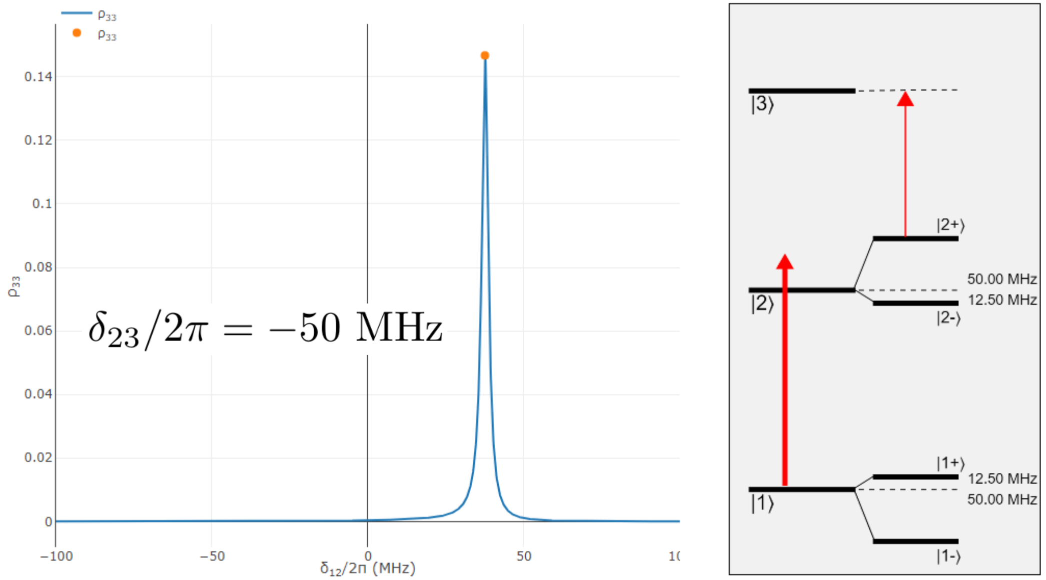
Varrendo a dessintonia do laser *pump*

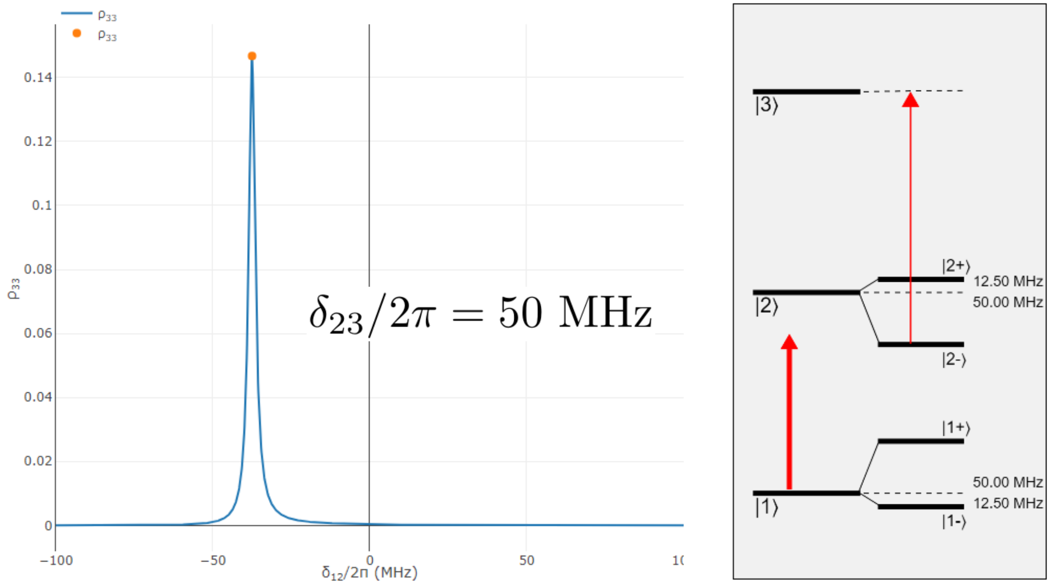
$$\delta_{12}$$

$$\Omega_{12}/2\pi = 25 \text{ MHz}$$

Não é possível *observar* o dubleto de Autler-Townes quando o feixe forte varre sua dessintonia

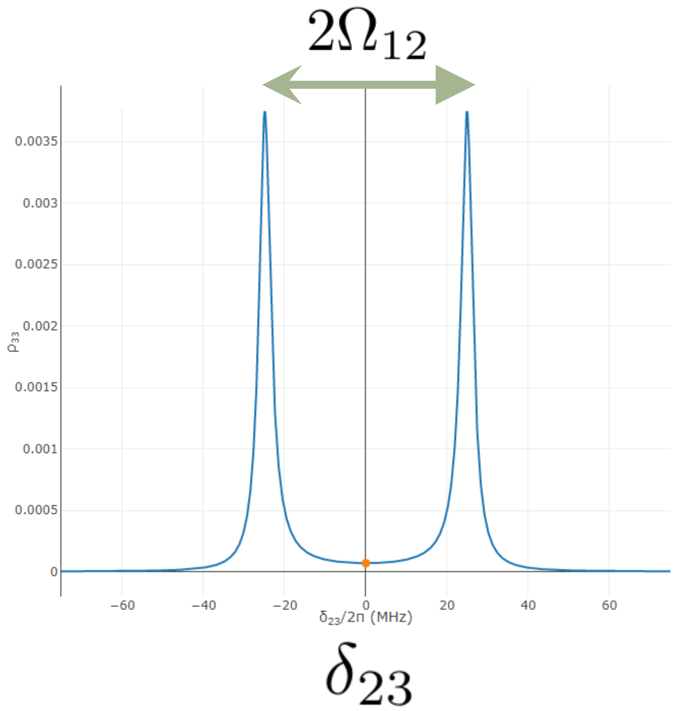


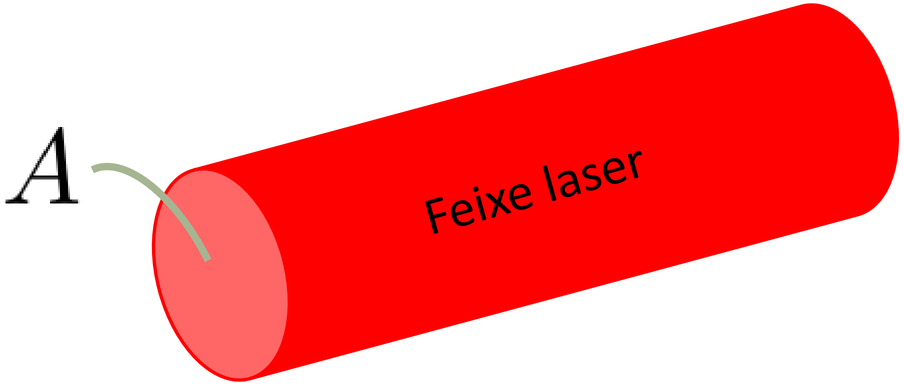




Aplicação

Aplicação: Medida de dipolo elétrico





$$I = \frac{P}{A} = \frac{1}{2} c \epsilon_0 E_0^2$$

$$\Omega_{12} = \frac{\mu_{12} E_0}{\hbar}$$

$$\boxed{\mu_{12} = \hbar \Omega_{12} \sqrt{\frac{\epsilon_0 c A}{2P}}}$$

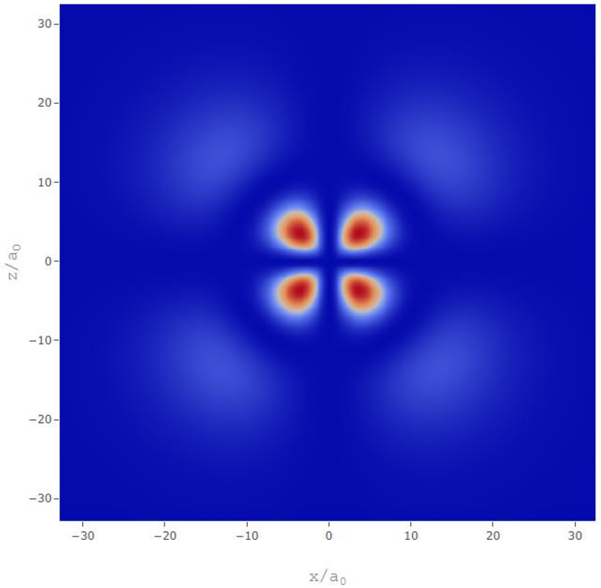
Aplicação: Medida de dipolo elétrico

New Journal of Physics
The open-access journal for physics

Measurement of the electric dipole moments for transitions to rubidium Rydberg states via Autler–Townes splitting (2011)

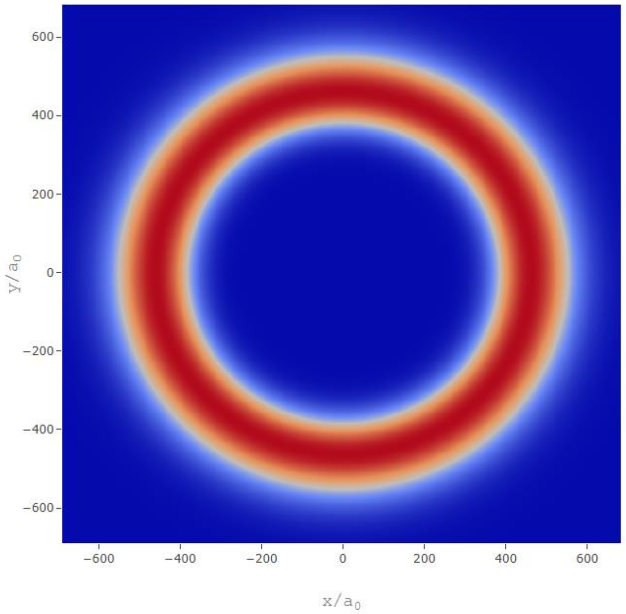
M J Piotrowicz[1], C MacCormick[1,3], A Kowalczyk[1], S Bergamini[1,3], I I Beterov[2] and E A Yakshina[2]

[1] Department of Physics and Astronomy, The Open University, Walton Hall, Milton Keynes, MK6 7AA, UK
[2] Institute of Semiconductor Physics, Lavrentyeva Avenue 13, 630090 Novosibirsk, Russia

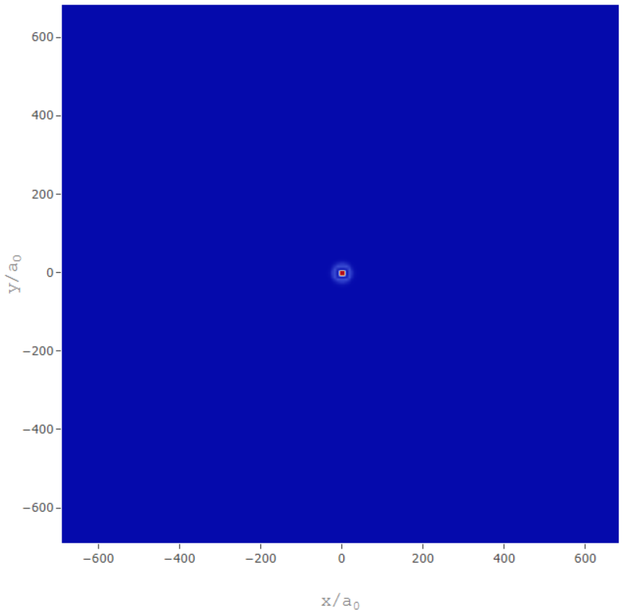


$$\psi_{n,\ell,m} = \psi_{4,2,1} \quad \text{(4D)}$$

Hidrogênio (simufisica.com)



