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Technologies quantiques émergentes

Pascale Senellart

9 février 2026

Processeurs quantiques à bases d'atomes

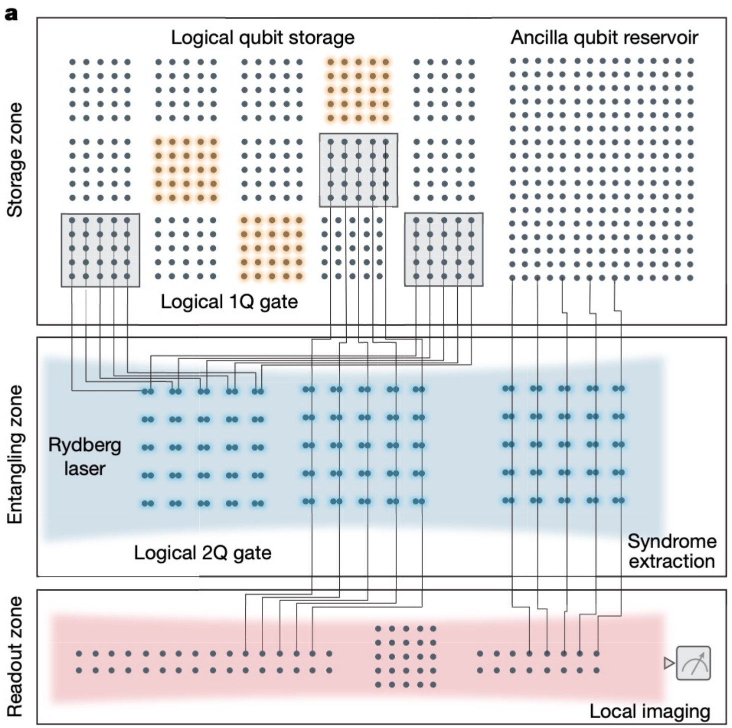
Processeurs quantiques atomiques : deux systèmes

Ions piégés *	Atomes neutres *
AQT	Pasqal
QUANTINUUM	QuEra
oxford ionics	atom computing
IONQ	planqc
	Infleqtion

(*) Listes non exhaustives

Processeurs quantiques atomiques : deux types de calcul

Digital

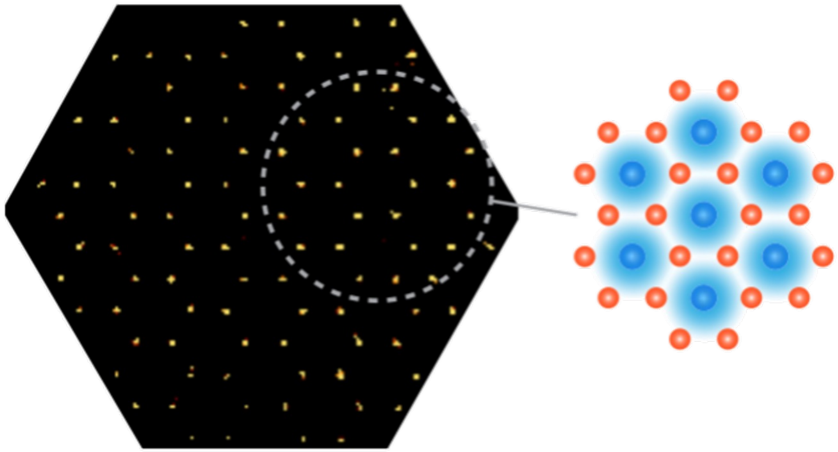


Nature 626, 58–65 (2024)

Analogique - Simulation

Feynman, R. P. Simulating physics with computers. Int. J. Theor. Phys. 21, 467–488 (1982).

Systèmes antiferromagnétiques bidimensionnels



Nature 595, 233–238 (2021)

Atouts et défis des processeurs atomiques

Atouts	Défis
➢ Héritage des horloges atomiques	➢ Miniaturisation / intégration
➢ Atomes, ions identiques	➢ Passage à l'échelle
➢ Faible décohérence naturelle	
➢ Cryogénie limitée	

À clarifier

- ➢ Fréquence d'horloge

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Critères de Di Vincenzo pour le calcul quantique

- Un système physique évolutif avec des qubits bien caractérisés
- Une capacité de mesure spécifique aux qubits
- La capacité d'initialiser l'état des qubits
- De longs temps de décohérence
- Un ensemble « universel » de portes quantiques

Processeurs quantiques à base d'atomes

Piéger des atomes

Pièges dipolaires, de Penning et de Paul

Choix des transitions et contrôle

Transitions "horloge"

