Laser cooling and trapping of atoms: beyond the limits

1. A breakthrough in the quest of low temperatures
2. Radiative forces
    1. Semi classical approach
    2. Atomic motion
    3. Radiative forces
    4. Resonance transition
3. Resonant radiation pressure
    1. Properties
    2. Stopping a laser beam with radiation pressure
    3. Photon momentum interpretation
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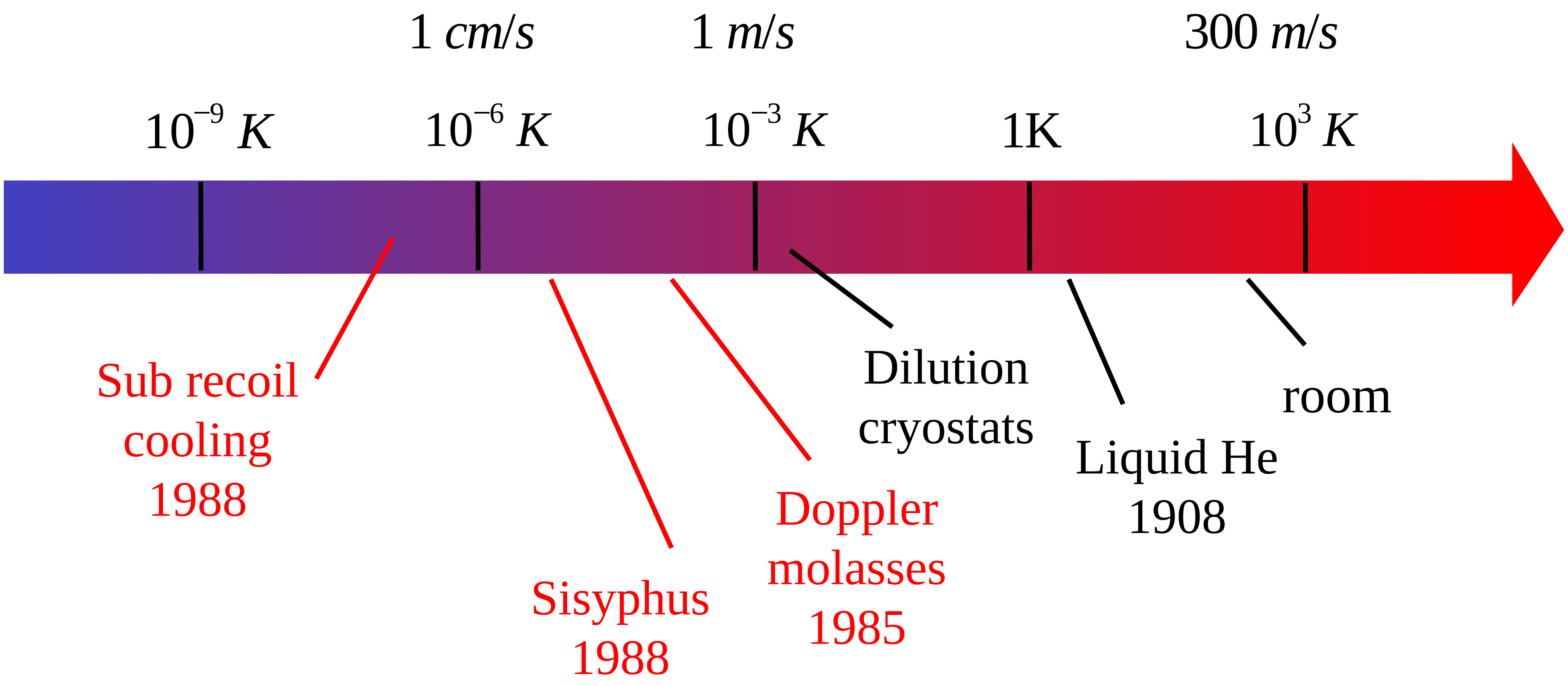
    4. Below Doppler limit: Sisyphus
6. Below the one photon recoil limit: dark resonance cooling and Lévy flights

Laser cooling of atoms: a breakthrough



L’échelle logarithmique montre l’ampleur du refroidissement, caractérisée par une division de la température absolue, pas par une soustraction.

Cooling and trapping: increase of phase space density

Cooling:

- Increase of density in velocity space
- $\neq$ filtering

Trapping :

- Confinement in real space

Cooling and Trapping :

- Increase of phase space density

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Semi classical model of atom-light interaction

Matter (atoms) is quantized

Light described by classical electromagnetic field

Successful to describe all matter-light interaction phenomenon known until 1970 (except spontaneous emission)

- Absorption, stimulated emission: lasers
- Photoelectric effect!!!

Modern quantum optics is about radiation that demand quantization of light

- Single photon wave packets
- Entangled photons

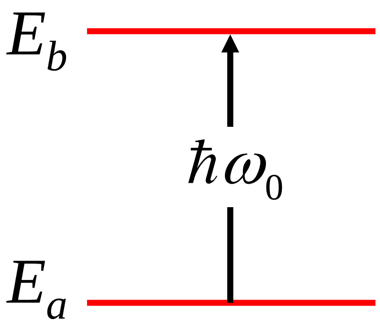
Semi-classical model is very useful, provided one knows its limits

Two level atom in motion: quantum description

Etat interne

$|\psi\rangle \in \mathcal{E}_{\text{int}}$ (dimension 2)

$$|\psi\rangle \leftrightarrow \begin{bmatrix} \gamma_a(t) \\ \gamma_b(t) \end{bmatrix}$$



$$\hat{H}_0 = \begin{bmatrix} 0 & 0 \\ 0 & \hbar\omega_0 \end{bmatrix}$$

Mouvement du centre de masse (observables **r** , P)

$$|\psi\rangle \in \mathcal{E}_{\mathbf{r}} \qquad |\psi\rangle \leftrightarrow \psi(\mathbf{r},t) \qquad \hat{H}_{\text{ext}} = \frac{\hat{\mathbf{P}}^2}{2M} \leftrightarrow \hat{H}_{\text{ext}} = -\frac{\hbar^2}{2M}\Delta$$

Description globale

$$|\psi\rangle \in \mathcal{E}_{\text{int}} \otimes \mathcal{E}_{\mathbf{r}} \qquad |\psi\rangle \leftrightarrow \begin{bmatrix} \psi_a(\mathbf{r},t) \\ \psi_b(\mathbf{r},t) \end{bmatrix} \leftrightarrow \text{ spineur} \qquad \hat{H} = \hat{H}_0 + \hat{H}_{\text{ext}}$$

Description quantique de la dynamique interne et du mouvement

Interaction avec une onde électromagnétique

classique

Interaction dipolaire électrique avec $\mathbf{E}(\mathbf{r},t)=\vec{\boldsymbol{\varepsilon}}\,E_0(\mathbf{r})\cos\left(\omega t-\varphi(\mathbf{r})\right)$

$$\hat{H}_\text{I}=-\hat{\mathbf{D}}\cdot\mathbf{E}=-\hat{D}_{\boldsymbol{\varepsilon}}\,E_{\boldsymbol{\varepsilon}}(\mathbf{r},t)=-\begin{bmatrix}0 & d\\ d & 0\end{bmatrix}E_{\boldsymbol{\varepsilon}}(\mathbf{r},t) \quad \text{avec} \quad \hat{D}_{\boldsymbol{\varepsilon}}=\hat{\mathbf{D}}\cdot\vec{\boldsymbol{\varepsilon}}$$

$$\hat{H}=\hat{H}_0+\hat{H}_\text{ext}+\hat{H}_\text{I}=\begin{bmatrix}0 & 0\\ 0 & \hbar\omega_0\end{bmatrix}+\frac{\hat{\mathbf{P}}^2}{2M}\Delta-\begin{bmatrix}0 & d_{\boldsymbol{\varepsilon}}\\ d_{\boldsymbol{\varepsilon}} & 0\end{bmatrix}E_{\boldsymbol{\varepsilon}}(\mathbf{r},t)$$

Agit sur $[\psi]=\begin{bmatrix}\psi_a(\mathbf{r},t)\\ \gamma_b(\mathbf{r},t)\end{bmatrix}$

L'hamiltonien dipolaire électrique est valable dans le cadre de l'approximation des grandes longueurs d'onde: distance électron-noyau << λ

Cela ne met aucune contrainte sur $\psi_a(\mathbf{r},t)$ et $\psi_b(\mathbf{r},t)$ qui pourraient être étalés sur une distance >> λ

Paquet d'onde localisé: limite classique

Atome localisé

Paquet d'onde étroit, identique pour les deux états

$$[\psi] = \begin{bmatrix} \psi_a(\mathbf{r},t) \\ \gamma_b(\mathbf{r},t) \end{bmatrix} = \begin{bmatrix} \gamma_a(t) \\ \gamma_b(t) \end{bmatrix} \psi(\mathbf{r},t)$$

$\psi(\mathbf{r},t)$ « piqué » autour de $\mathbf{r}_{\text{at}}$ largeur << λ

Position classique

$$\langle \hat{\mathbf{r}} \rangle(t) = \langle \psi | \hat{\mathbf{r}} | \psi \rangle = \int \psi^*(\mathbf{r},t)\, \mathbf{r}\, \psi(\mathbf{r},t)\, d^3r \simeq \mathbf{r}_{\text{at}}(t)$$

Vitesse classique

définie par $\mathbf{V}_{\text{at}} = \frac{d}{dt}\mathbf{r}_{\text{at}}(t) = \frac{d}{dt}\langle \hat{\mathbf{r}} \rangle(t)$