$$\psi_{22,21,21} \quad (n = 22)$$



Aplicação: Medida de dipolo elétrico

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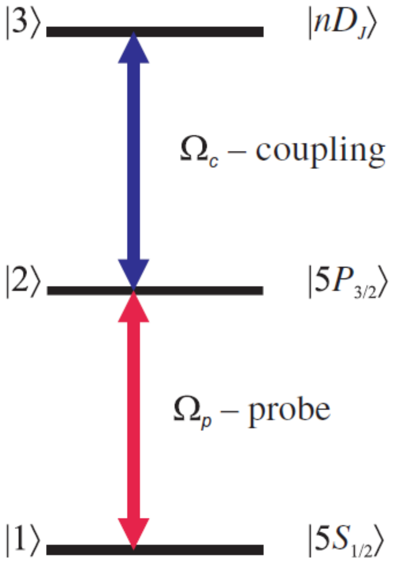
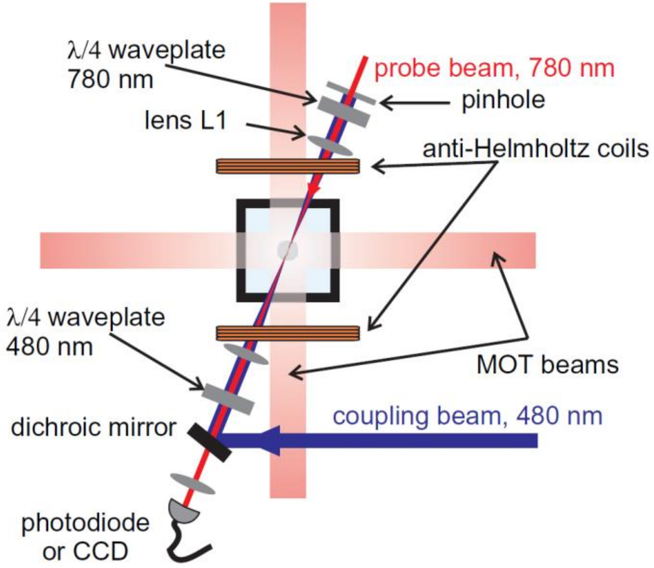
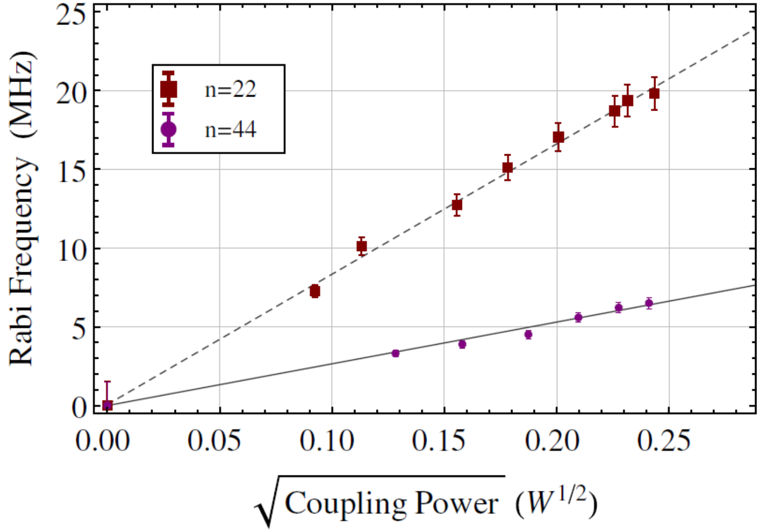
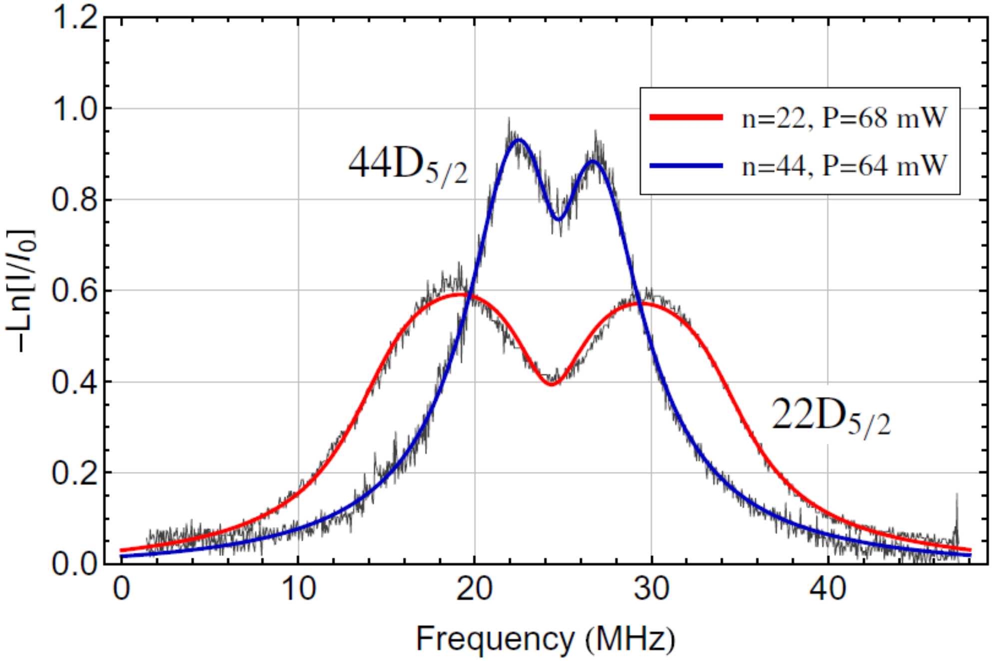


rubídio

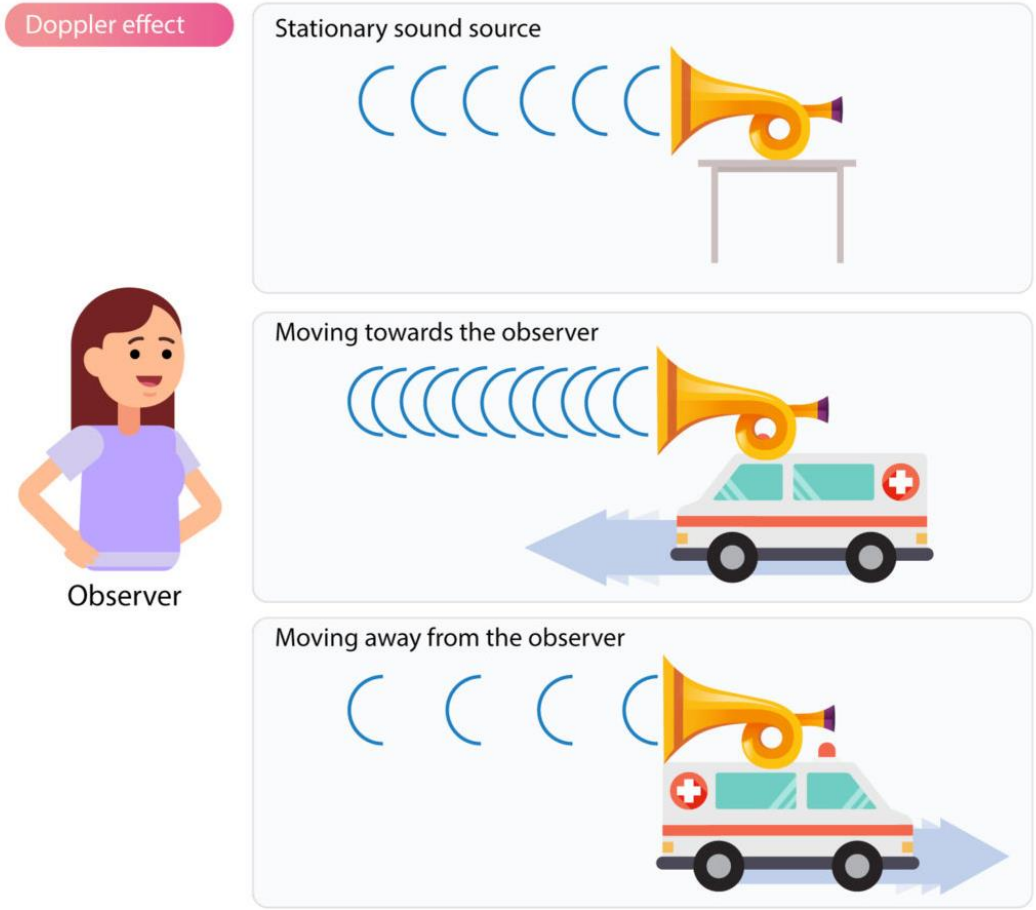




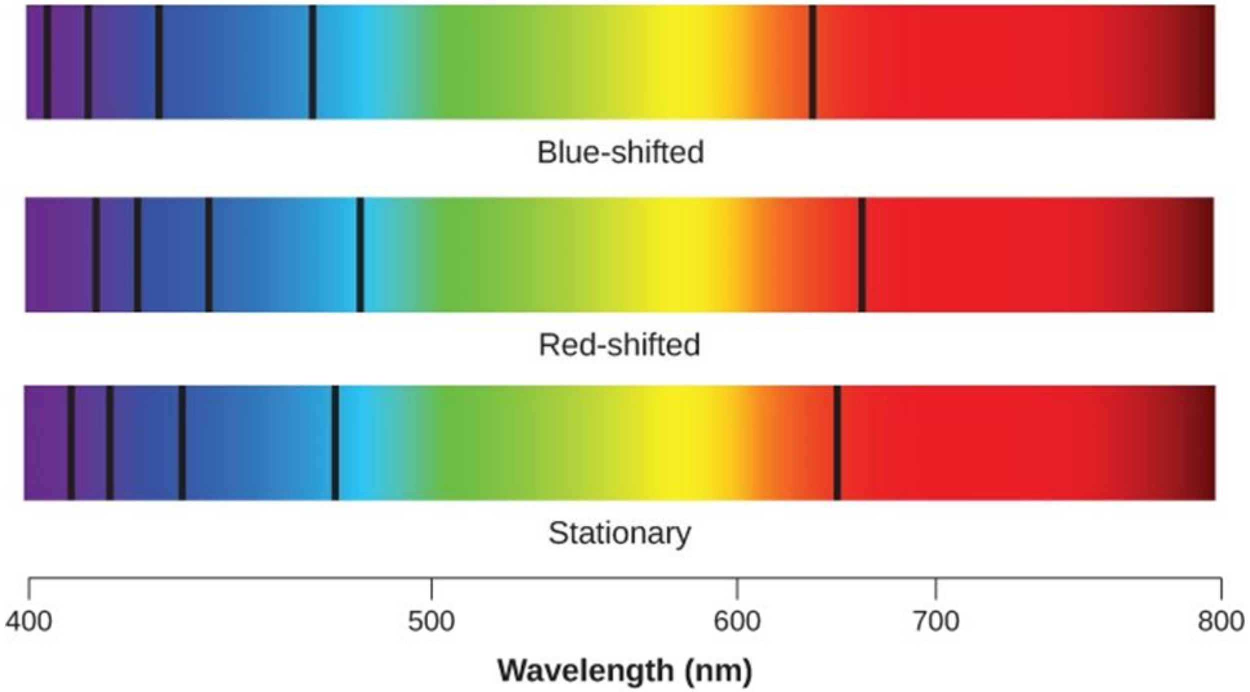


O efeito Autler-Townes na presença do deslocamento Doppler

Efeito Doppler

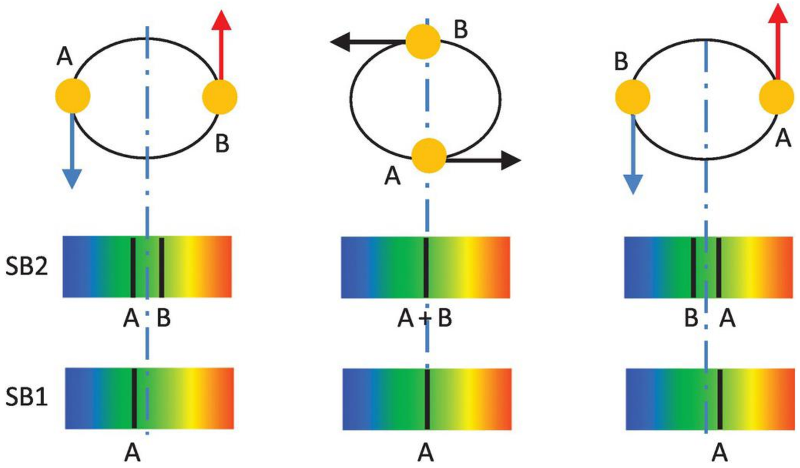


Efeito Doppler



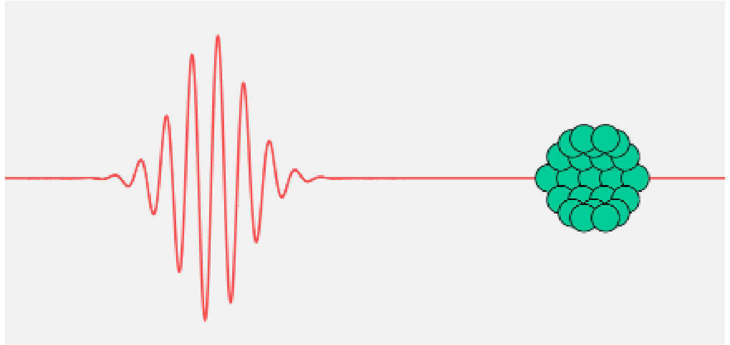
Lei de Hubble (expansão da Universo)