Portes logiques à 2 qubits

Porte Cirac Zoller

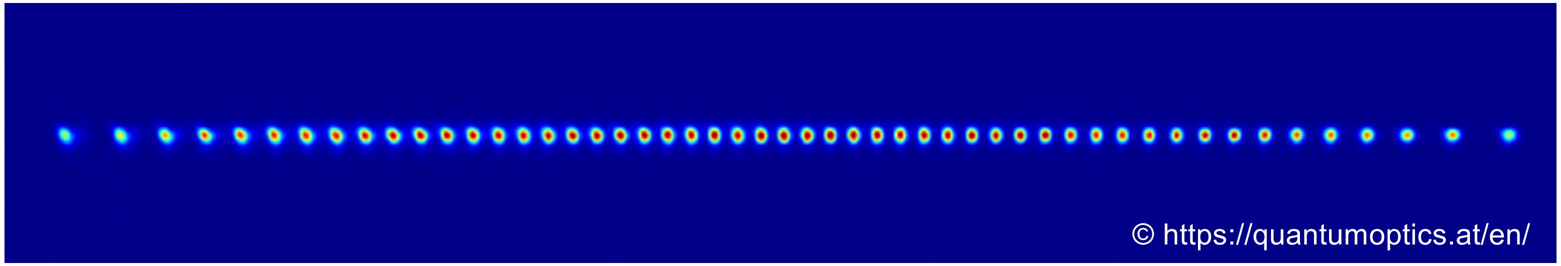
Démonstrations récentes

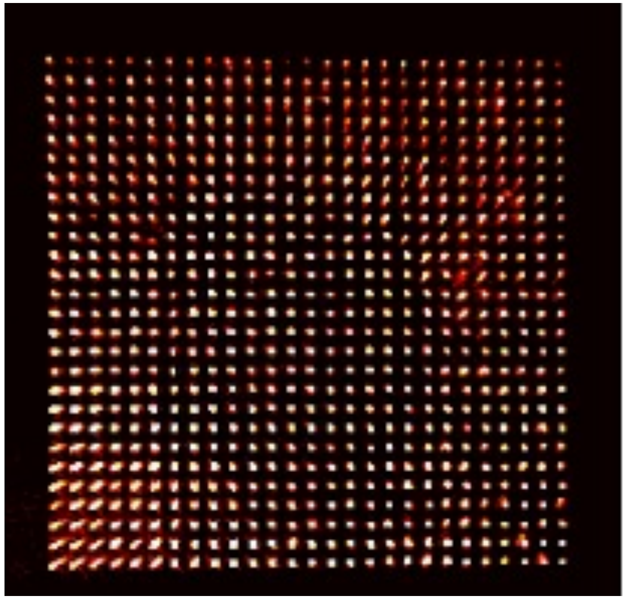
Séminaire Pr. Antoine Browaeys

Piéger des atomes

- Un système physique évolutif avec des qubits bien caractérisés

Piéger des ions et des atomes



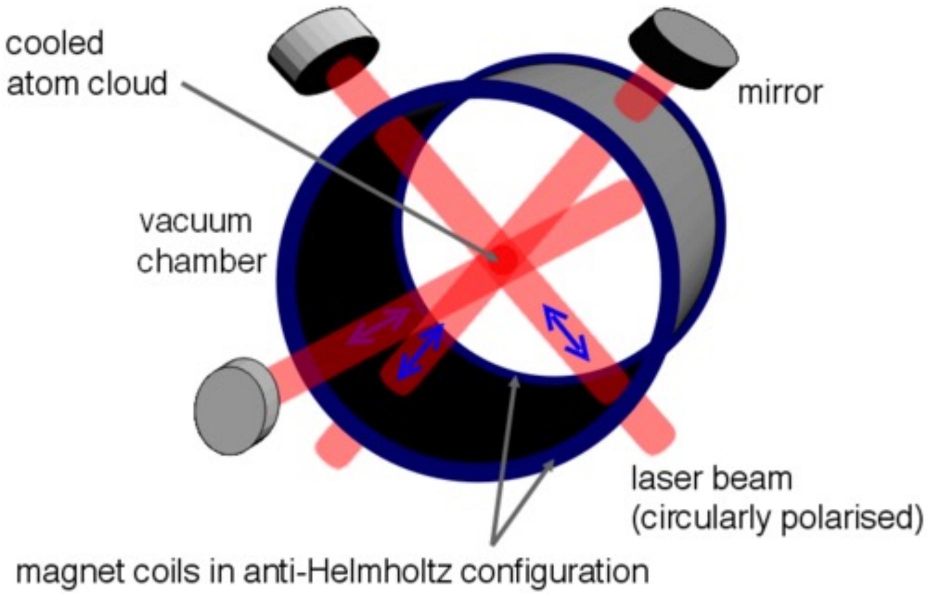


© Antoine Browaeys

Piéger des atomes et des ions

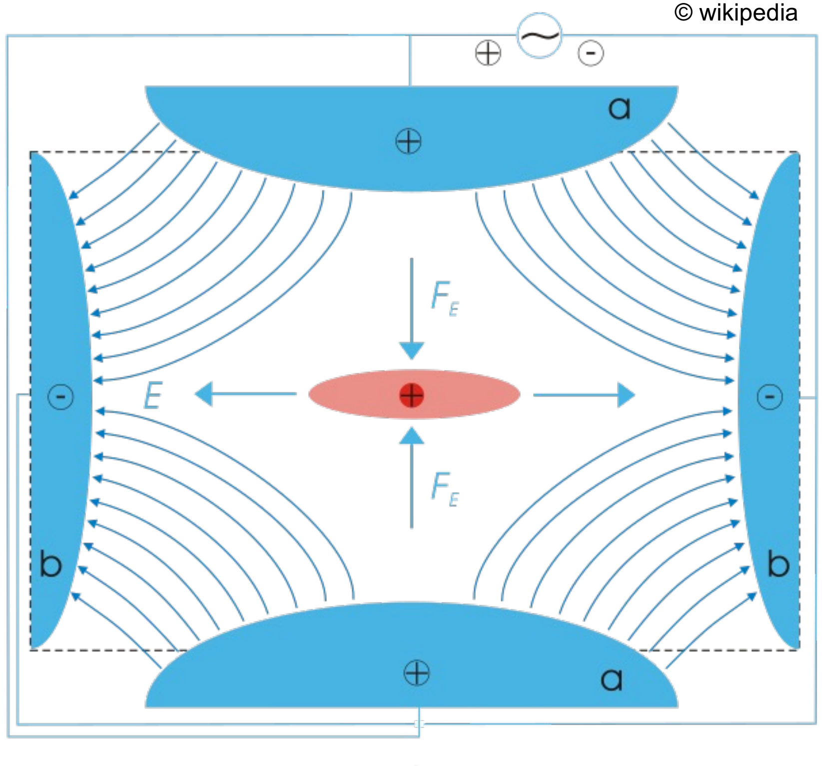