Th. d'Ehrenfest:

$$\mathbf{V}_{\text{at}} = \frac{d}{dt}\langle \hat{\mathbf{r}} \rangle = \frac{1}{i\hbar}\left\langle \left[\hat{\mathbf{r}}, \hat{H} \right] \right\rangle = \left\langle \frac{\hat{\mathbf{P}}}{M} \right\rangle$$

car $\left\langle \left[\hat{\mathbf{r}}, \frac{\hat{\mathbf{P}}^2}{2M} \right] \right\rangle = 2\frac{\hat{\mathbf{P}}}{2M}\left\langle \left[\hat{\mathbf{r}}, \hat{\mathbf{P}} \right] \right\rangle = \frac{\hat{\mathbf{P}}}{M} i\hbar$

Dynamique de la position classique

On applique le th. d'Ehrenfest à la vitesse classique $\frac{d\mathbf{r}_{\text{at}}}{dt} = \mathbf{V}_{\text{at}} = \left\langle \frac{\hat{\mathbf{P}}}{M} \right\rangle$

$$M \frac{d}{dt}\mathbf{V}_{\text{at}} = \frac{1}{i\hbar}\left\langle \left[\hat{\mathbf{P}}, \hat{H} \right] \right\rangle = \frac{1}{i\hbar}\left\langle \left[\hat{\mathbf{P}}, \hat{H}_{\text{I}} \right] \right\rangle$$

$$\left[\hat{\mathbf{P}}, \hat{H}_{\text{I}} \right] = -\hat{D}_{\varepsilon} \left[\hat{\mathbf{P}}, E(\mathbf{r},t) \right] = -\frac{\hbar}{i} \hat{D}_{\varepsilon} \vec{\nabla} \left\{ E(\mathbf{r},t) \right\}$$

$$M \frac{d^2}{dt^2}\mathbf{r}_{\text{at}} = M \frac{d}{dt}\mathbf{V}_{\text{at}} = \left\langle \hat{D}_{\varepsilon} \vec{\nabla} \left\{ E(\mathbf{r},t) \right\} \right\rangle = \left\langle \hat{D}_{\varepsilon} \right\rangle \left[\vec{\nabla} \left\{ E_{\varepsilon}(\mathbf{r},t) \right\} \right]_{\mathbf{r}_{\text{at}}}$$

L'atome suit une trajectoire classique moyenne déterminée par la force

$$\mathbf{F} = \left\langle \hat{D}_{\varepsilon} \right\rangle \left[\vec{\nabla} \left\{ E_{\varepsilon}(\mathbf{r},t) \right\} \right]_{\mathbf{r}_{\text{at}}}$$

cf. électrodynamique classique, pour un dipôle d_{ε} dans $\mathbf{E} = \vec{\boldsymbol{\varepsilon}} E_{\varepsilon}(\mathbf{r},t)$

$\mathbf{F} = d_{\varepsilon} \vec{\nabla} E_{\varepsilon}$ (et pas $\vec{\nabla}(d_{\varepsilon} E_{\varepsilon})$: important quand d_{ε} dépend de E_{ε})

Forces radiatives

Oscillation forcée du dipôle atomique, sous l'effet du champ

$$\mathbf{E}(\mathbf{r},t) = \vec{\boldsymbol{\varepsilon}}\, E_0(\mathbf{r}) \cos\left(\omega t - \varphi(\mathbf{r})\right) = \vec{\boldsymbol{\varepsilon}}\, \mathcal{E}(\mathbf{r},t) + \text{c.c.}$$

$$\text{avec} \quad \mathcal{E}(\mathbf{r},t) = \frac{E_0(\mathbf{r})}{2} \exp\{i\varphi(\mathbf{r})\} \exp\{-i\omega t\}$$

$$\left\langle \hat{D}_{\boldsymbol{\varepsilon}} \right\rangle = \varepsilon_0 \alpha\, \mathcal{E}(\mathbf{r},t) + \varepsilon_0 \alpha^* \mathcal{E}^*(\mathbf{r},t) \quad \text{après amortissement du transitoire}$$

Polarisabilité complexe $\alpha = \alpha' + i\alpha''$ (*cf.* chap II)

Force due à l'interaction entre le champ et le dipôle atomique induit

$$\mathbf{F} = \left\langle \hat{D}_{\boldsymbol{\varepsilon}} \right\rangle \left[\vec{\nabla} \{E(\mathbf{r},t)\} \right]_{\mathbf{r}_{\text{at}}} = \varepsilon_0 \left(\alpha \mathcal{E} + \alpha^* \mathcal{E}^* \right) \vec{\nabla} \left\{ \mathcal{E} + \mathcal{E}^* \right\}$$

En ne gardant que les termes qui n'oscillent pas (moyenne temporelle)

$$\mathbf{F} = \varepsilon_0 \alpha\, \mathcal{E} \left[\vec{\nabla} \mathcal{E}^* \right]_{\mathbf{r}_{\text{at}}} + \text{c.c.}$$

Radiation pressure vs Dipole force

$$\mathbf{F} = \varepsilon_0 \alpha \, \mathcal{E} \left[\vec{\nabla} \mathcal{E}^* \right]_{\mathbf{r}_{\mathrm{at}}} + \text{ c.c.}$$

avec $\mathcal{E}(\mathbf{r},t) = \frac{E_0(\mathbf{r})}{2} \exp\{i\varphi(\mathbf{r})\} \exp\{-i\omega t\}$

$$\alpha = \alpha' + i\alpha''$$

$$\mathbf{F} = \frac{\varepsilon_0 \alpha}{4} E_0(\mathbf{r}) \left(\vec{\nabla}\left[E_0(\mathbf{r})\right] - i\vec{\nabla}\left[\varphi(\mathbf{r})\right] E_0(\mathbf{r}) \right) + \text{ c.c.}$$

$$= \frac{\varepsilon_0 \alpha'}{2} E_0(\mathbf{r}) \vec{\nabla}\left[E_0(\mathbf{r})\right] + \frac{\varepsilon_0 \alpha''}{2} \left(E_0(\mathbf{r})\right)^2 \vec{\nabla}\left[\varphi(\mathbf{r})\right]$$

l'expression étant évaluée en $\mathbf{r} = \mathbf{r}_{\mathrm{at}}$

$$\mathbf{F}_{\mathrm{dip}} = \frac{\varepsilon_0 \alpha'}{2} E_0(\mathbf{r}) \vec{\nabla}\left[E_0(\mathbf{r})\right]$$

Force dipolaire

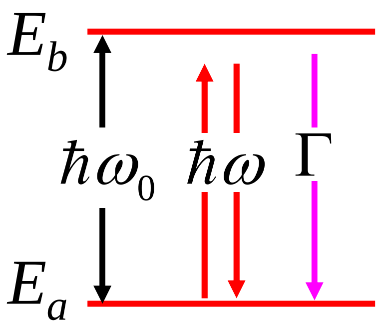
- Partie réactive (réelle) de la polarisabilité
- Gradient de l'amplitude

$$\mathbf{F}_{\mathrm{res}} = \frac{\varepsilon_0 \alpha''}{2} \left(E_0(\mathbf{r})\right)^2 \vec{\nabla}\left[\varphi(\mathbf{r})\right]$$

Pression de radiation résonnante

- Partie dissipative (imaginaire) de la polarisabilité
- Gradient de la phase

Closed two level transition (resonance line)



Raie « de résonance »: niveau du bas fondamental

- Durée de vie infinie $\Gamma_a = 0$
- Largeur de raie $\Gamma = \Gamma_b$
- Transition fermée

Dipôle forcé sous l'effet de $\mathbf{E} = \vec{\boldsymbol{\varepsilon}}\, E_0 \cos\left(\omega t - \varphi\right) = \vec{\boldsymbol{\varepsilon}}\left(\mathcal{E} + \mathcal{E}^*\right)$

Utilisation du formalisme de la matrice densité et des équations de Bloch optiques (dissipation, *cf.* Maj. 2)

$$\left\langle \mathbf{D} \right\rangle = \vec{\boldsymbol{\varepsilon}} \left\langle \hat{D}_{\boldsymbol{\varepsilon}} \right\rangle$$

$$\left\langle \hat{D}_{\boldsymbol{\varepsilon}} \right\rangle = \varepsilon_0 \alpha\, \mathcal{E} + \varepsilon_0 \alpha^* \mathcal{E}^*(\mathbf{r}, t)$$

$$\hbar\Omega_1 = -d\, E_0$$

$$\hat{D}_{\boldsymbol{\varepsilon}} = -\begin{bmatrix} 0 & d \\ d & 0 \end{bmatrix}$$

$$\alpha = \frac{d^2}{\varepsilon_0 \hbar} \frac{1}{(\omega_0 - \omega) - i\frac{\Gamma}{2}} \frac{1}{1+s}$$

$$s = \frac{\Omega_1^{\ 2}/2}{(\omega_0 - \omega)^2 + \Gamma^2/4}$$

Réponse linéaire

saturation

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Pression de radiation résonnante

Onde plane progressive $$\mathcal{E}(\mathbf{r},t)=\frac{E_0}{2}\exp\{i\mathbf{k}\cdot\mathbf{r}\}\exp\{-i\omega t\}$$

amplitude E_0 constante $$\Rightarrow \mathbf{F}_{\text{dip}}=\frac{\varepsilon_0\alpha'}{2}E_0(\mathbf{r})\vec{\nabla}\left[E_0(\mathbf{r})\right]=0$$

$$\mathbf{F}_{\text{res}}=\frac{\varepsilon_0\alpha''}{2}\left(E_0(\mathbf{r})\right)^2\vec{\nabla}\left[\varphi(\mathbf{r})\right]=\mathbf{k}\frac{d^2E_0{}^2}{2\hbar}\frac{\Gamma/2}{(\omega_0-\omega)^2+\Gamma^2/4}\frac{1}{1+s}$$