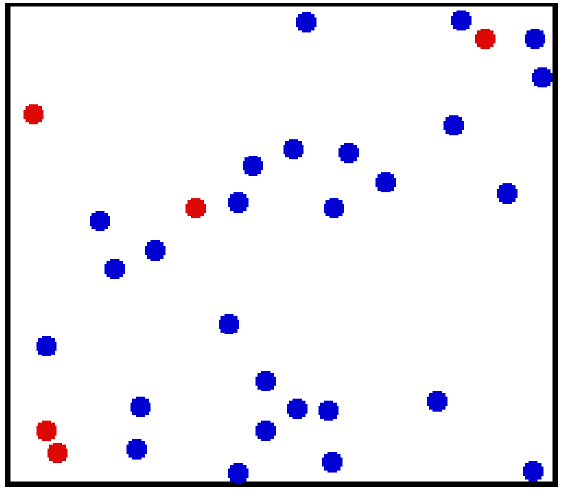
Detecção de estrelas binárias

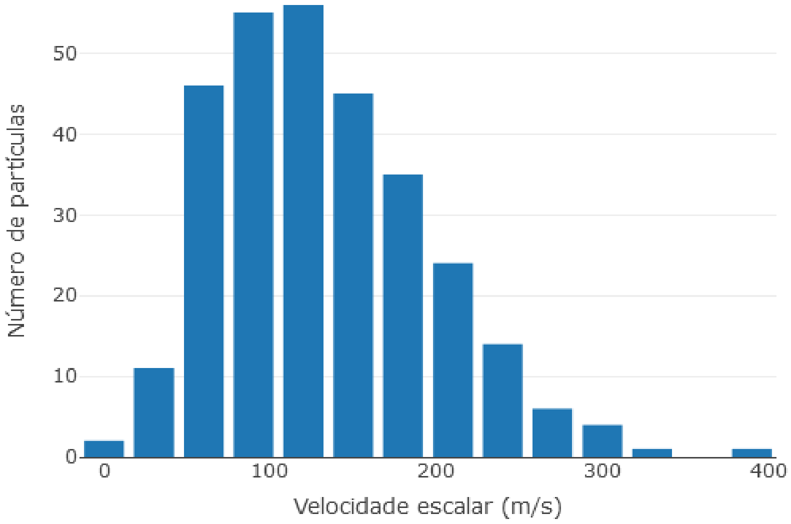


Alargamento de linhas espectrais

Efeito Doppler

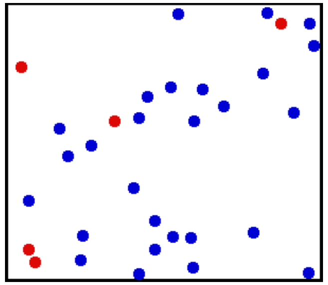


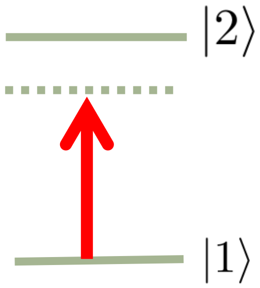




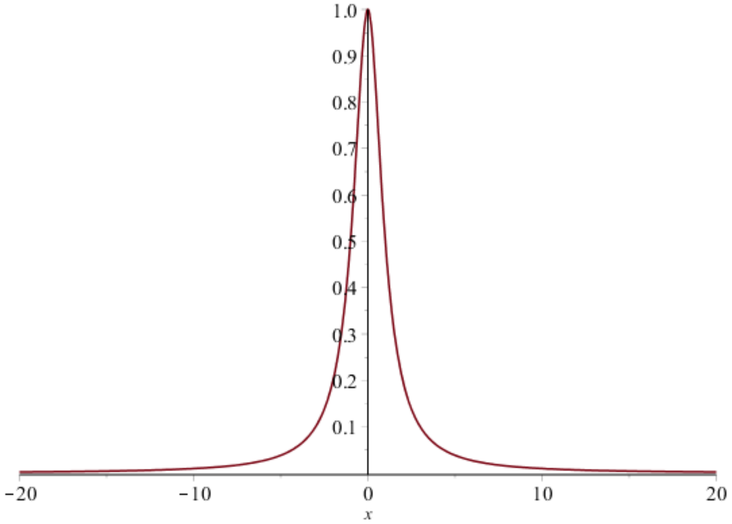
$$f(v)dv = 4\pi \left(\frac{m}{2\pi k_B T} \right)^{3/2} v^2 e^{-mv^2/2k_B T}$$

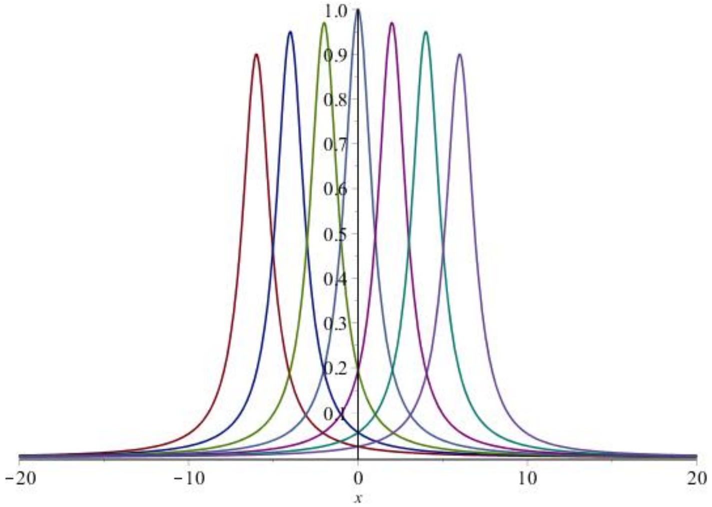
Efeito Doppler

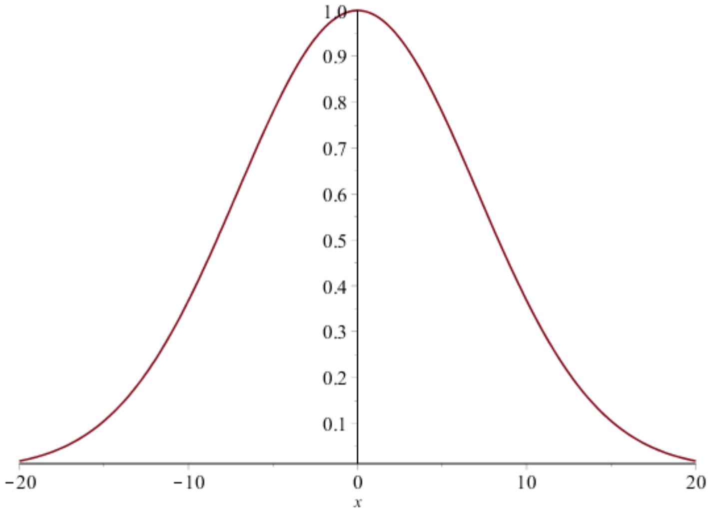




$$\Delta\omega = kv = \frac{2\pi v}{\lambda}$$



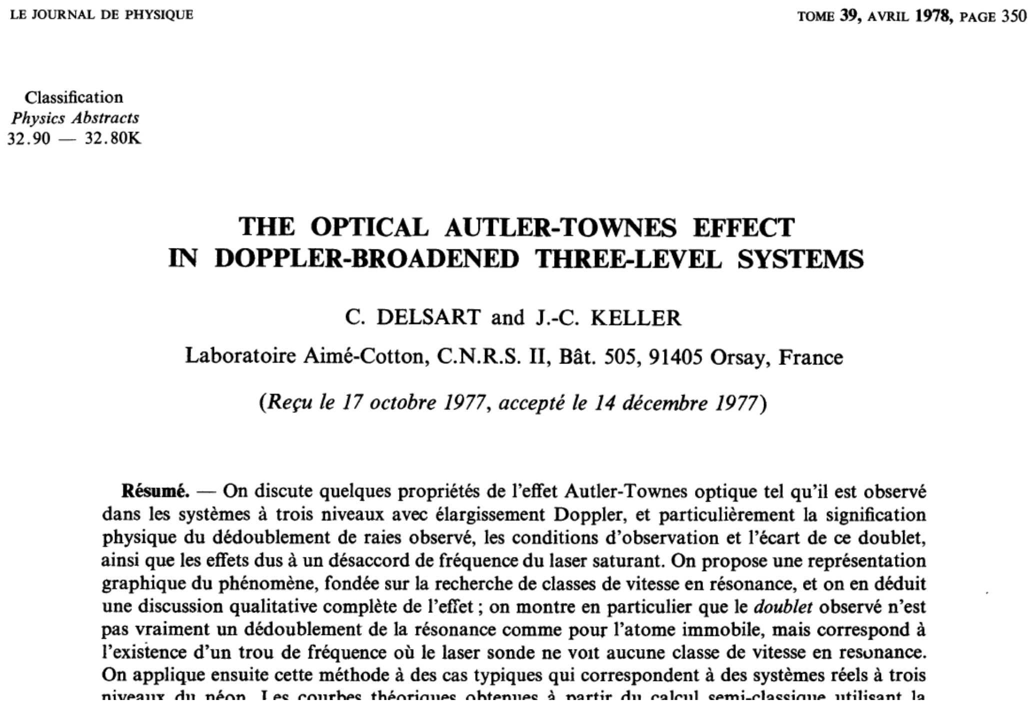




Alargamento Doppler

Efeito Doppler no ATS

O alargamento Doppler “escode” o efeito Autler-Townes?


LE JOURNAL DE PHYSIQUE TOME 39, AVRIL 1978, PAGE 350

Classification
Physics Abstracts
32.90 — 32.80K

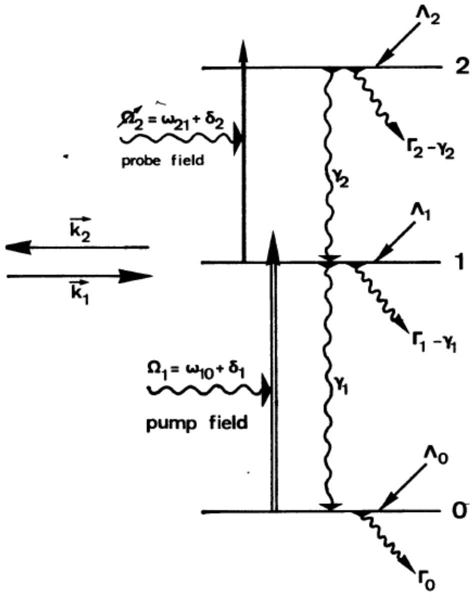
THE OPTICAL AUTLER-TOWNES EFFECT IN DOPPLER-BROADENED THREE-LEVEL SYSTEMS

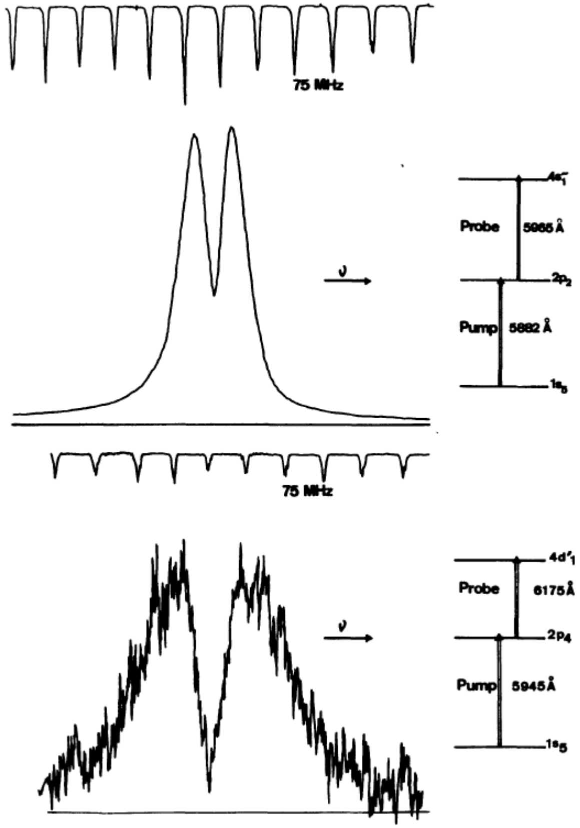
C. DELSART and J.-C. KELLER

Laboratoire Aimé-Cotton, C.N.R.S. II, Bât. 505, 91405 Orsay, France

(*Reçu le 17 octobre 1977, accepté le 14 décembre 1977*)

Résumé. — On discute quelques propriétés de l’effet Autler-Townes optique tel qu’il est observé dans les systèmes à trois niveaux avec élargissement Doppler, et particulièrement la signification physique du dédoublement de raies observé, les conditions d’observation et l’écart de ce doublet, ainsi que les effets dus à un désaccord de fréquence du laser saturant. On propose une représentation graphique du phénomène, fondée sur la recherche de classes de vitesse en résonance, et on en déduit une discussion qualitative complète de l’effet ; on montre en particulier que le *doublet* observé n’est pas vraiment un dédoublement de la résonance comme pour l’atome immobile, mais correspond à l’existence d’un trou de fréquence où le laser sonde ne voit aucune classe de vitesse en resonance. On applique ensuite cette méthode à des cas typiques qui correspondent à des systèmes réels à trois niveaux du néon. Les courbes théoriques obtenues à partir du calcul semi-classique utilisant la



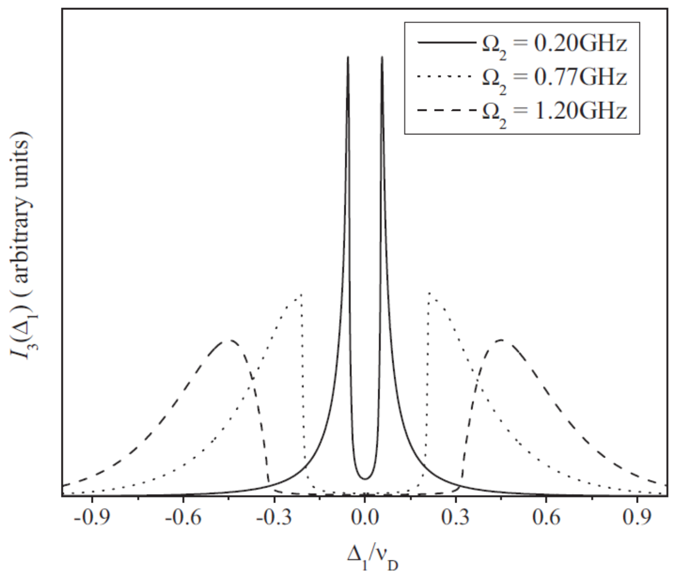


Efeito Doppler no ATS

PHYSICAL REVIEW A **76**, 053407 (2007)