Piège magneto-optique

© wikipedia



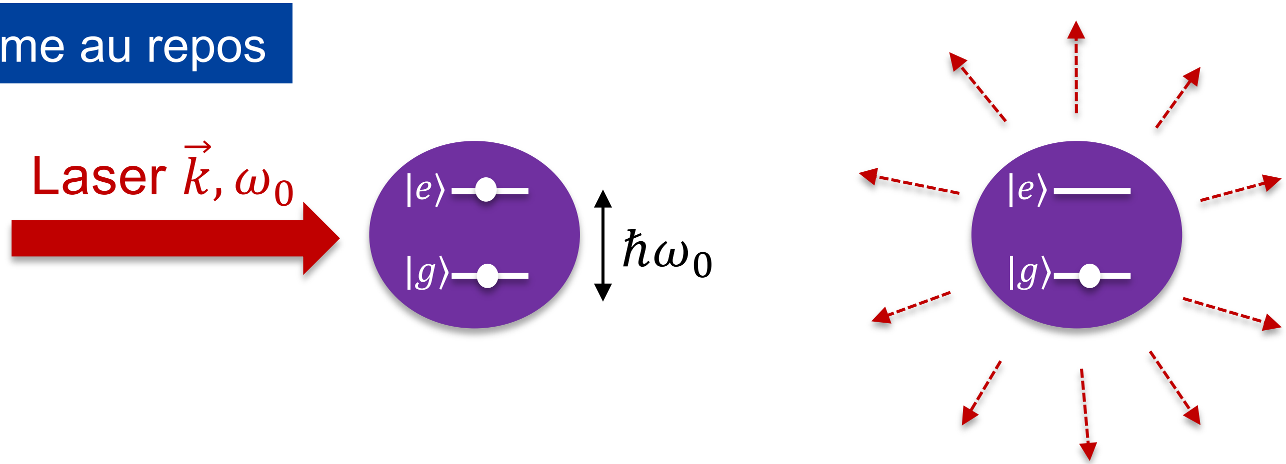
Piège de Paul

© wikipedia



Piéger des atomes : refroidissement Doppler

Atome au repos

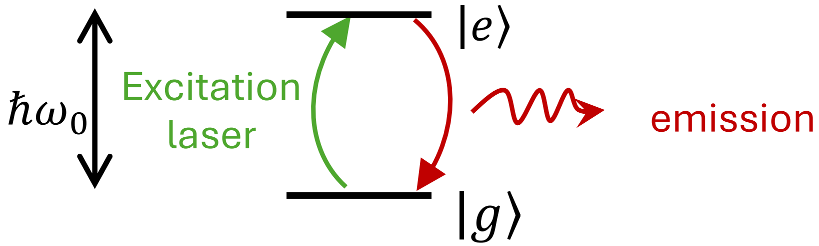


Force nette exercée sur l'atome

$$\boxed{\mathbf{F} = \hbar \mathbf{k}\, \Gamma\, \rho_{ee}}$$

Décohérence par intrication : environnement fluctuant

Atome à deux niveaux dans un champ électrique δE fluctuant +pertes + champ appliqué