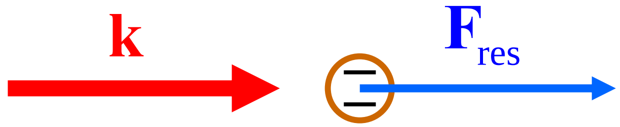
$$\mathbf{F}_{\text{res}}=\hbar\mathbf{k}\frac{\Omega_1{}^2}{2}\frac{\Gamma/2}{(\omega_0-\omega)^2+\Gamma^2/4}\frac{1}{1+s}=\hbar\mathbf{k}\frac{\Gamma}{2}\frac{s}{1+s}$$

$$s=\frac{\Omega_1{}^2/2}{(\omega_0-\omega)^2+\Gamma^2/4}=\frac{I}{I_{\text{sat}}}\frac{1}{1+4(\omega_0-\omega)^2/\Gamma^2}$$ paramètre de saturation

Resonant radiation pressure: properties

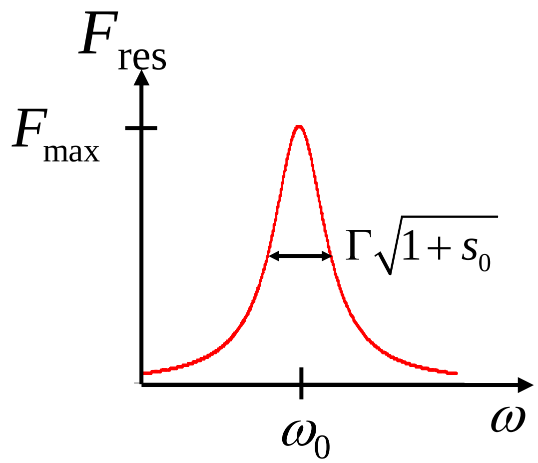
$$\mathbf{F}_{res} = \hbar \mathbf{k} \frac{\Gamma}{2} \frac{s}{1+s}$$

- Dirigée suivant le vecteur d'onde du laser



$$\mathbf{F}_{res} = \hbar \mathbf{k} \frac{\Gamma}{2} \frac{\Omega_1^2/2}{(\omega_0-\omega)^2 + \Omega_1^2/2 + \Gamma^2/4}$$

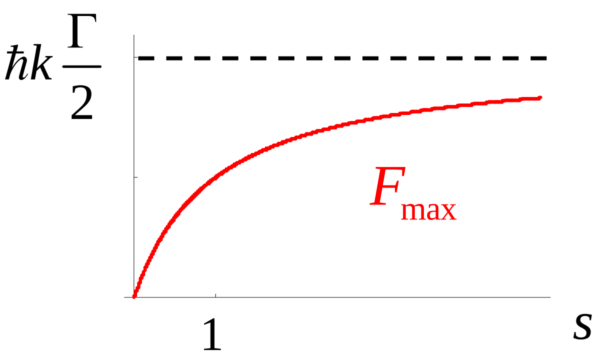
- Lorentzian resonance (power broadening)



- Saturation

$$s_0 = \frac{\Omega_1^2/2}{\Gamma^2/4} = \frac{I}{I_{sat}}$$

$$\mathbf{F}_{max} = \hbar \mathbf{k} \frac{\Gamma}{2} \frac{s_0}{1+s_0}$$



Order of magnitude

Rb $\begin{cases} \Gamma/2\pi = 6 \text{ MHz} \\ I_{sat} = 1.6 \text{ mW/cm}^2 \end{cases}$ $\quad \frac{\hbar k}{M} = 5.9\times 10^{-3} \text{ m/s}$

$$\frac{F^{max}_{max}}{M} = \frac{\hbar k}{M}\frac{\Gamma}{2} \approx 10^5 \text{ m/s}^{-2} \approx 10^4 \text{ g}$$

Easily achievable with lasers

Decelerating atoms with radiation pressure

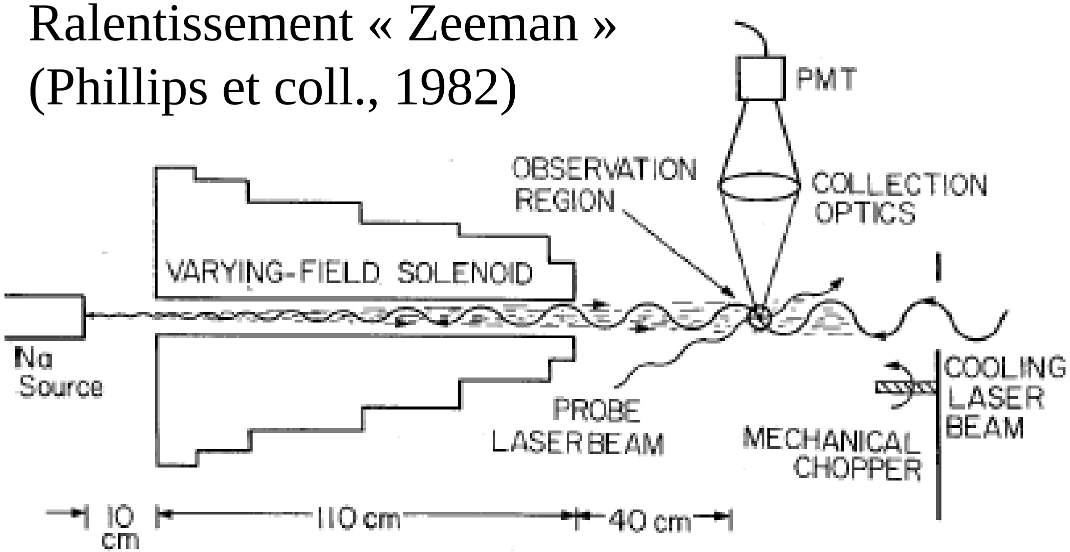
Jet thermique de sodium

$$V \approx \sqrt{\frac{2k_B T}{M}} \approx 600 \text{ m / s}$$

$$\text{distance d'arret} = \frac{V^2}{2\gamma} \approx \frac{36\times10^4}{2\times10^5} = 1.8 \text{ m}$$

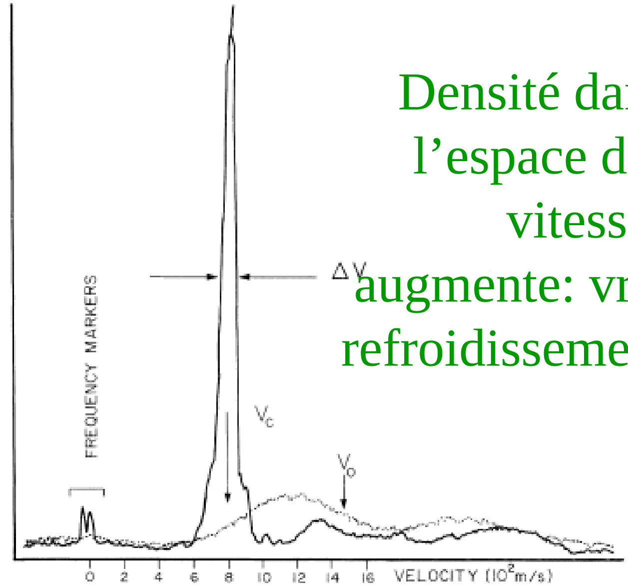
Challenges (Phillips, 2002): keep atoms on resonance during deceleration (Doppler effect changes); avoid optical pumping into other levels

Ralentissement « Zeeman »
(Phillips et coll., 1982)