Effect of Doppler broadening on Autler-Townes splitting in the molecular cascade excitation scheme

E. Ahmed and A. M. Lyyra
Department of Physics, Temple University, Philadelphia, Pennsylvania 19122, USA

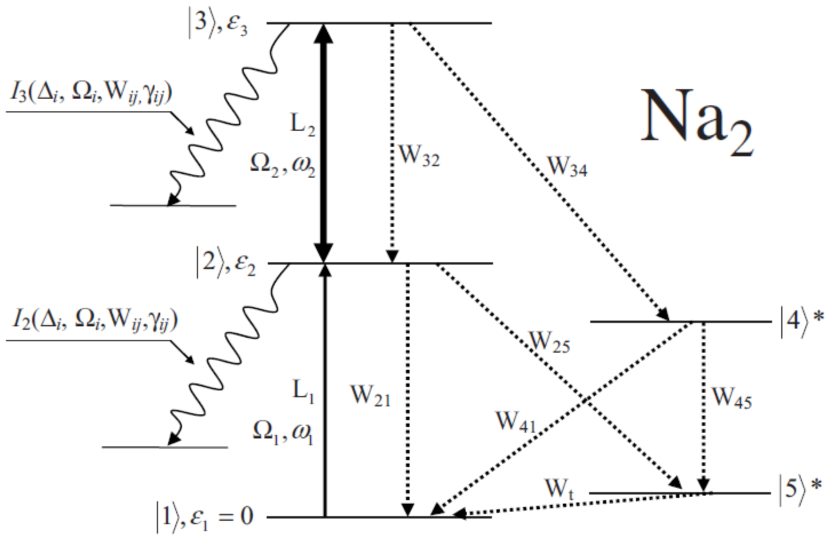


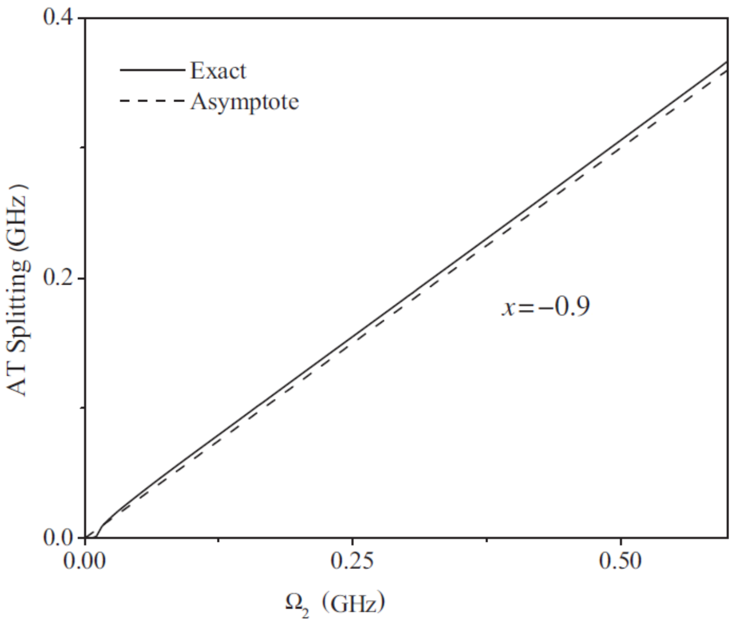
$$\Delta_1^{AT\ splitting} = 2\sqrt{-x(1+x)}\,\Omega_2$$

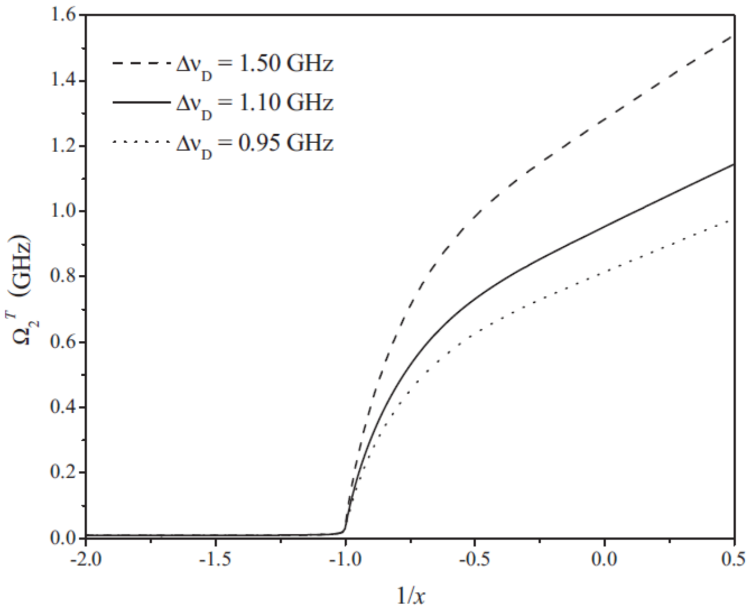
$$x = \frac{k_1}{k_2}$$

$x < 0$ for counterpropagating laser beams

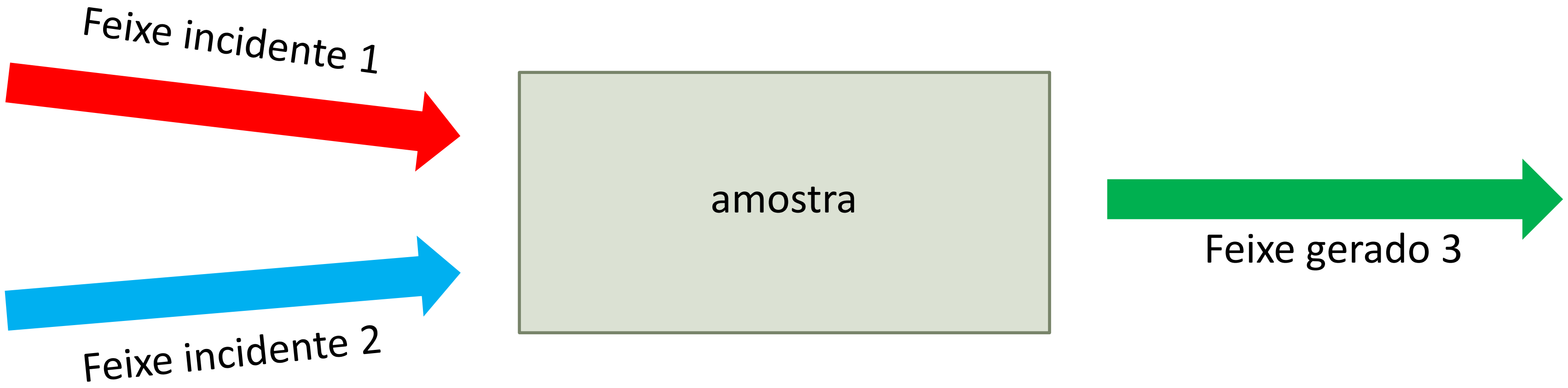
$x > 0$ for copropagating laser beams







O efeito Autler-Townes na mistura de ondas

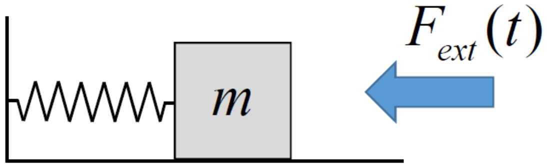


Feixe incidente 1
amostra
Feixe gerado 3
Feixe incidente 2

A mistura de ondas

Fórmula geral:

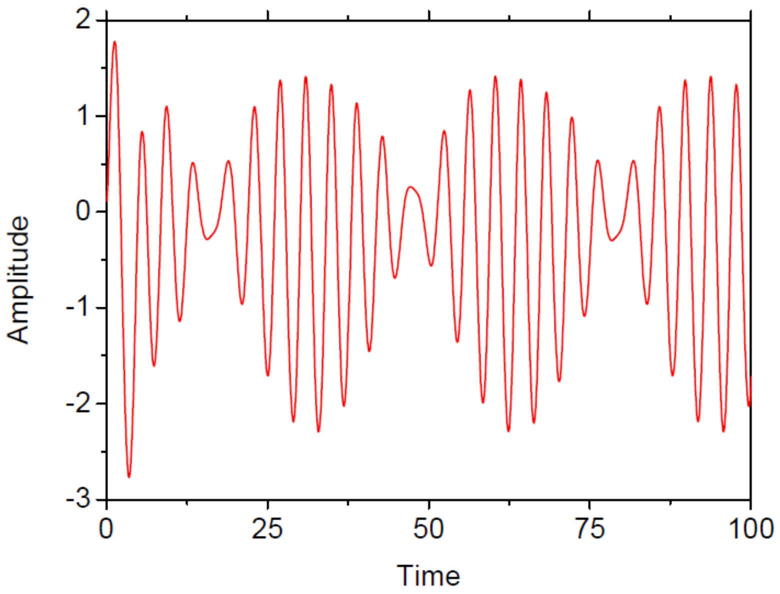
$$\omega_1, \omega_2, \omega_3, \ldots \longrightarrow \alpha_1\omega_1 \pm \alpha_2\omega_2 \pm \alpha_3\omega_3 \pm \cdots$$



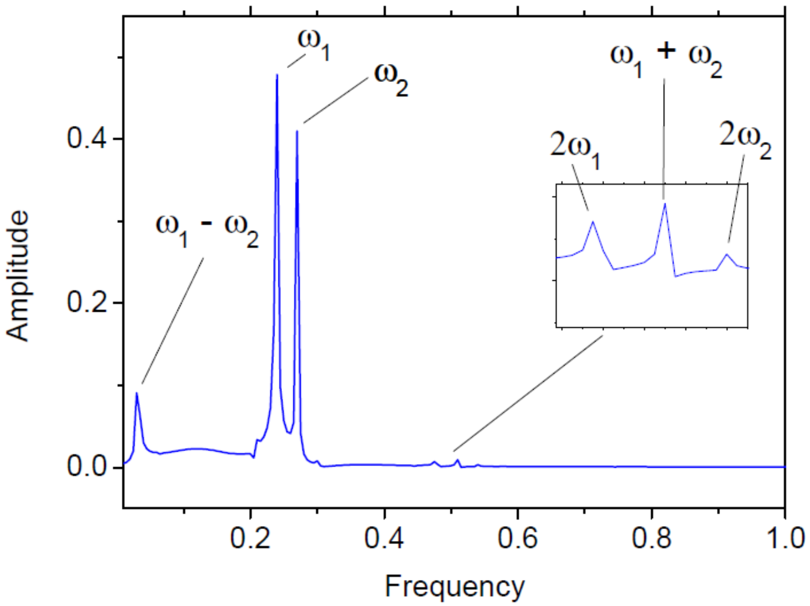
$$F_{ext}(t) = F_0\left(\cos\omega_1 t + \cos\omega_2 t\right)$$

Mola não linear: $F_{el} = -kx - k_2x^2$

$$m\ddot{x} + \gamma\dot{x} + kx + k_2x^2 = F_{ext}(t)$$



Transformada de Fourier



$$\omega_1, \omega_2 \longrightarrow \begin{cases} \omega_1 \\ \omega_2 \\ 2\omega_1 \\ 2\omega_2 \\ \omega_1 + \omega_2 \\ \omega_1 - \omega_2 \\ 0 \end{cases}$$

Eletromagnetismo:

$$P = \epsilon_0 \chi^{(1)} E + \epsilon_0 \chi^{(2)} E^2 + \epsilon_0 \chi^{(3)} E^3 + \cdots$$

$$\begin{aligned} \chi^{(1)} &\approx 1 \\ \chi^{(2)} &\approx 10^{-12}\ m/V \\ \chi^{(3)} &\approx 10^{-24}\ m^2/V^2 \end{aligned}$$

A mistura de ondas no rubídio

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Coherent and collimated blue light generated by four-wave mixing in Rb vapour