$$\boxed{\hat{H} = -\hat{\vec{d}} \cdot \vec{E}}$$

$\vec{E}(t) = E_1 \cos(\omega t)$

$\omega_0 = -E_e - E_g, \quad \omega_1 = dE_1/\hbar$

$\Delta = \omega_0 - \omega$

Cf. Cours 3

Equations de Bloch optiques

$$\frac{d\tilde{\rho}_{ee}}{dt} = -\Gamma\,\tilde{\rho}_{ee} + i\frac{\omega_1}{2}\left(\tilde{\rho}_{ge} - \tilde{\rho}_{eg}\right), \longrightarrow = 0$$

$$\frac{d\tilde{\rho}_{gg-}}{dt} = \Gamma\,\tilde{\rho}_{ee} + -i\frac{\omega_1}{2}\left(\tilde{\rho}_{ge} - \tilde{\rho}_{eg}\right),$$

$$\frac{d\tilde{\rho}_{eg}}{dt} = -i\Delta\,\tilde{\rho}_{eg} - \left(\frac{\Gamma}{2} + \Gamma_\phi\right)\tilde{\rho}_{eg} + i\frac{\omega_1}{2}\left(\tilde{\rho}_{gg} - \tilde{\rho}_{ee}\right) \longrightarrow = 0$$

$$\Gamma = \frac{1}{T_1}, \qquad \Gamma_\phi = \frac{1}{T_2^*}, \qquad \frac{1}{T_2} = \frac{1}{2T_1} + \frac{1}{T_2^*}$$

Stationnaire

$$\tilde{\rho}_{ee} + \tilde{\rho}_{gg} = 1$$

Pas de déphasage pur

$$\longrightarrow \Gamma\, T_2 = 2$$

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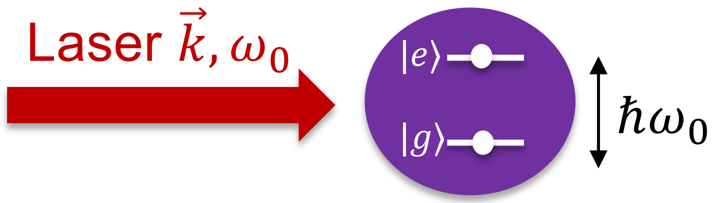
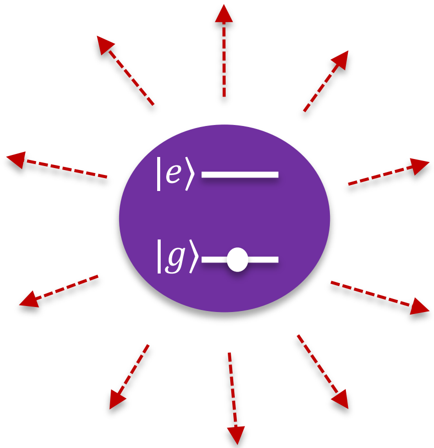
Piéger des atomes : refroidissement Doppler

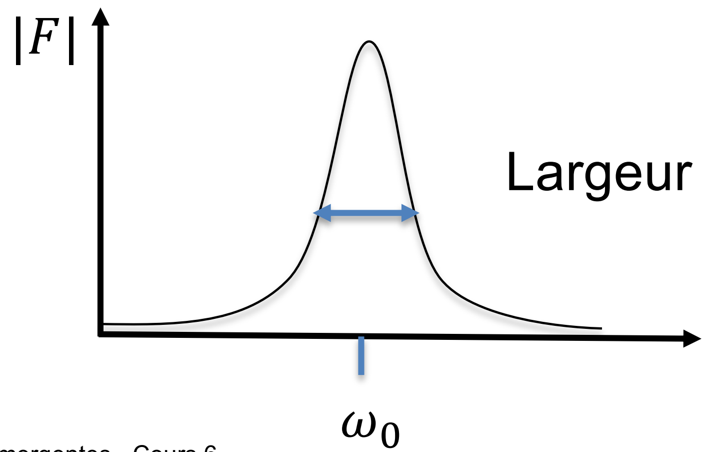
Atome au repos





Force nette exercée sur l'atome

$$\boxed{\mathbf{F} = \hbar\mathbf{k}\,\Gamma\,\rho_{ee}}$$



Largeur $\sqrt{\Gamma^2 + 2\omega_1^2}$.

$$\tilde{\rho}_{ee} = \frac{\omega_1^2/4}{\Delta^2 + \omega_1^2/2 + \Gamma^2/4},$$