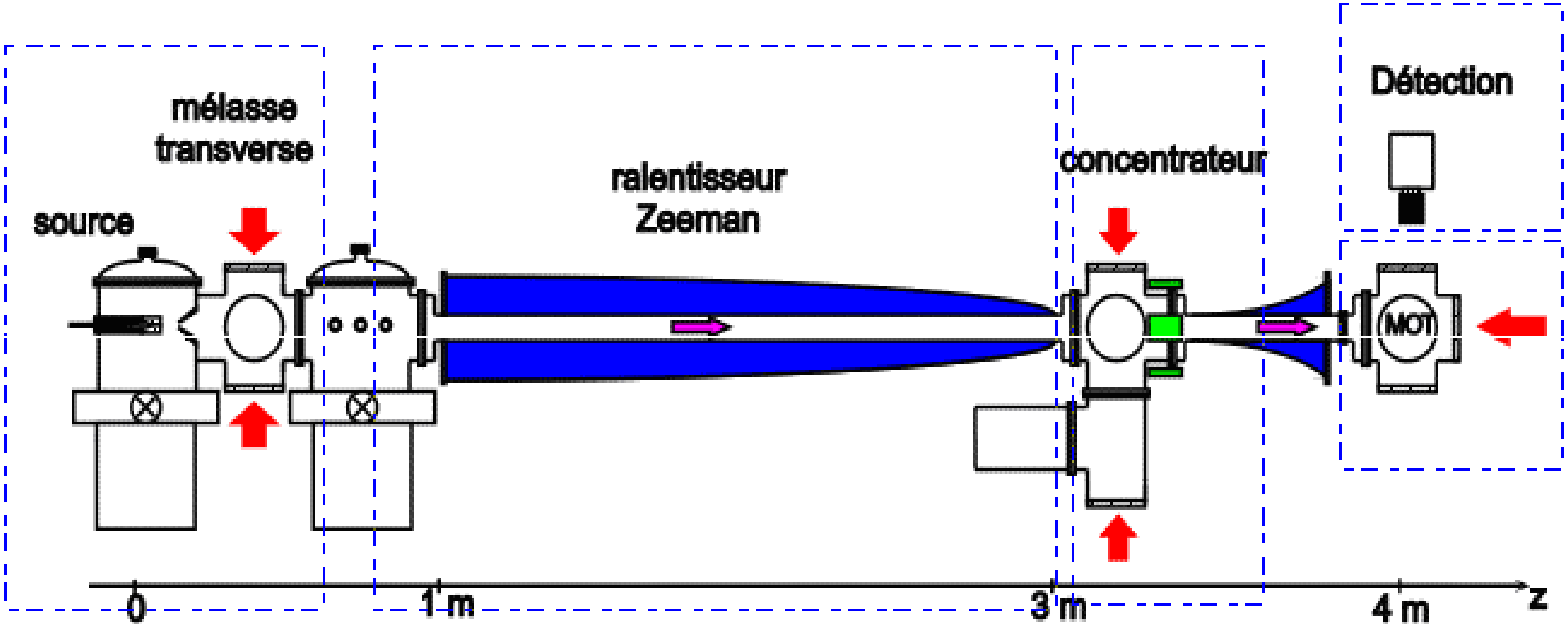
Full stop achieved in 1985

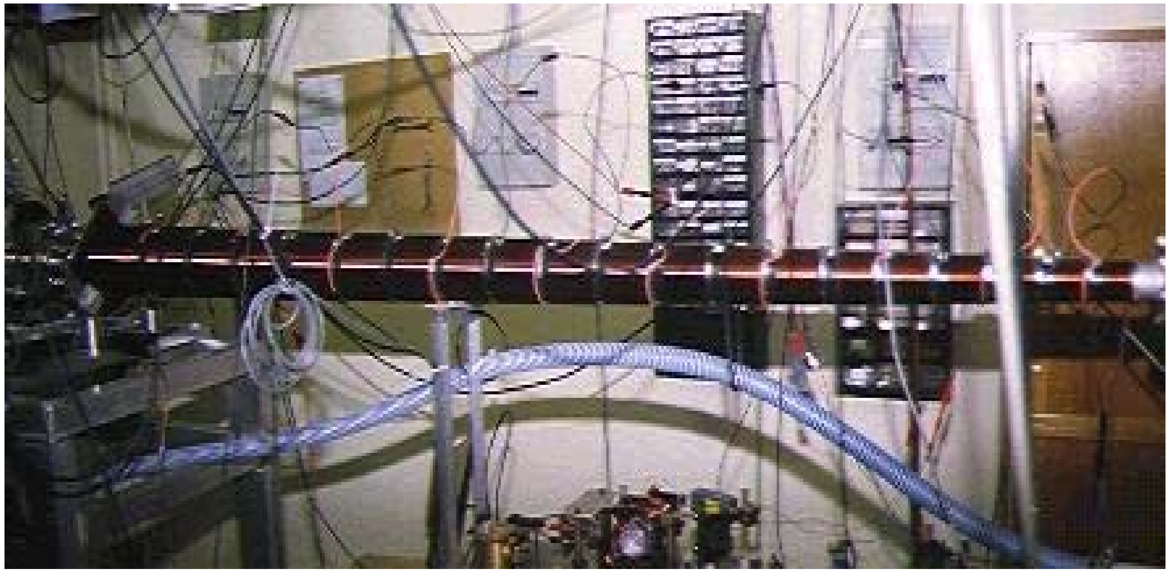
Distribution des vitesses



Densité dans l’espace des vitesses augmente: vrai refroidissement

Stopping metastable Helium atoms





Radiation pressure and fluorescence rate

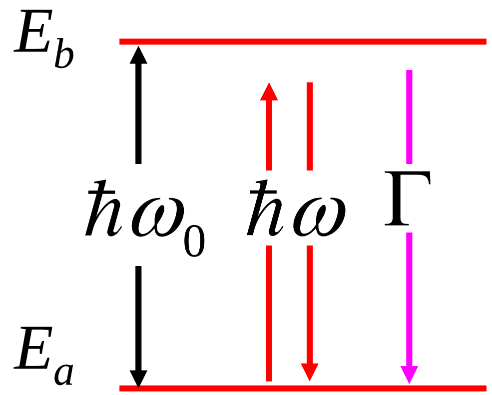
Pression de radiation résonnante

$$\mathcal{E}(\mathbf{r},t) = \frac{E_0}{2}\exp\{i\mathbf{k}\cdot\mathbf{r}\}\exp\{-i\omega t\}$$

$$\mathbf{F}_{\text{res}} = \hbar\mathbf{k}\,\frac{\Gamma}{2}\,\frac{s}{1+s} \qquad s = \frac{\Omega_1^{\,2}/2}{(\omega_0-\omega)^2+\Gamma^2/4}$$

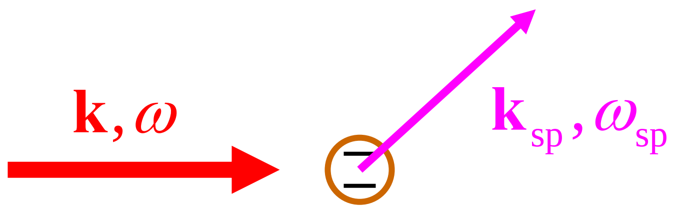
$$\hbar\Omega_1 = -d\cdot E_0$$

$$R_{\text{fluo}} = \frac{\Gamma}{2}\,\frac{s}{1+s} \qquad \mathbf{F}_{\text{res}} = \hbar\mathbf{k}R_{\text{fluo}}$$



Taux de fluorescence (nombre de cycles par seconde, calcul par EBO)

Cycle de fluorescence: Un photon du faisceau incident est diffusé dans une direction différente, avec une énergie égale (diffusion élastique) ou un peu différente (diffusion inélastique)



$\mathbf{k}_{\text{sp}}$: direction aléatoire

Réinterprétation de la pression de radiation résonnante ?

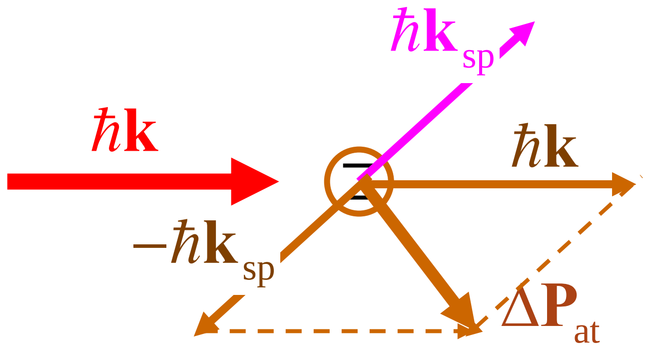
Radiation pressure and photon momentum

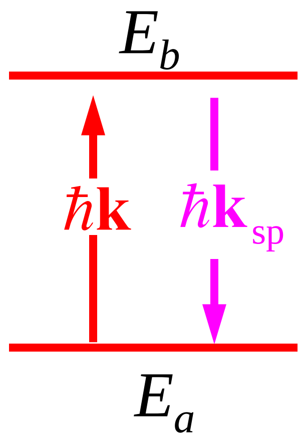
Bilan d'impulsion dans un cycle de fluorescence (diffusion d'un photon)

Photon dans une onde plane
de vecteur d'onde **k** : $\mathbf{p} = \hbar\mathbf{k}$

Absorption-Réémission

$$\Delta\mathbf{P}_{\text{at}} = \hbar\mathbf{k} - \hbar\mathbf{k}_{\text{sp}}$$





Moyenné sur un grand nombre de cycles

$$\langle \mathbf{k}_{\text{sp}} \rangle = 0 \quad \Rightarrow \quad \langle \Delta\mathbf{P}_{\text{at}} \rangle_{1\text{ cycle}} = \hbar\mathbf{k}$$

Force moyenne

$$\mathbf{F}_{\text{res}} = R_{\text{fluo}} \langle \Delta\mathbf{P}_{\text{at}} \rangle_{1\text{ cycle}} = R_{\text{fluo}}\, \hbar\mathbf{k} = \hbar\mathbf{k}\, \frac{\Gamma}{2} \frac{s}{1+s}$$

Modèle tout quantique (photons): calcul plus simple, image plus simple, même résultat ! De plus, suggère l'existence de fluctuations de la force liées aux fluctuations de la direction d'émission.

The problem of many ground state levels: avoiding optical depumping

Alkali atoms have an hyperfine structure

Ground state is split in many components

Optical pumping into non interacting levels leads to deceleration stopping.

Take advantage of selection rules (choice of polarization)

Use repumping lasers

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Force dipolaire

$$\mathbf{F}_{\text{dip}} = \frac{\varepsilon_0 \alpha'}{2} E_0(\mathbf{r}) \vec{\nabla}\left[E_0(\mathbf{r})\right]$$

avec $\mathcal{E}(\mathbf{r},t) = \frac{E_0(\mathbf{r})}{2} \exp\{i\varphi(\mathbf{r})\} \exp\{-i\omega t\}$

$\mathbf{F}_{\text{dip}} \neq 0$ pour une onde inhomogène : $\vec{\nabla} E_0 \neq 0$

$$\mathbf{F}_{\text{dip}} = \frac{d^2}{\hbar} \frac{\omega_0 - \omega}{(\omega_0 - \omega)^2 + \frac{\Gamma^2}{4}} \frac{\vec{\nabla}\left[E_0(\mathbf{r})\right]^2}{1 + s(\mathbf{r})} = \frac{\hbar(\omega_0 - \omega)}{2} \frac{\vec{\nabla}\left[s(\mathbf{r})\right]}{1 + s(\mathbf{r})}$$

$\mathbf{F}_{\text{dip}} = -\vec{\nabla}\left[U(\mathbf{r})\right]$ avec $U(\mathbf{r}) = \frac{\hbar(\omega - \omega_0)}{2} \log\left[1 + s(\mathbf{r})\right]$

Dérive d'un potentiel (partie réactive de la polarisabilité) variant comme l'intensité

$$s(\mathbf{r}) = \frac{I(\mathbf{r})}{I_{\text{sat}}} \frac{1}{1 + 4(\omega_0 - \omega)^2 / \Gamma^2}$$