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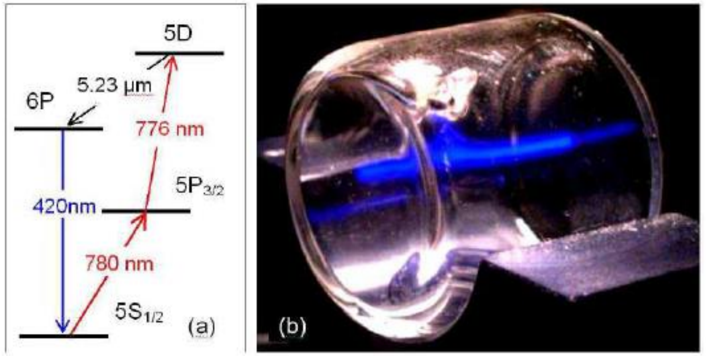
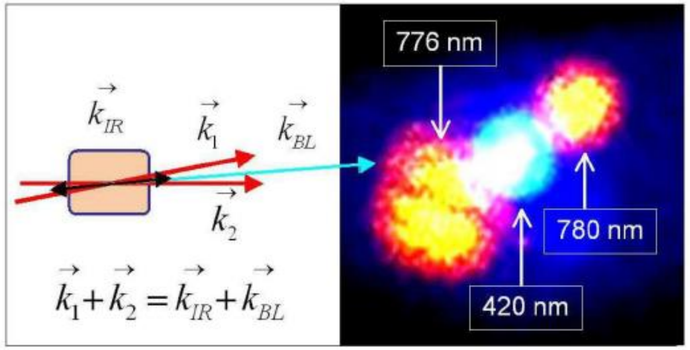
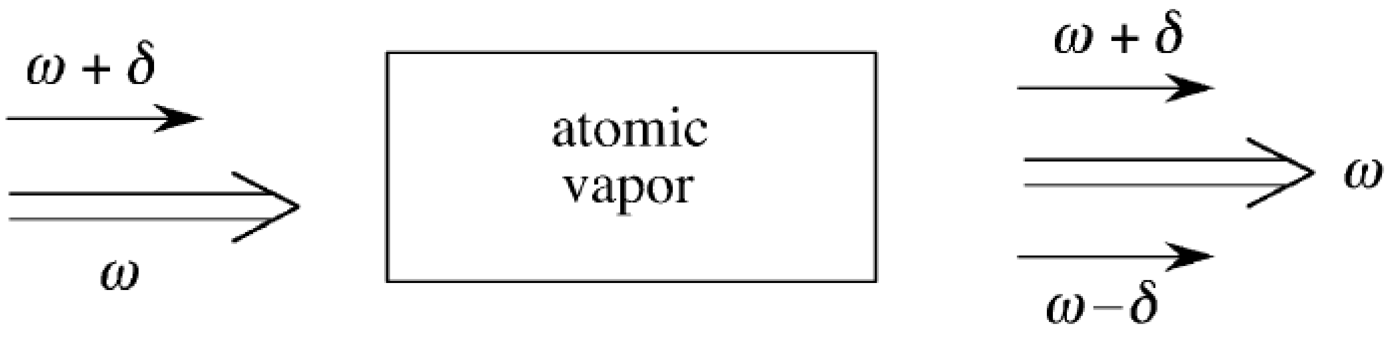


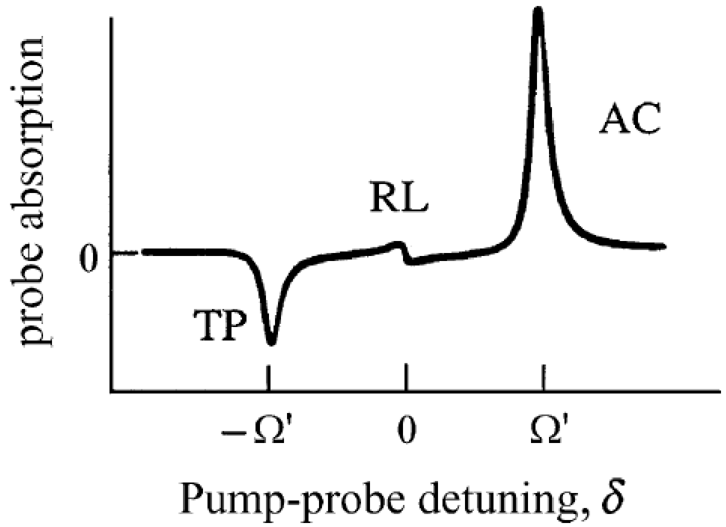


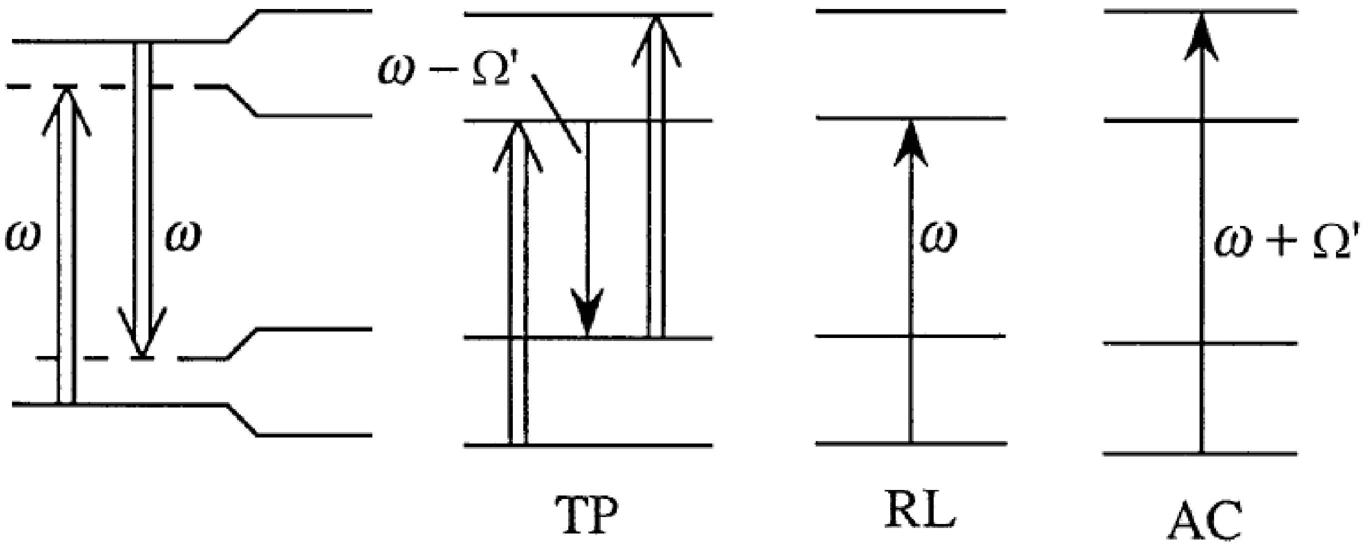
A mistura de ondas



$$\Delta T_2 = -3$$

$$\Omega T_2 = 8$$





A mistura de ondas no rubídio

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Mollow triplet in cold atoms

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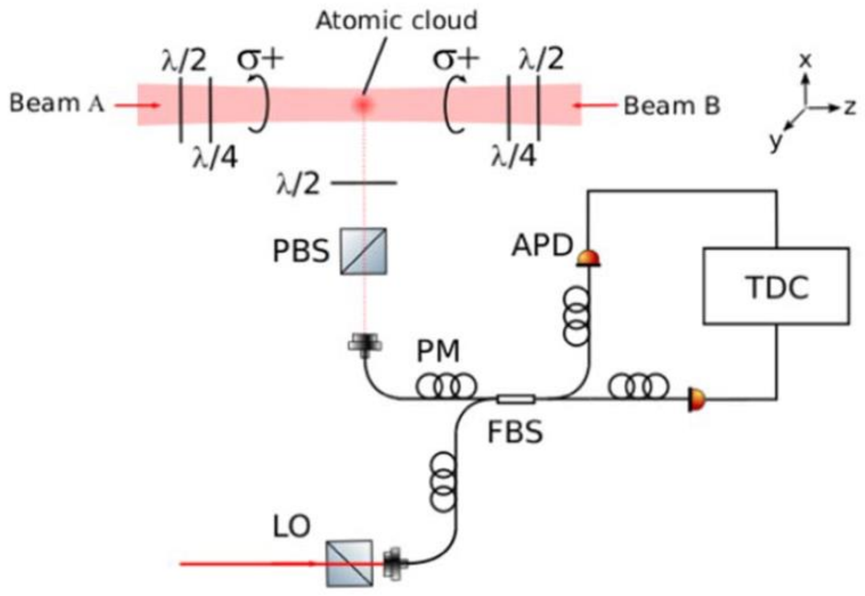
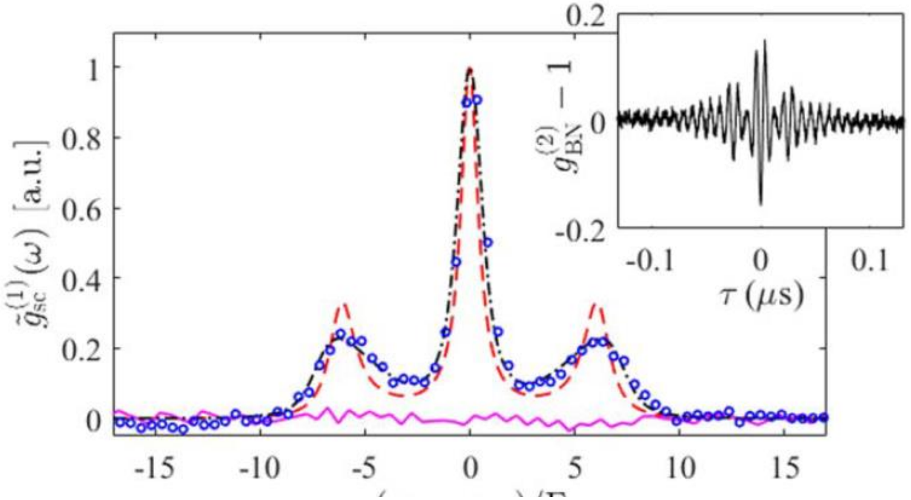
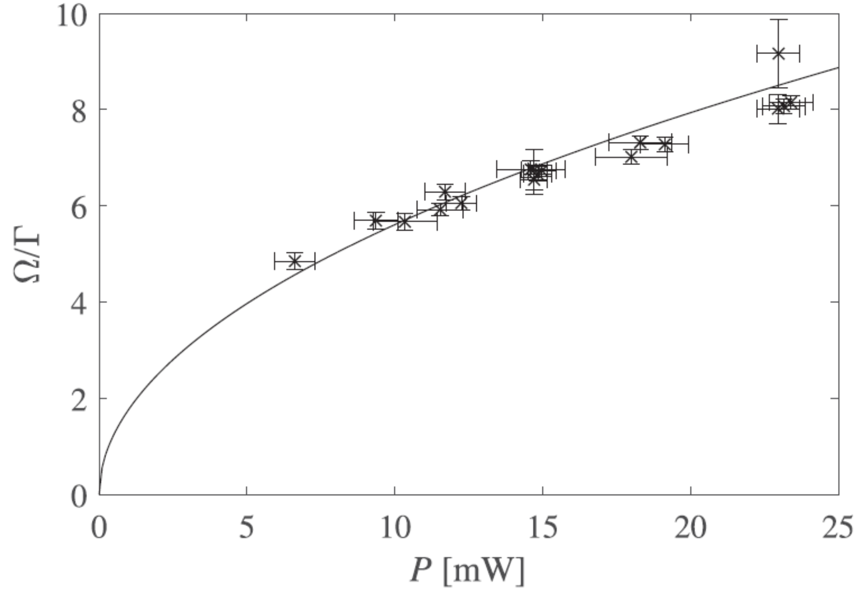
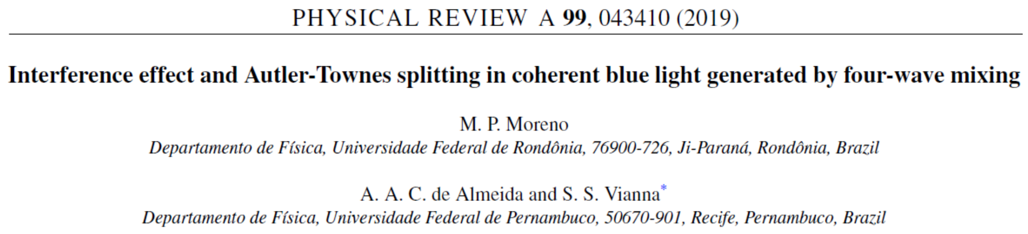