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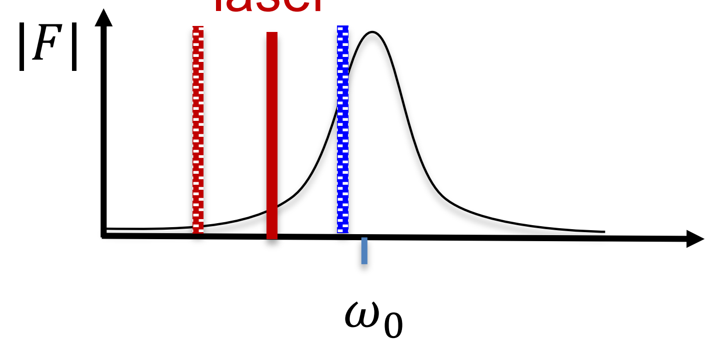
Piéger des atomes : refroidissement Doppler

$$\mathbf{F} = \hbar \mathbf{k}\, \Gamma \frac{\omega_1^2/4}{\Delta^2 + \omega_1^2/2 + \Gamma^2/4},$$



Atome contre propageant

Laser $\vec{k}, \omega_\ell$

$\omega' = \omega_\ell - \vec{k}.\vec{v}$ augmente

=> freine

Atome co-propageant

Laser $\vec{k}, \omega_\ell$

$\omega' = \omega_\ell - \vec{k}.\vec{v}$ réduit

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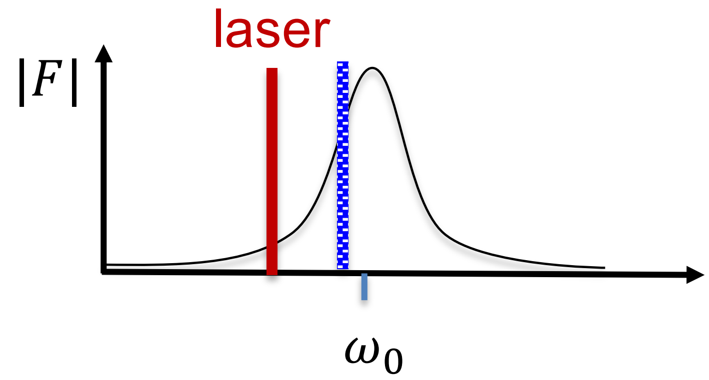
Piéger des atomes : refroidissement Doppler

$$\mathbf{F} = \hbar \mathbf{k}\,\Gamma \frac{\omega_1^2/4}{\Delta^2 + \omega_1^2/2 + \Gamma^2/4},$$



Atome contre propageant

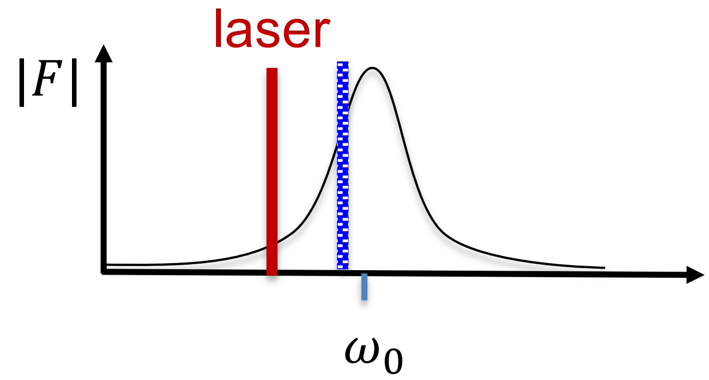
$\omega' = \omega_\ell - \vec{k}.\vec{v}$ augmente
=> freine

Freinage : $\delta p = \hbar\, k$

Chauffage : $\delta p^2 = \hbar^2 \left(k^2 + k'^2 - 2\vec{k}.\vec{k'}\right) \approx 2\hbar^2\, k^2$

Piéger des atomes : refroidissement Doppler

$$\mathbf{F} = \hbar \mathbf{k}\,\Gamma \frac{\omega_1^2/4}{\Delta^2 + \omega_1^2/2 + \Gamma^2/4},$$



Atome contre propageant

$\Delta_{\text{eff}} = \Delta - \mathbf{k}\cdot\mathbf{v}$ réduit

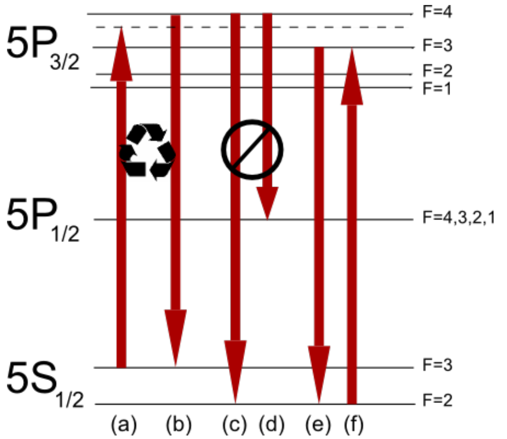
=> freine

Température limite atteinte par refroidissement Doppler $T_D = \dfrac{\hbar\Gamma}{2k_B}$