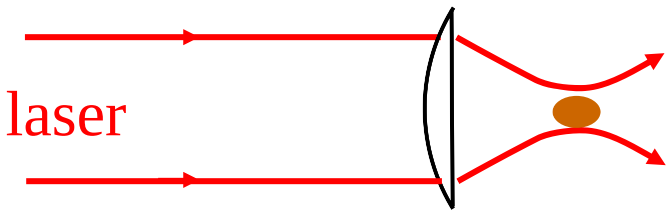
Applications

atome:
- attiré vers haute intensité si $\omega < \omega_0$
- repoussé par haute intensité si $\omega > \omega_0$

An optical trap: optical tweezer

$$U_{\text{dip}}(\mathbf{r}) = \frac{\hbar(\omega-\omega_0)}{2}\log\left[1+s(\mathbf{r})\right] \qquad \text{avec} \quad s(\mathbf{r}) = \frac{I(\mathbf{r})}{I_{\text{sat}}}\frac{1}{1+4(\omega_0-\omega)^2/\Gamma^2}$$

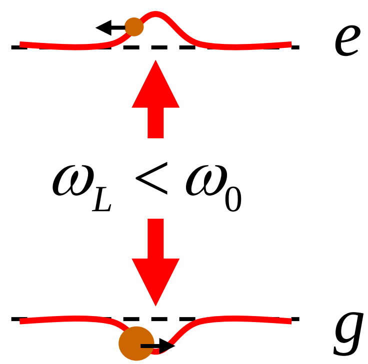
Trapping by a focused laser beam with $\omega < \omega_0$: optical tweezer



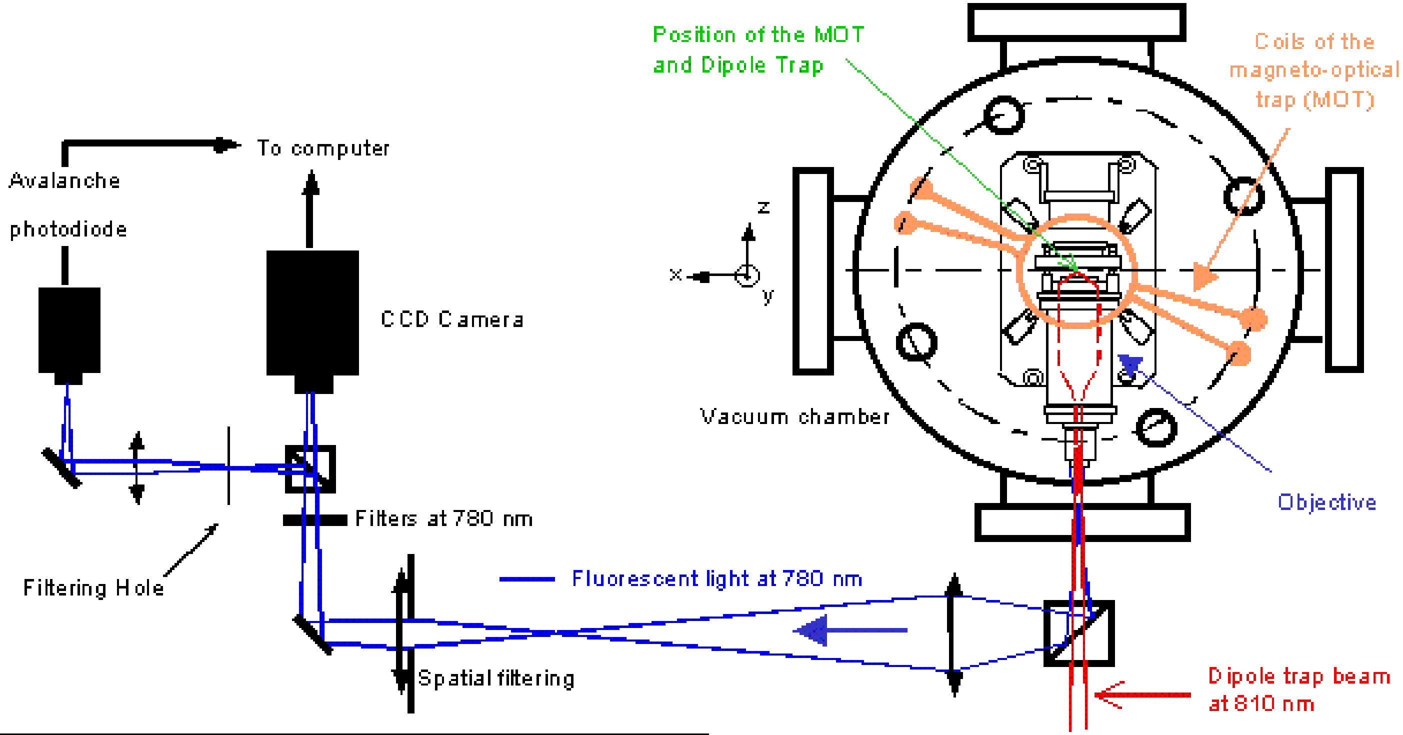
Shallow trap: demands very cold atoms ($T < 1$ mK)

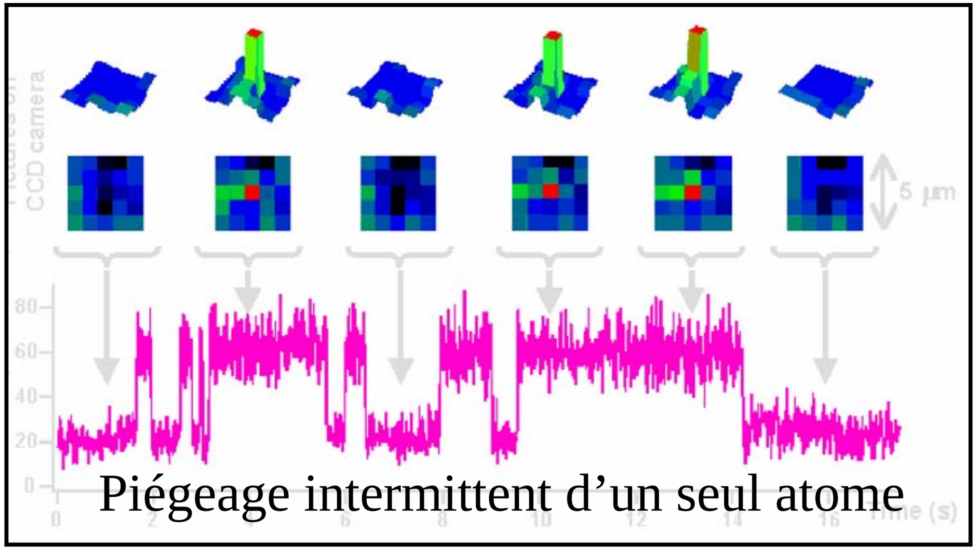
Classical interpretation: coupling of the field with the induced dipole

Interpretation by light shifts of the atomic levels (Cohen-Tannoudji, Dalibard):
Atom spends more time in ground state.
Case of large detuning: atom in *g*: no fluctuation, but very shallow, ultra cold atoms

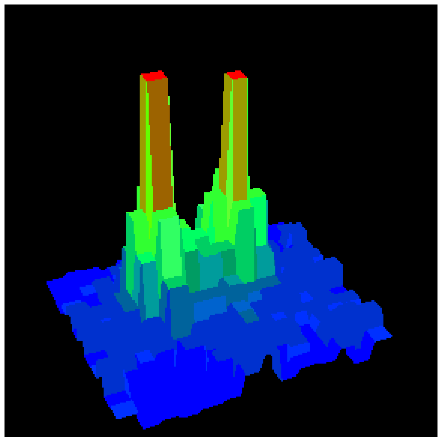


Manipulation d'atomes individuels (P. Grangier)