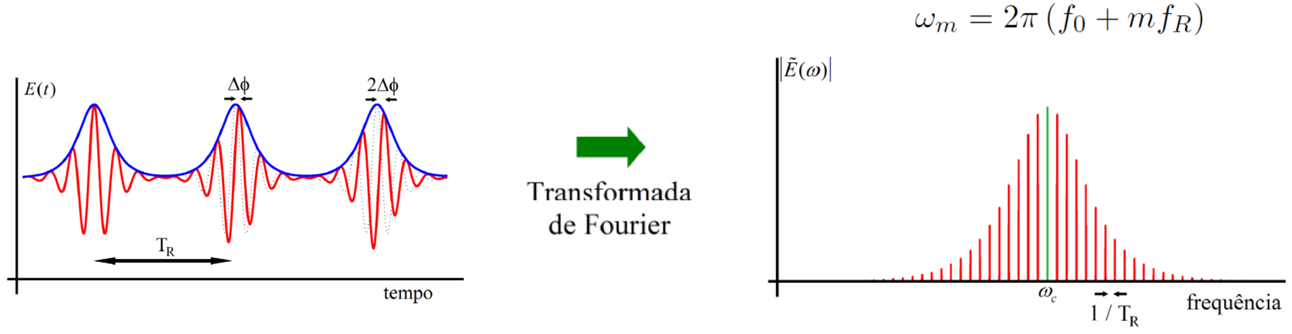


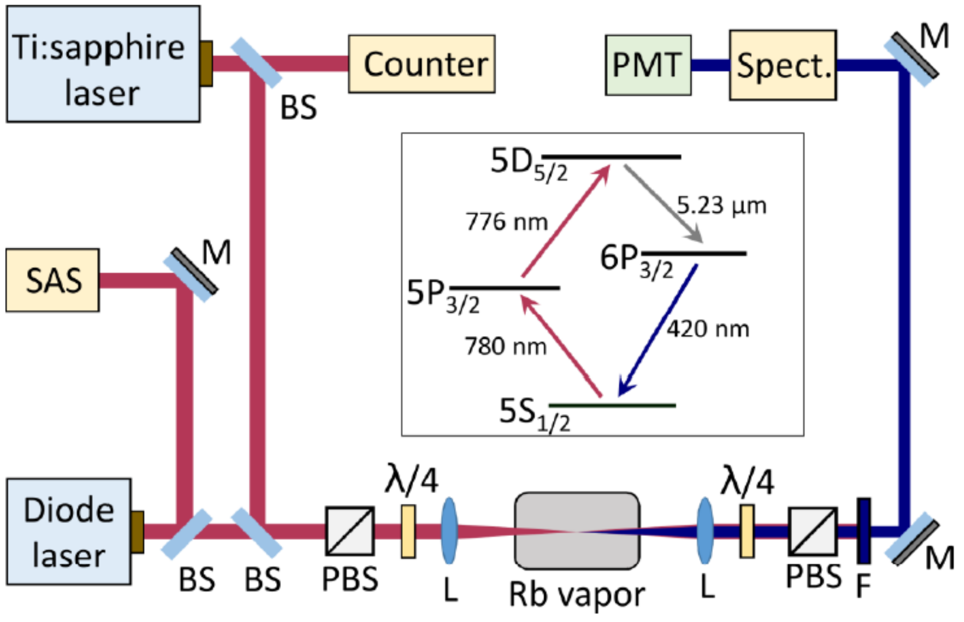


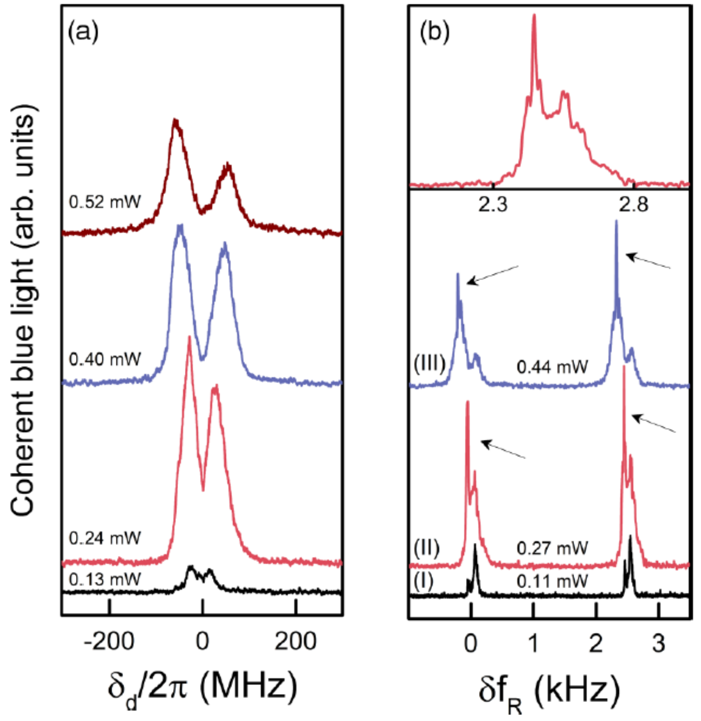
O efeito Autler-Townes na FWM



$$\omega_m = 2\pi\left(f_0 + m f_R\right)$$







Resultados recentes

Resultados recentes

Dynamic Stark shift in a Doppler-broadened four-wave mixing

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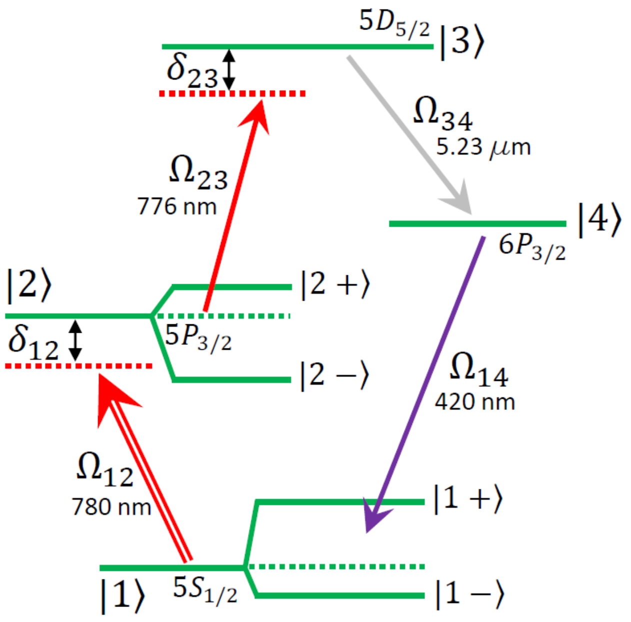


$$P = N\langle\hat{\mu}\rangle$$

$$P = N\mathrm{Tr}(\hat{\rho}\hat{\mu})$$

$$P(\omega = \omega_{41}) = 2N\mu_{14}\mathrm{Re}(\rho_{14})$$

$$\bar{\rho}_{33} = \int_{-\infty}^{\infty} \rho_{33}(v) f(v) dv$$

$$\bar{\sigma}_{14} = \int_{-\infty}^{\infty} \sigma_{14}(v) f(v) dv,$$

Integração Doppler

$$\rho_{14}(t) = \sigma_{14}(t) e^{i\omega_{14}t}$$

$$\frac{\partial\hat{\rho}}{\partial t} = -\frac{i}{\hbar}[\hat{H}, \hat{\rho}]$$

Equação de Liouville-von Neumann

→ Equações de Bloch (16 EDOs acopladas)

Programação paralela (CUDA)

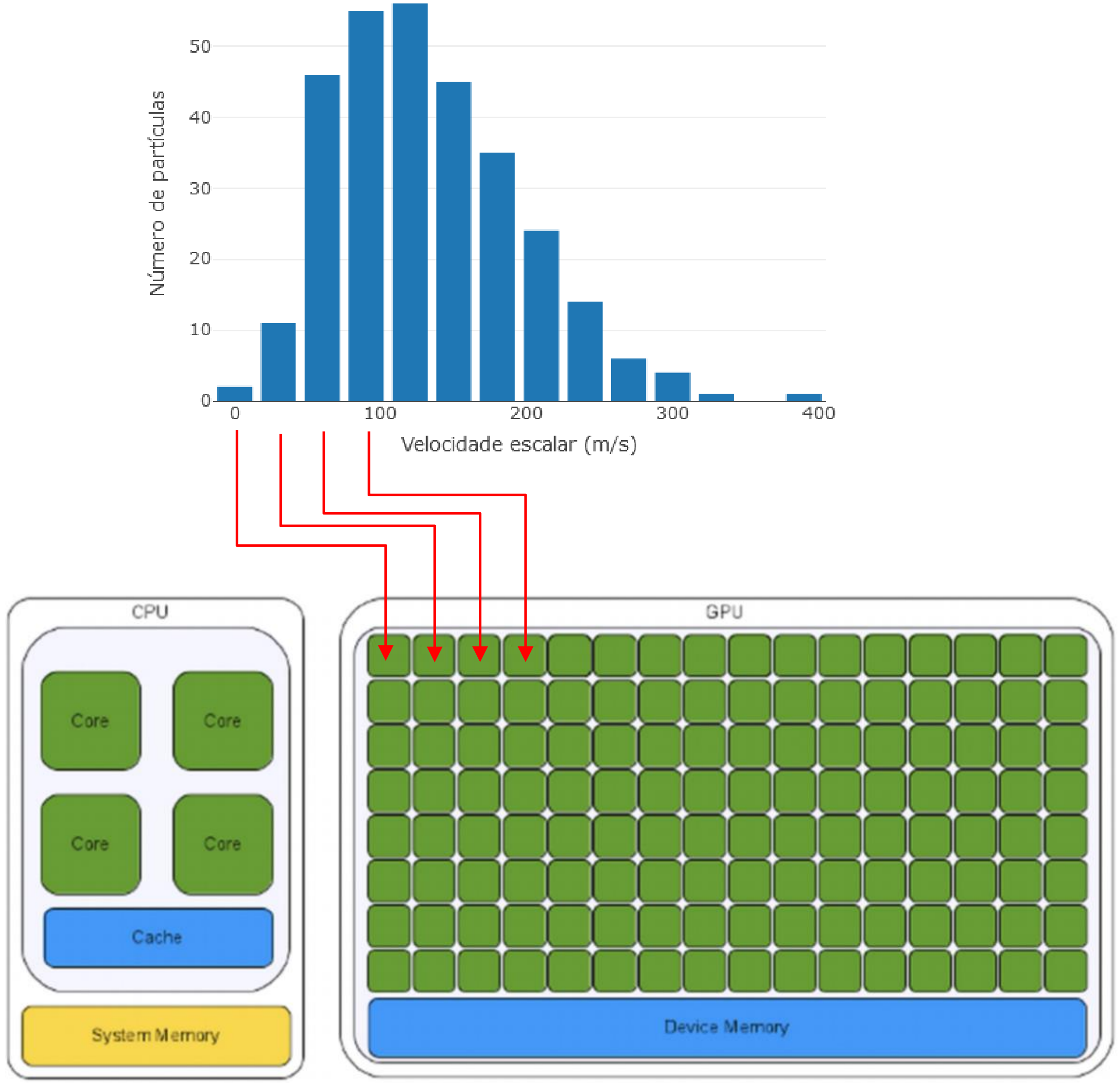
$$\bar{\rho}_{33} = \int_{-\infty}^{\infty} \rho_{33}(v) f(v) dv$$