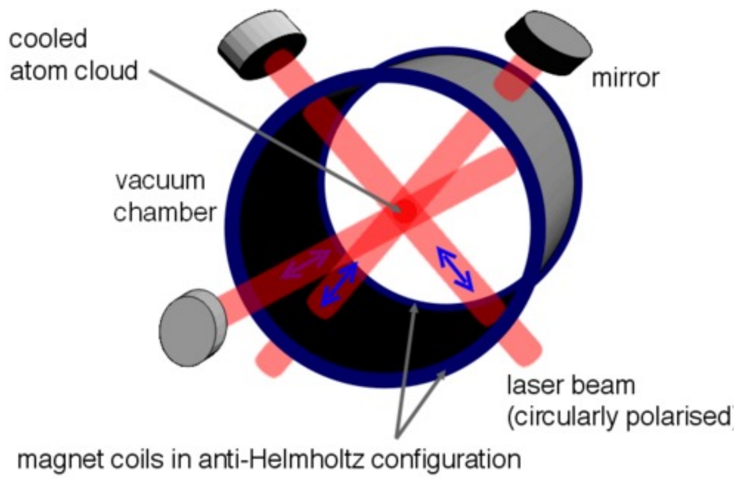
~100-200 μK (Rb)

Piéger des atomes : Piège magnéto-optique

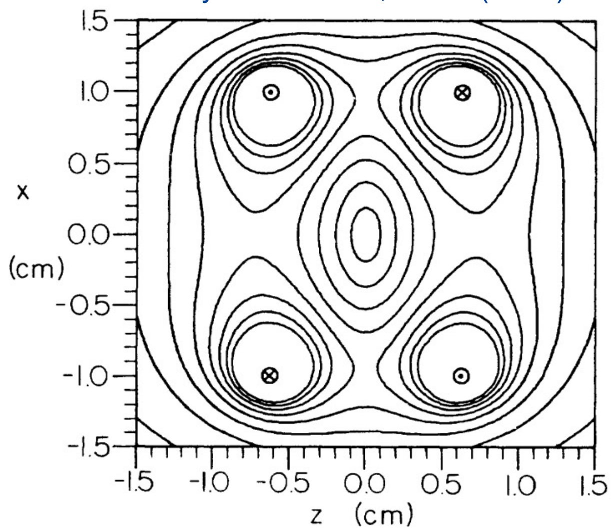
En pratique : transitions cycliques, repompage



Ajout d'un piège magnétique



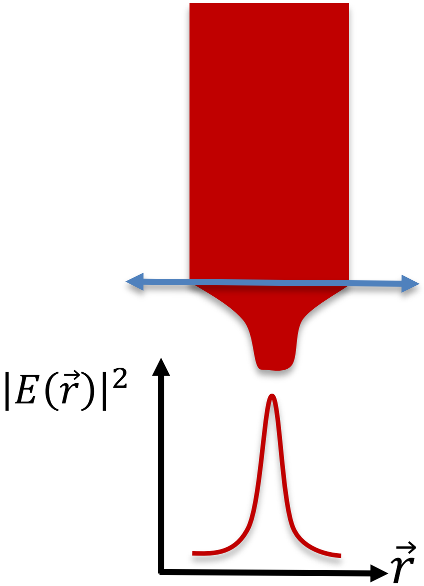
Phys. Rev. A 35, 1535 (1987)



$$F = -\alpha\, v\ - \kappa\, x$$

- $-\alpha v$: friction Doppler (refroidissement),
- $-\kappa x$: force harmonique de rappel (piégeage)

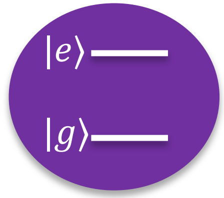
Piéger des atomes : Pièges dipolaires – pinces optiques



$$I(r,z) = I_0 \left(\frac{w_0}{w(z)}\right)^2 \exp\left(-\frac{2r^2}{w(z)^2}\right)$$