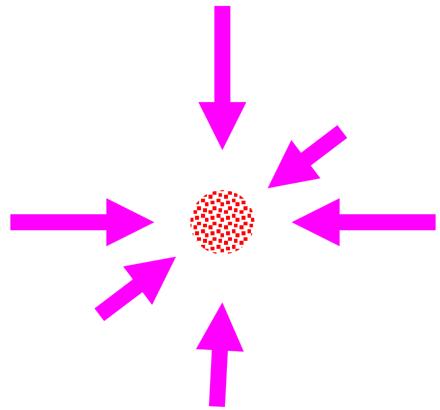
Piégeage intermittent d'un seul atome

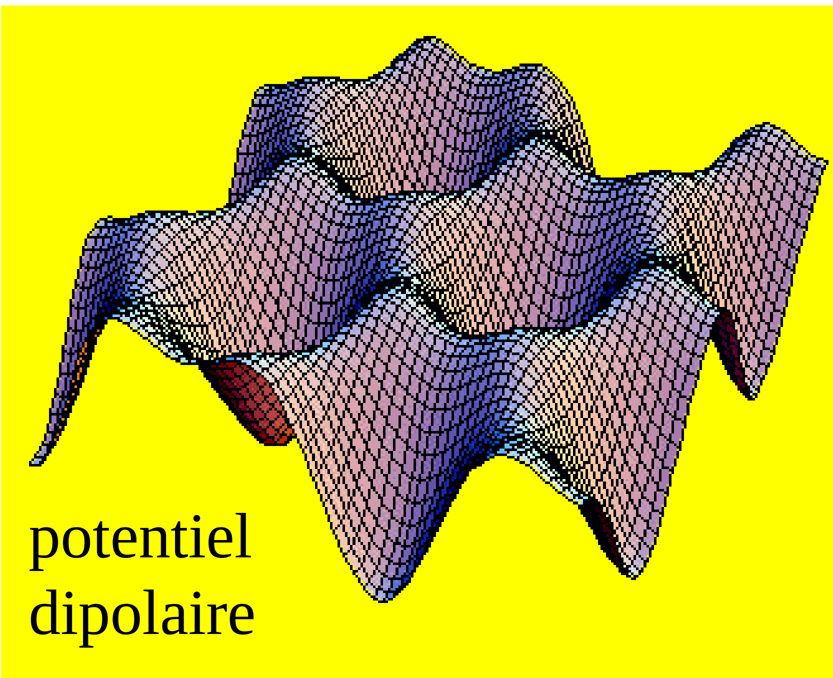


2 atomes
côte à côte

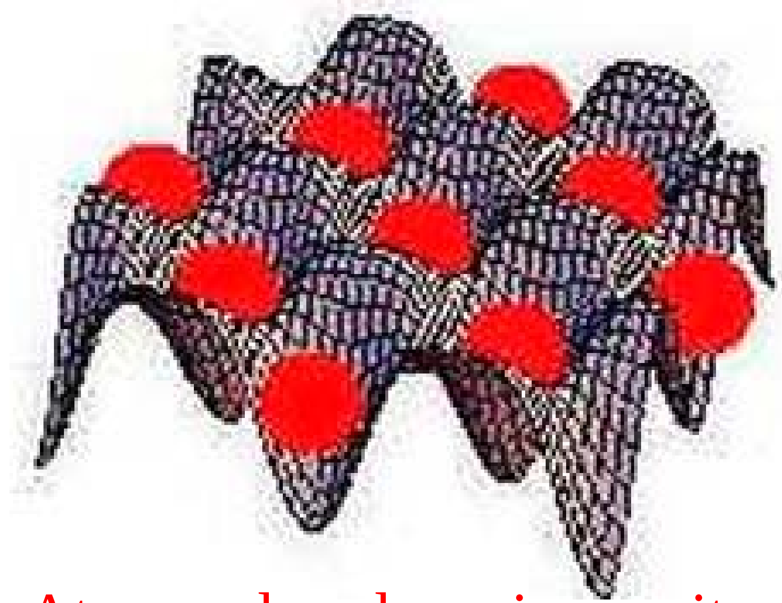
Piège dipolaire: réseau optique

Piégeage aux ventres ($\omega < \omega_0$) ou aux nœuds ($\omega > \omega_0$) d'une onde stationnaire 3 dimensions:



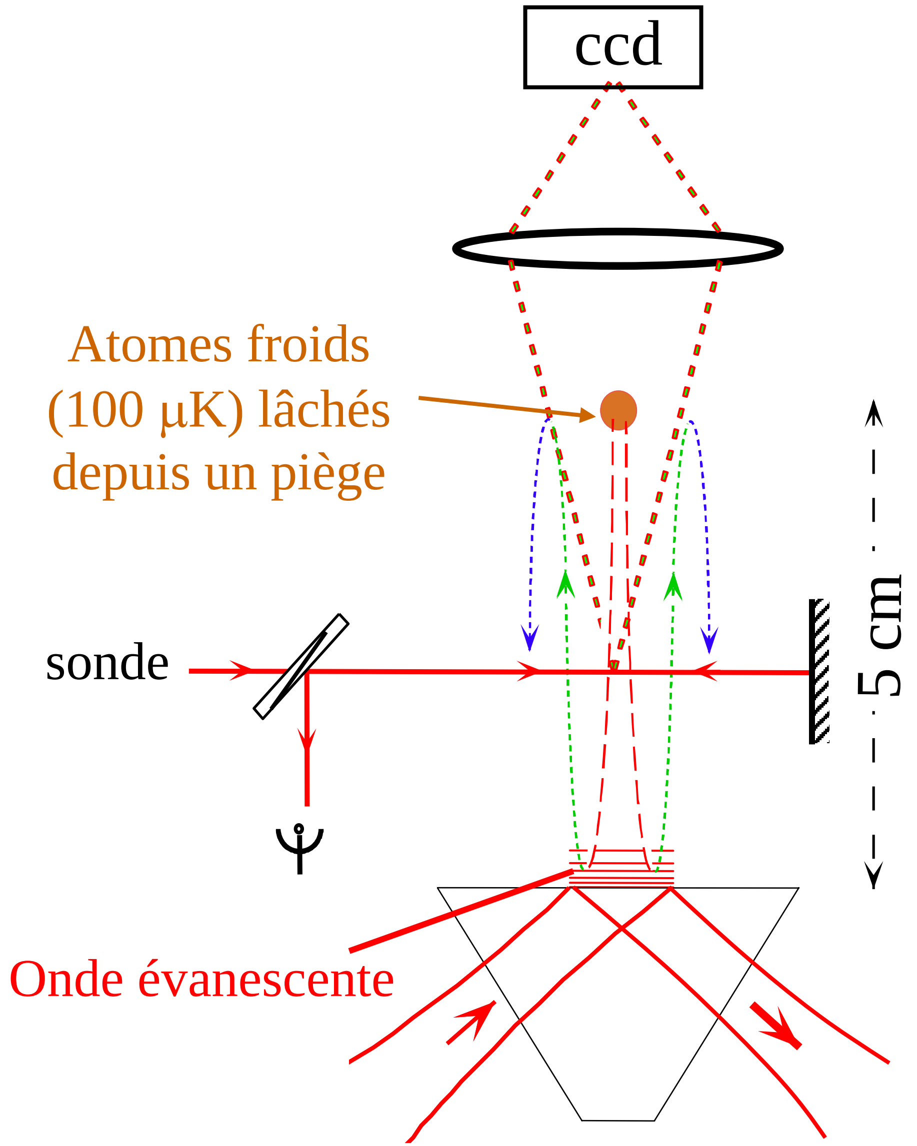


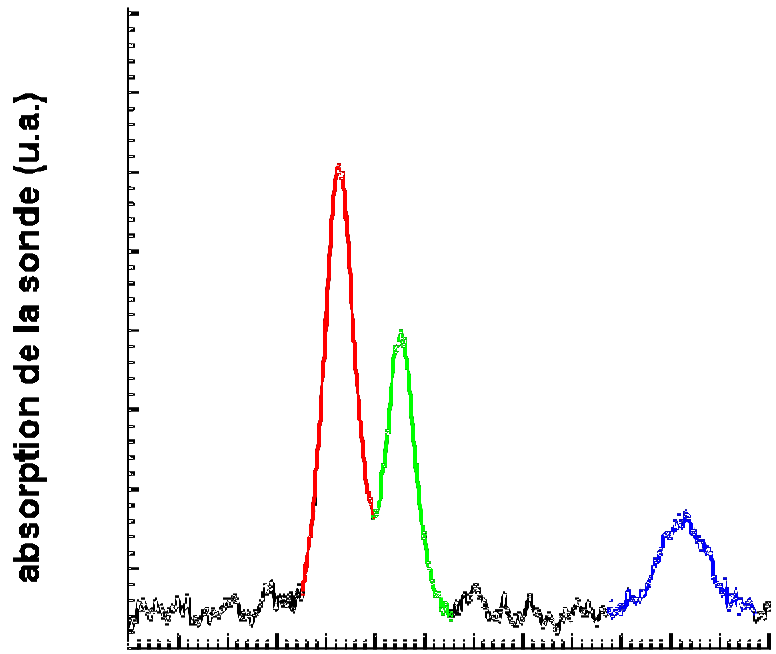
cf. G. Grynberg et coll.



Atomes dans les micro puits

Miroir atomique à ondes évanescentes





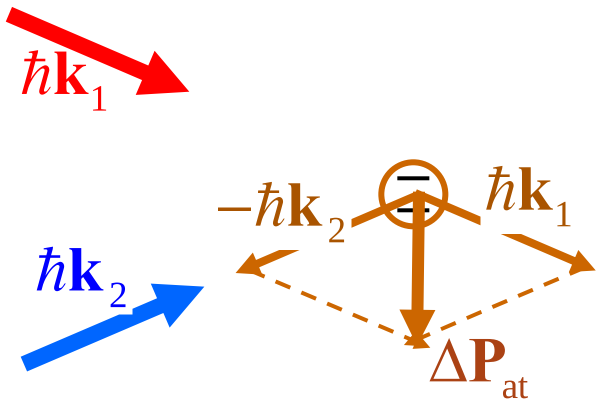
Atomes repoussés ($\omega > \omega_0$: barrière de potentiel) quand ils entrent dans l'onde évanescente : rebond

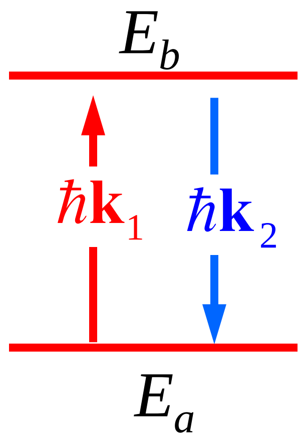
Dipole force and photon momentum

Onde inhomogène = plusieurs ondes planes

- Absorption de $\hbar\mathbf{k_1}$
- Emission stimulée de $\hbar\mathbf{k_2}$

$$\Delta\mathbf{P}_{\mathrm{at}} = \hbar\mathbf{k}_1 - \hbar\mathbf{k}_2$$





Mais on doit aussi considérer:

- Absorption de $\hbar\mathbf{k_2}$
- Emission stimulée de $\hbar\mathbf{k_1}$

⇒ Force de signe opposé !!??

La phase relative des ondes 1 et 2 détermine quel processus domine.