$$\bar{\sigma}_{14} = \int_{-\infty}^{\infty} \sigma_{14}(v) f(v) dv,$$

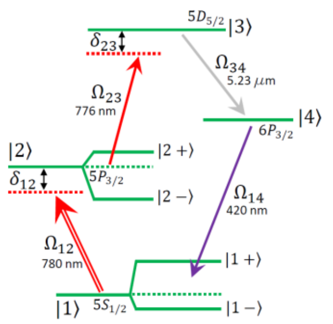
Nvidia RTX 2070 SUPER

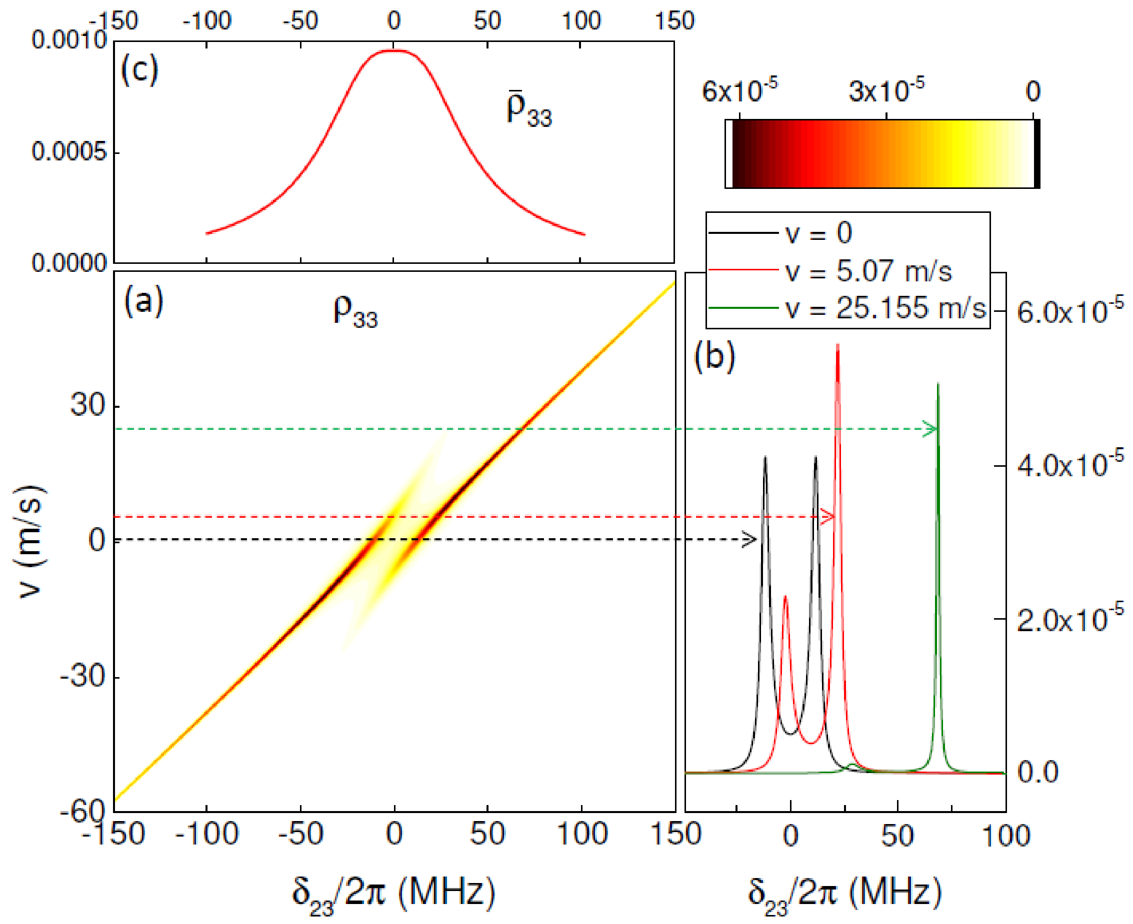
2560 núcleos CUDA @ 1.9 GHz

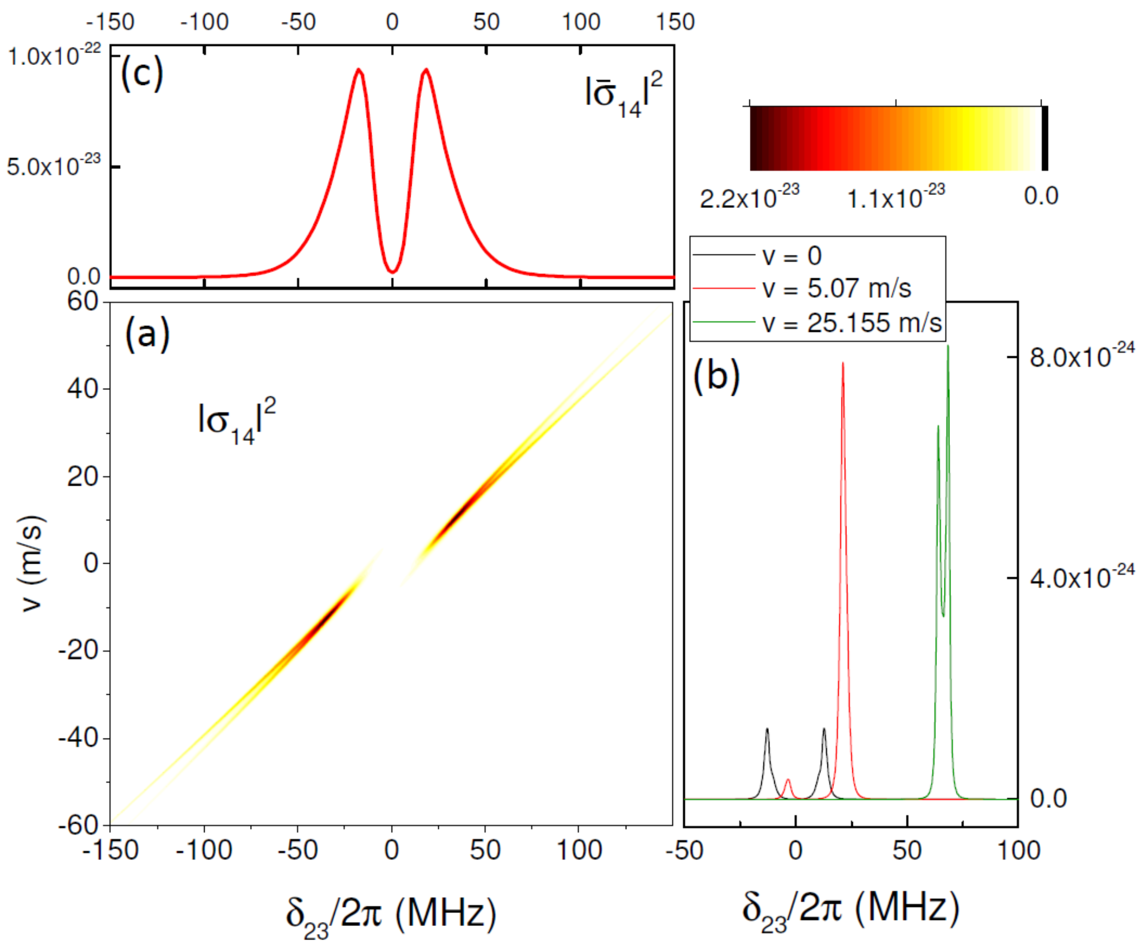
9 TFLOPS



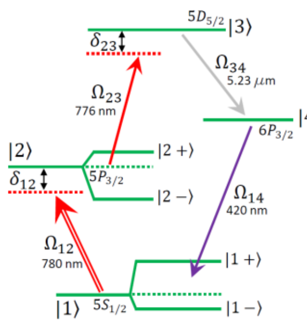
Varrendo o feixe fraco

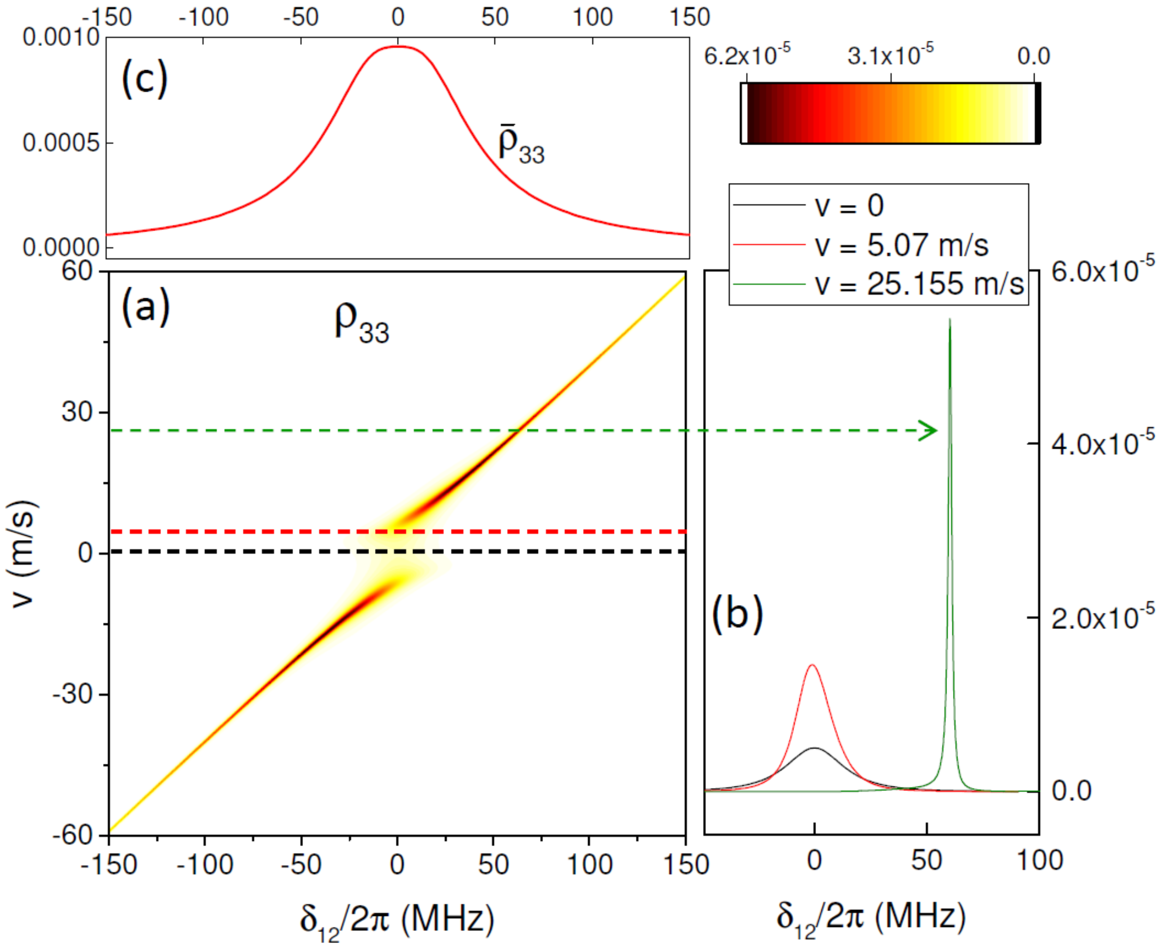


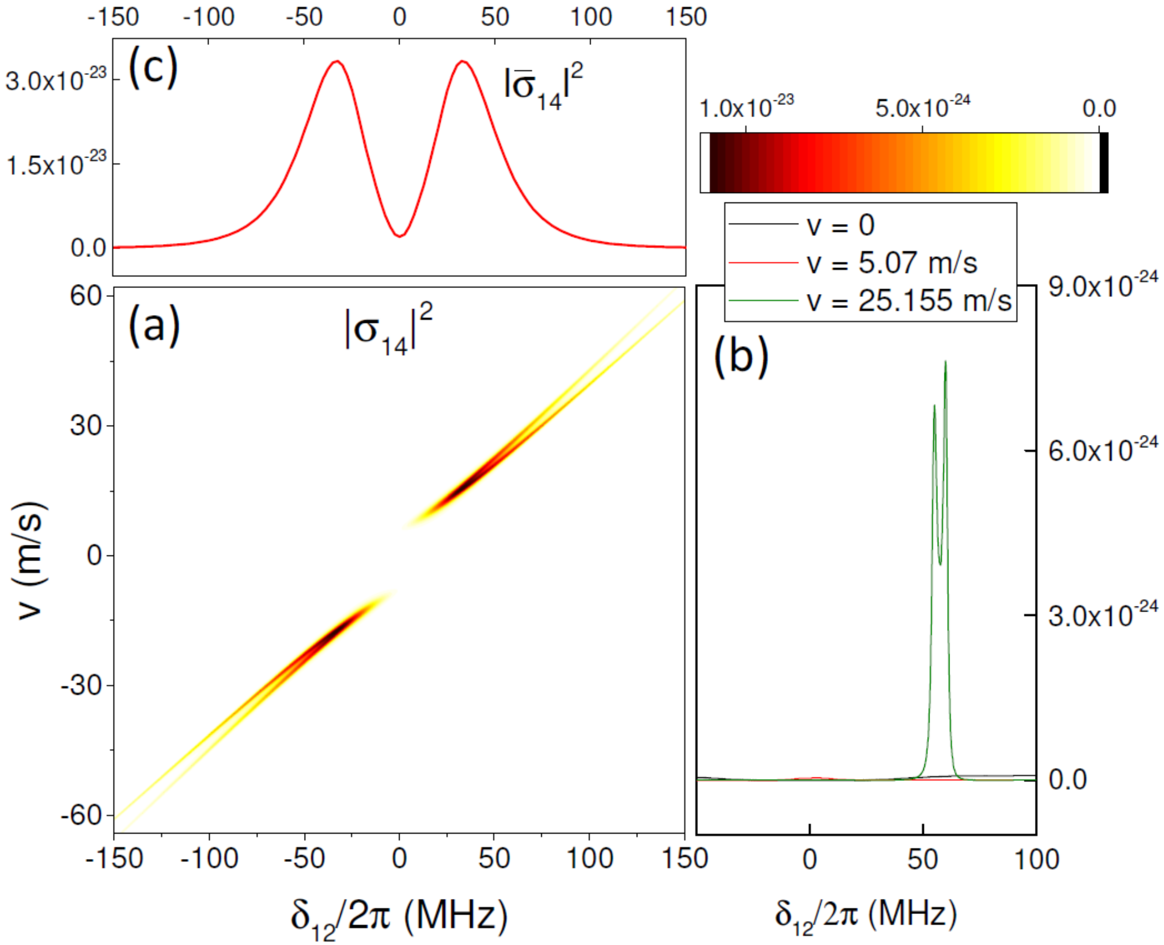




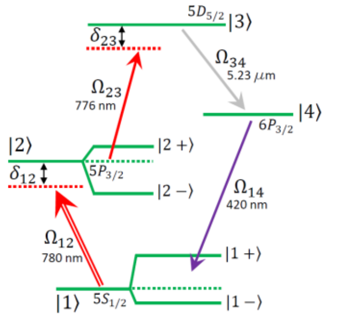
Varrendo o feixe forte







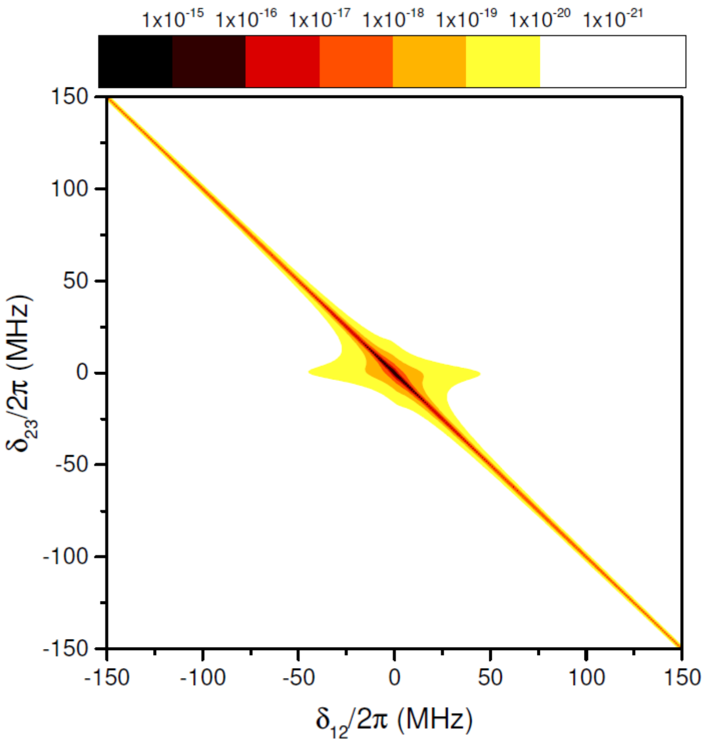
Análise mais detalhada

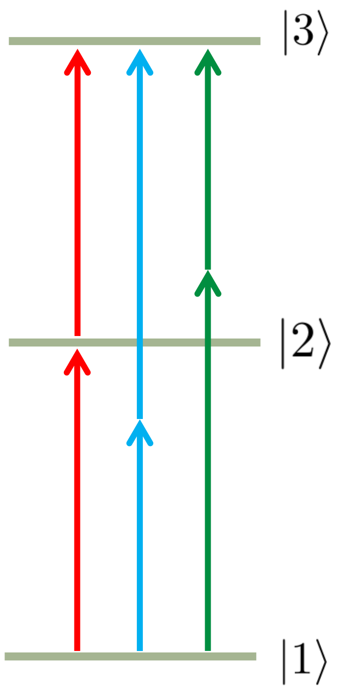


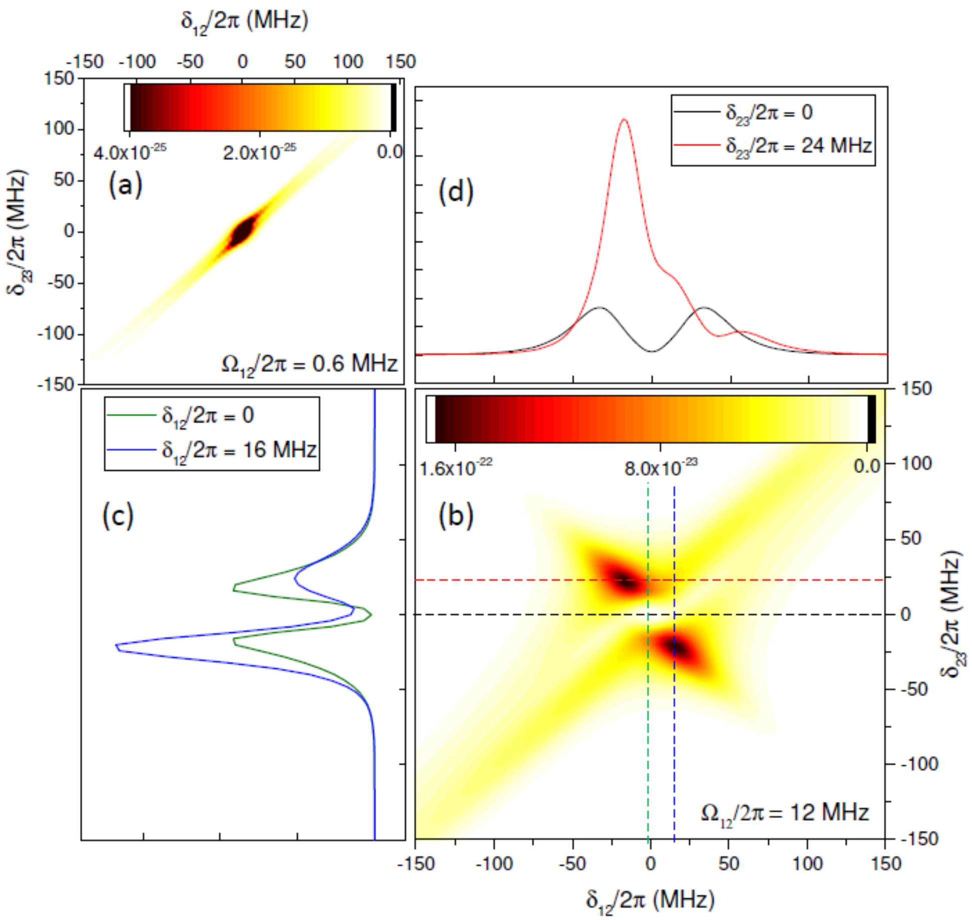