Polarisabilité

$$\mathbf{d} = \alpha(\omega)\mathbf{E}$$

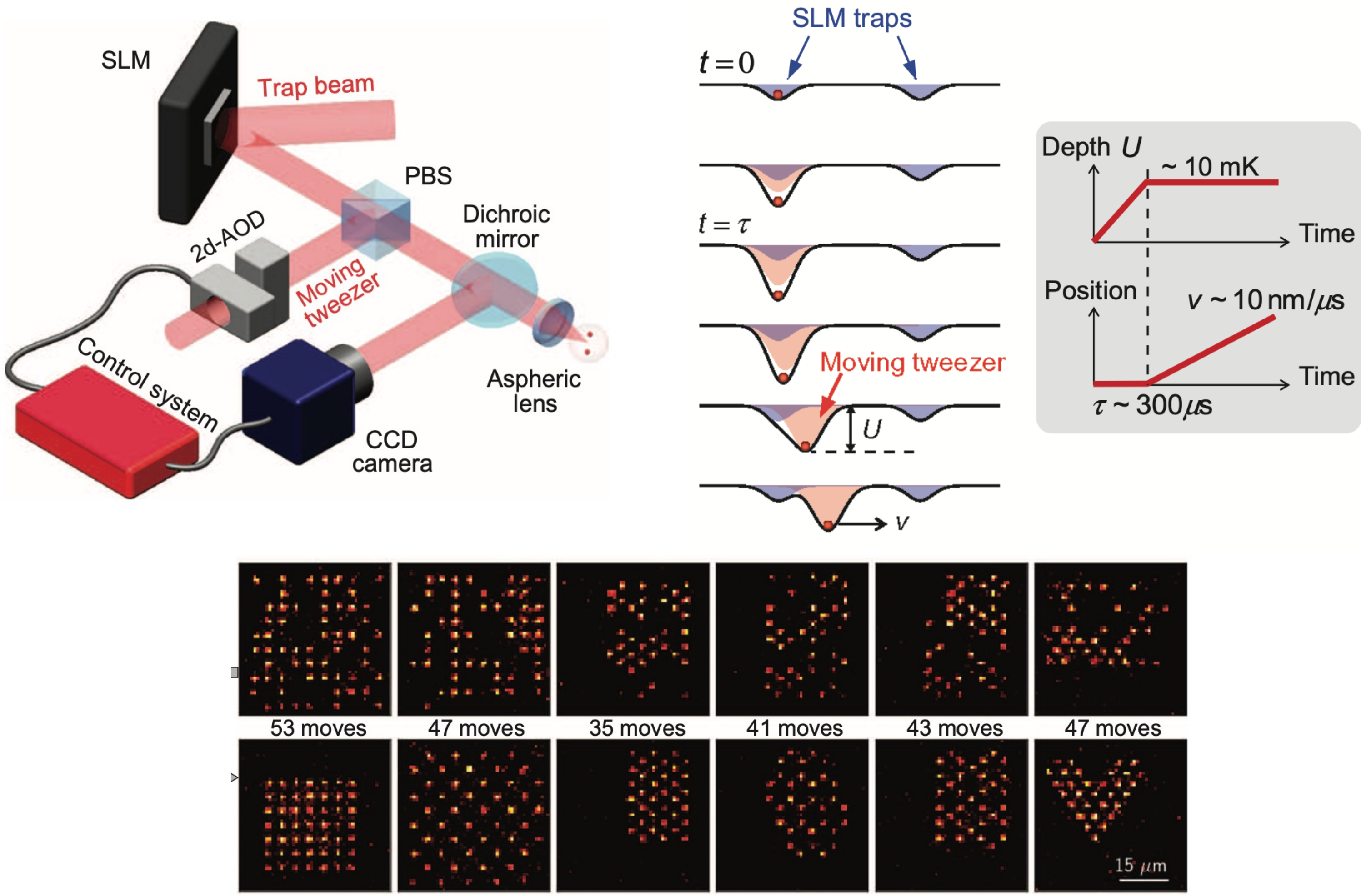


$$\boxed{\alpha(\omega) \propto \frac{1}{\Delta + i\Gamma/2}}$$

$$U(\mathbf{r}) = -\frac{1}{2}\,\mathrm{Re}[\alpha(\omega_L)]\,\langle E^2(\mathbf{r})\rangle \qquad \mathrm{Re}[\alpha(\omega_L)] \propto \frac{\Delta}{\Delta^2 + (\Gamma/2)^2},$$

$\Delta < 0$ potentiel attractif
$\Delta > 0$ potentiel répulsif

Piéger des atomes : Pinces optiques



Science 354,1021-1023(2016)