- Délicat dans le modèle tout quantique (photons)
- Automatiquement pris en compte dans le modèle classique du champ (la phase relative détermine le gradient d'intensité)

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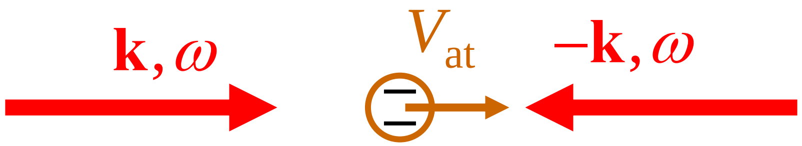
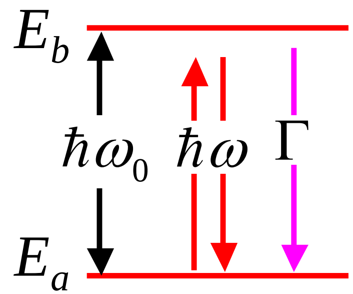
   3. Limit temperature of Doppler c.
   4. Below Doppler limit: Sisyphus
6. Below the one photon recoil limit: dark resonance cooling and Lévy flights

Refroidissement Doppler

Pression de radiation par deux ondes opposées



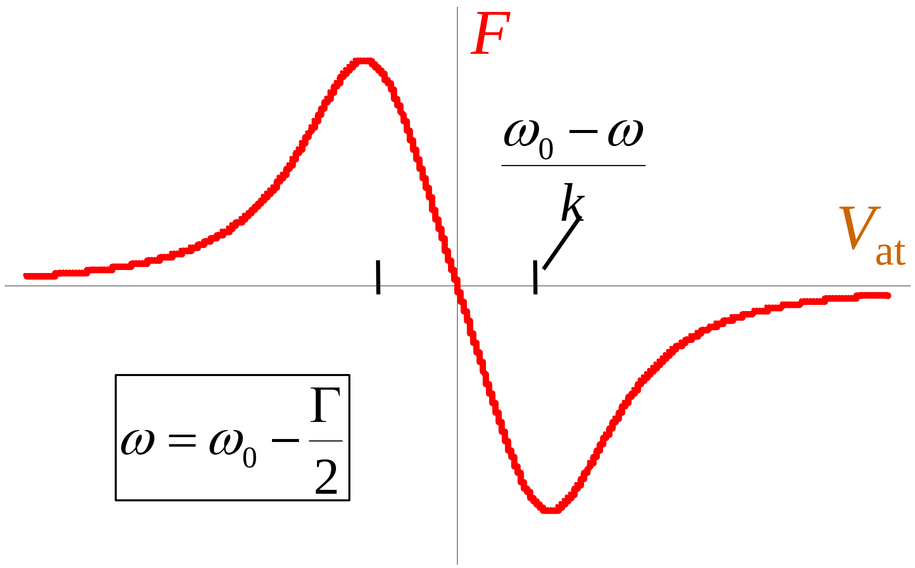
$\omega < \omega_0$



Lasers non saturants, désaccordés sous la résonance

Vitesse atomique: effet Doppler différent pour les deux ondes

$$\mathbf{F}_{res} = \mathbf{F}_0 \left\{ \frac{\Gamma^2/4}{(\omega - \mathbf{k}\cdot\mathbf{V}_{at} - \omega_0)^2 + \Gamma^2/4} - \frac{\Gamma^2/4}{(\omega + \mathbf{k}\cdot\mathbf{V}_{at} - \omega_0)^2 + \Gamma^2/4} \right\}$$

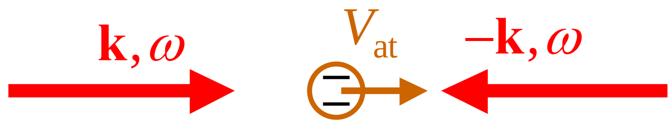


Force opposée à la vitesse: freinage ⇒ refroidissement

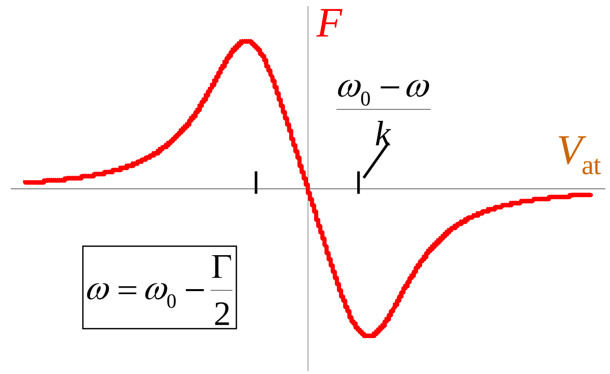
Généralisable à 3 dimensions

Mélasse Doppler

Autour de $V = 0$: frottement visqueux



$$F = -\alpha M V \quad \text{ou} \quad \frac{dV}{dt} = -\alpha V$$



$$\alpha = \frac{\hbar k^2}{M} s_0 \quad \text{pour} \quad \omega = \omega_0 - \frac{\Gamma}{2}$$

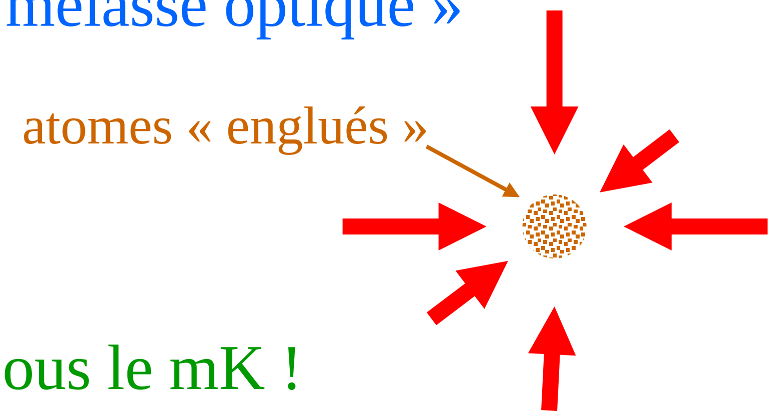
Ordre de grandeur (rubidium, $s_0 = 0.5$)

$$\alpha \simeq 2.5 \times 10^{-4} \ \text{s}^{-1}$$

Temps d'amortissement : 40 µs !

Milieu très visqueux: « mélasse optique »

Refroidissement exponentiel !

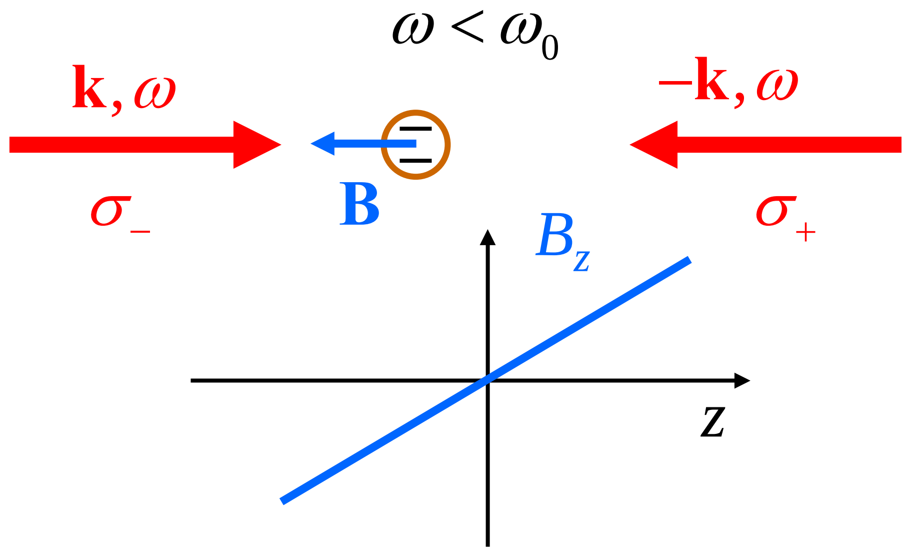


$$\frac{d}{dt}\left\langle V^2 \right\rangle = -2\alpha \left\langle V^2 \right\rangle$$

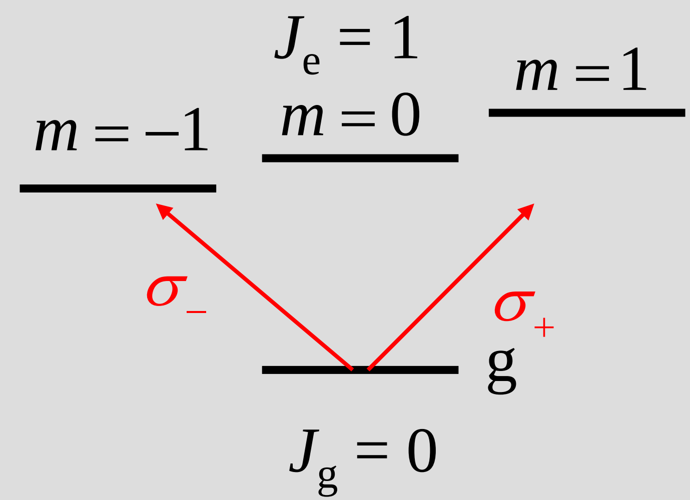
La température décroît : jusqu'où ? Sous le mK !

Magneto Optical Trap: molasses with a restoring force

Zeeman differential detuning and polarized lasers



Quadrupole magnetic field: sign changes at $z = 0$



$B_z < 0$: σ_- polarized beam more efficient than σ_+

Atom pushed towards z = 0: trapping. Doppler molasses also at work.

$\Rightarrow$ Overdamped trap. Works in 3D . “The work horse of cold atoms”

What is the limit temperature in doppler molasses of Magneto Optical trap?

We have a cooling process that never stops.

Is there a heating process?