Sem alargamento Doppler
(todos os átomos com v = 0)

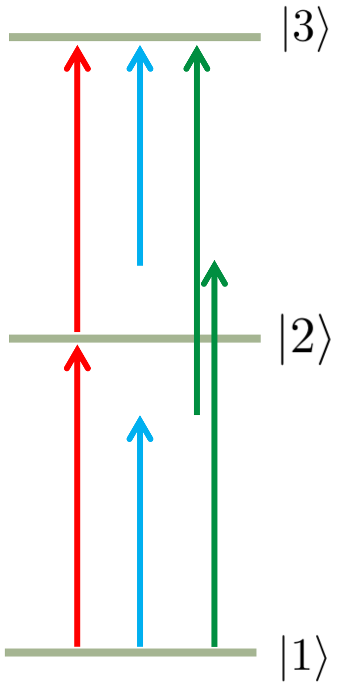
$$\delta_{12} + \delta_{23} = 0$$

$$\delta_{12} = \delta_{23} = 0$$



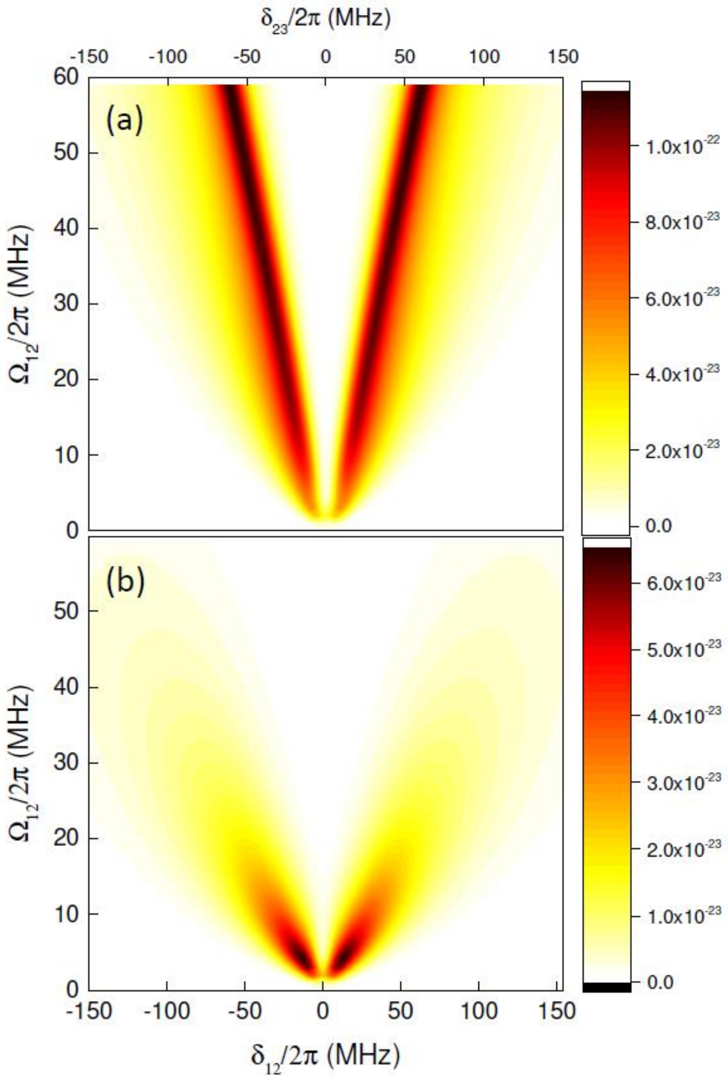






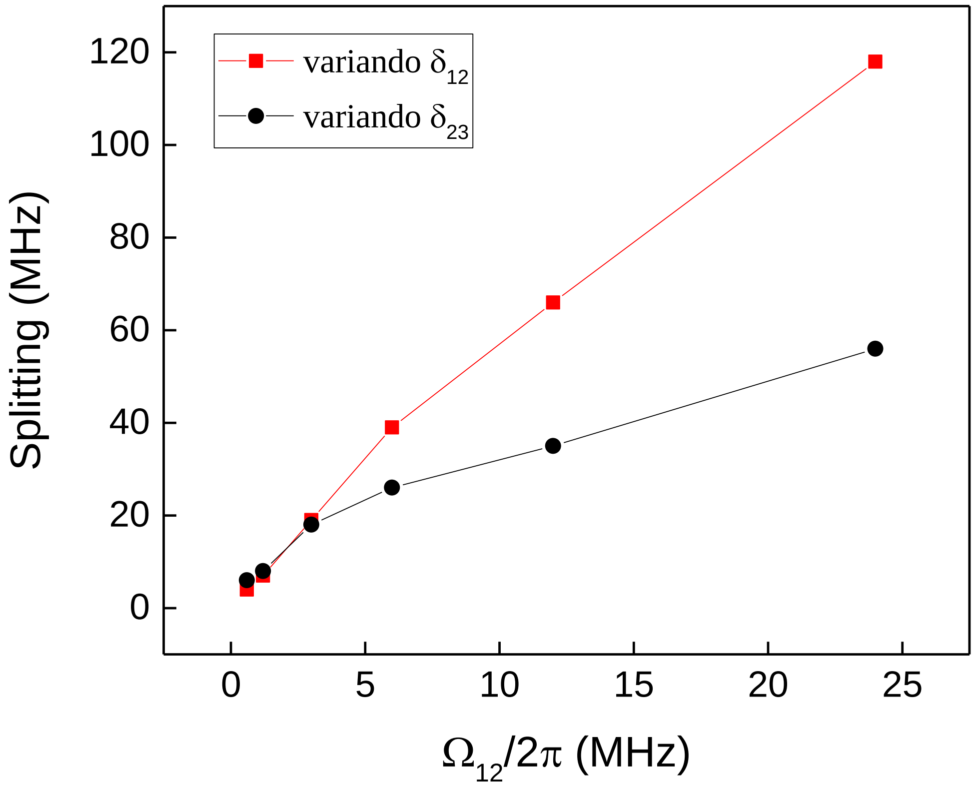
$$\Omega_{12} = \Omega_{23} = 2\pi \times 0.6\ \text{MHz}$$

Análise mais detalhada

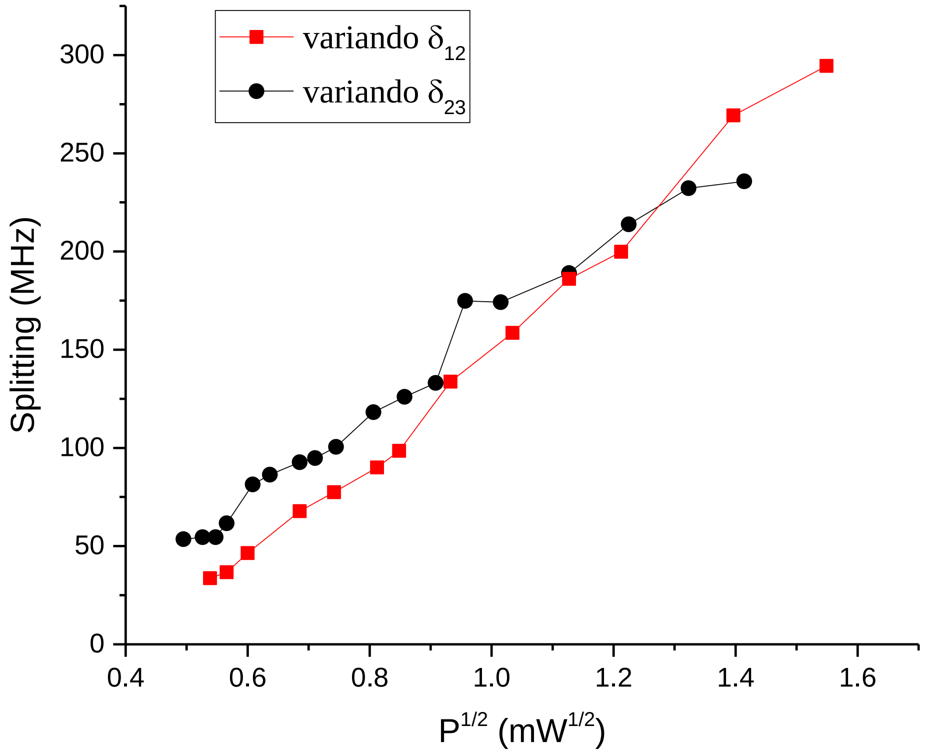


Comparação teoria/experimento

Resultados teóricos



Resultados experimentais



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Obrigado pela atenção!

fapero

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