Heating: fluctuations of radiative forces

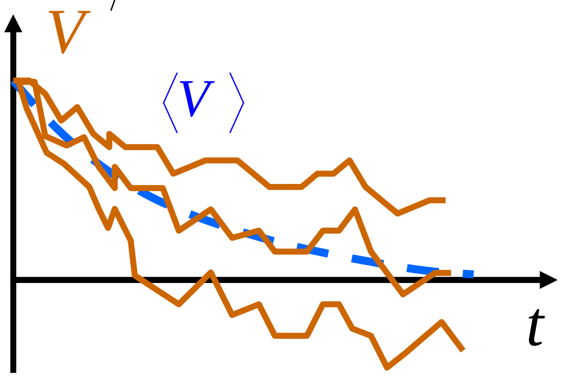
Semi-classical approach $\mathbf{F} = \left\langle \hat{D}_{\boldsymbol{\varepsilon}} \right\rangle \left[\vec{\nabla} \{ E(\mathbf{r}, t) \} \right]_{\mathbf{r}_{\text{at}}}$

$\langle D \rangle$: quantum average, over an ensemble of atoms, submitted to the same radiation. Many atoms: a genuine ensemble!

Each atom is submitted to a different force $\mathcal{F}$, whose average is **F.**

$$\left\langle \vec{\mathcal{F}}(t) \right\rangle = \mathbf{F}(t) \qquad \left\langle \vec{\mathcal{F}}^2(t) \right\rangle - \mathbf{F}^2(t) = \Delta \mathcal{F}^2$$

$\Rightarrow$ Velocity dispersion increases with time



$\Delta V^2 \nearrow$

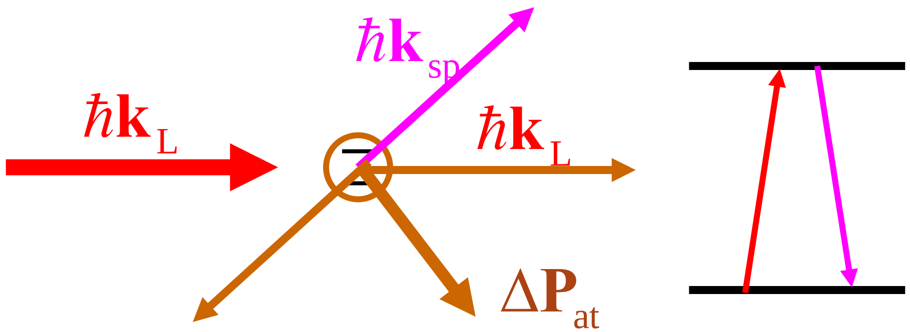
$\Rightarrow$ heating

Heating due to the quantum character of atomic dipole.

There is another point of view, based on momentum exchanges with photons

Fluctuations of radiation pressure: a photon point of view

At each fluorescence cycle, there is a spontaneous emission random recoil which is not taken into account in the average force



Random walk in the atom momentum space: step $\hbar k$, rate R_{fluo}

$$2D_{\mathbf{P}} = (\hbar k)^2 \, R_{\text{fluo}}$$

Diffusion coefficient (Einstein)

$$\frac{d}{dt}\left\langle \mathbf{P}^2 \right\rangle = 2D$$

Heating

Limit of Doppler cooling

Cooling
$$\frac{d}{dt}\left\langle \mathbf{P}^2 \right\rangle = -2\alpha \left\langle \mathbf{P}^2 \right\rangle$$

Heating
$$\frac{d}{dt}\left\langle \mathbf{P}^2 \right\rangle = 2D$$

Steady state
$$\left\langle \mathbf{P}_{\text{at}}{}^2 \right\rangle = \frac{D}{\alpha}$$

Relation d'Einstein

Can be described with a Langevin equation
$$\frac{d}{dt}\mathbf{P}_{\text{at}} = -\alpha \mathbf{P}_{\text{at}} + \vec{\mathcal{F}}_{\text{chauff}}$$

Température finale

$$\frac{3}{2}k_{\text{B}}T = \frac{\left\langle \mathbf{P}_{\text{at}}{}^2 \right\rangle}{2M} = \frac{3}{4}\hbar\Gamma$$

Ordre de grandeur : 100 μK

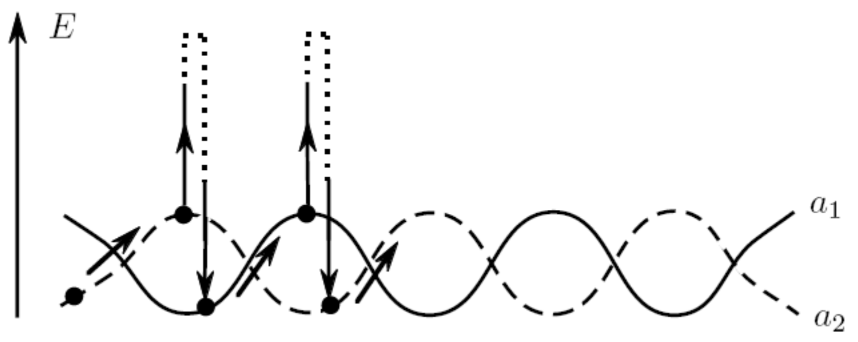
Demonstrated in 1985 (S. Chu)

Below the Doppler limit: Sisyphus cooling

Doppler limit: 100 μK range (observed in 1985, S. Chu)

1988: limit temperature found in the 10 μK range, well below the "theroretical" limit of Doppler cooling (WD Phillips)

Interprétation (C. Cohen-Tannoudji, J. Dalibard): "Sisyphus effect".
Must take into account ground state degeneracy, and light polarization gradients that one cannot avoid in a 3D standing wave.



Because of delay to reach internal steady state (motion) the atom tends to spends more time climbing hills than descending: looses kinetic energy.

Residual velocity: a few recoil velocity $V_R = \dfrac{\hbar k}{M}$ Ultimate limit?

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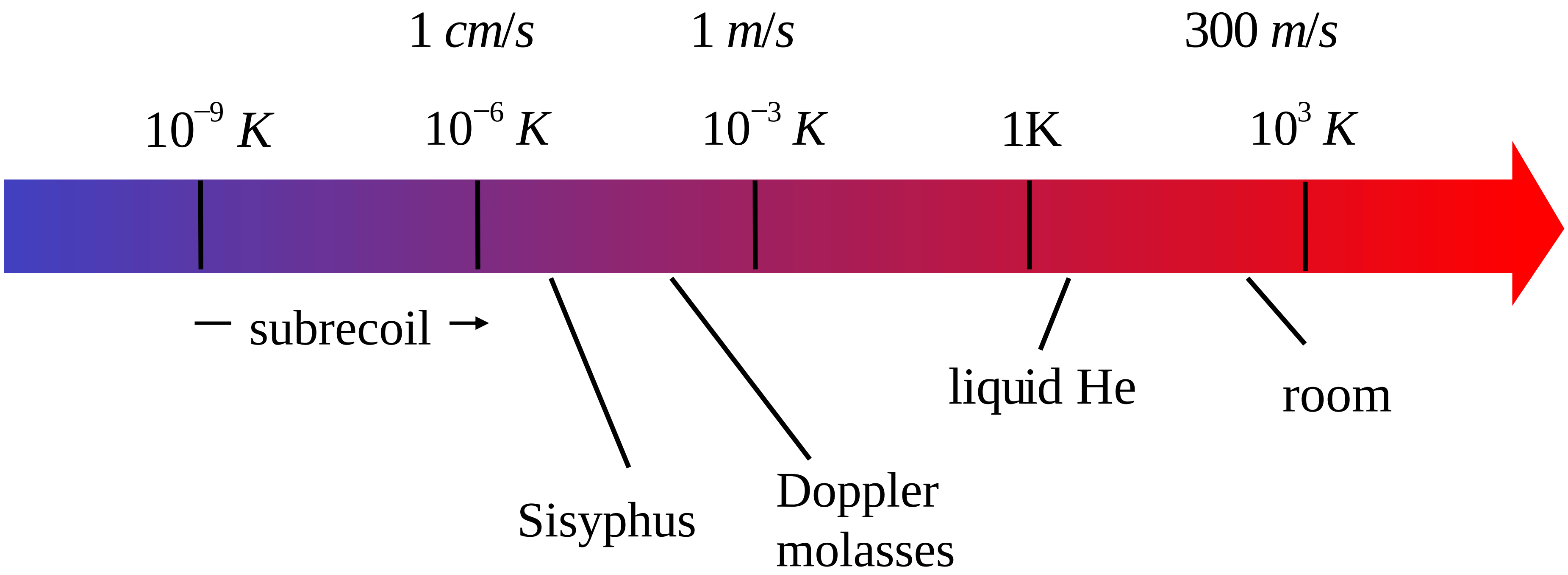
The one photon recoil: an ultimate limit?



Experiments show that ultimate limit of Sisyphus corresponds to a few single photon recoil

$$\frac{3}{2}k_B T \approx 10\frac{(\hbar k)^2}{2M}$$

In agreement with the concept that spontaneous emission is necessary (dissipation, non hamiltonian), and cannot be controlled.

Below the recoil limit: velocity selective coherent population trapping ("dark resonance cooling")

1988 (ENS Paris; CCT, AA): demonstration of a method allowing one to obtain a gas with velocity distribution narrower than the recoil velocity associated with the emission or absorption of a single photon $V_R = \frac{\hbar k}{M}$

Necessary to use a quantum description of the atomic motion

New theoretical approaches:

- Quantum Monte-Carlo; delay function
- Lévy flights statistics

See "special" (vintage) seminar

Laser cooling and trapping of atoms: a fantastic new tool

In less than one decade (1980's), it has been possible to reach goals that were thought to be very far ahead:

- Cooling atoms in the μK range
- Trapping atoms and keeping them for seconds

Experimental surprises as well as ingenuity has allowed physicits to break several so called "limits", and prompted them to revisit atom-light interaction.

This new tool for atomic physics has paved the way to gaseous Bose Einstein Condensates and the many recent developments at the frontier between Condensed Matter Physics and Atomic Molecular and Optical Physics