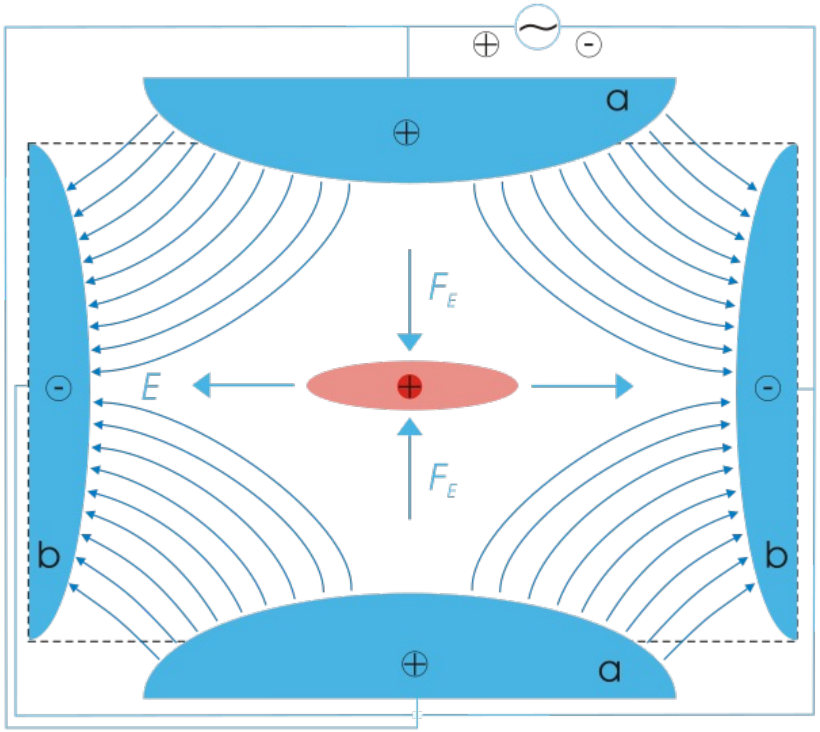
Piéger des particules charges : Pièges de Paul

Piège de Paul

$U(x, y, z) = a(2z^2 - x^2 - y^2)$

$$\begin{aligned} m\ddot{x} &= 2q\,ax \\ m\ddot{y} &= 2q\,ay \\ m\ddot{z} &= -4q\,az \end{aligned}$$

Si $q\,a \geq 0$, piège selon l'axe z
Si $q\,a \leq 0$, piège selon les axes x et y



1

$U(x, y, z) = a(t)(2z^2 - x^2 - y^2)$
$a(t) = a_0 cos(\omega t)$

Piéger des particules charges : Pièges de Paul

https://www.youtube.com/watch?v=a5v-W_pAqIs

Piéger des particules charges : Pièges de Penning

Piège de Penning

Piège électrostatique : $U(x,y,z) = a(2z^2 - x^2 - y^2)$

$$\begin{aligned} m\ddot{x} &= 2q\,ax \\ m\ddot{y} &= 2q\,ay \\ m\ddot{z} &= -4q\,az \end{aligned}$$

avec $q\,a \geq 0$
Champ magnétique : $\vec{B} = B\vec{e}_z$

$$\vec{A} = \vec{B} \times \vec{r}/2 = \begin{pmatrix} -By/2 \\ Bx/2 \\ 0 \end{pmatrix}.$$

$$\boxed{\hat{H} = \frac{(\hat{\vec{p}} - q\vec{A})^2}{2m} + qU(\hat{\vec{r}})}$$

$$\hat{H} = \hat{H}_{xy} + \hat{H}_z - \frac{\omega_c}{2}\hat{L}_z$$

$$\hat{H}_z = \frac{\hat{p}_z^2}{2m} + \frac{1}{2}m\omega_z^2\hat{z}^2$$

$$\hat{H}_{xy} = \frac{\hat{p}_x^2}{2m} + \frac{\hat{p}_y^2}{2m} + \frac{1}{2}m\Omega^2(\hat{x}^2 + \hat{y}^2)$$

$$\omega_c = qB/m$$

$$4qa = m\omega_z^2$$

$$\Omega^2 = \left(\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}\right)$$

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Piéger des particules charges : Pièges de Penning

$$\hat{H} = \hat{H}_{xy} + \hat{H}_z - \frac{\omega_c}{2}\hat{L}_z$$

$$\hat{H}_z = \frac{\hat{p}_z^2}{2m} + \frac{1}{2}m\omega_z^2\hat{z}^2$$

$$\hat{H}_{xy} = \frac{\hat{p}_x^2}{2m} + \frac{\hat{p}_y^2}{2m} + \frac{1}{2}m\Omega^2(\hat{x}^2 + \hat{y}^2)$$

$$\hat{H}_{xy} = \hbar\Omega(\hat{a}_x^\dagger\hat{a}_x + \hat{a}_y^\dagger\hat{a}_y)$$

$$\omega_c = qB/m$$

$$4qa = m\omega_z^2$$

$$\Omega^2 = \left(\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}\right)$$

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Piéger des particules charges : Pièges de Penning

$$\hat{H} = \hat{H}_{xy} + \hat{H}_z - \frac{\omega_c}{2}\hat{L}_z$$

$$\hat{H}_z = \frac{\hat{p}_z^2}{2m} + \frac{1}{2}m\omega_z^2\hat{z}^2$$

$$\hat{H}_{xy} = \hbar\Omega\left(\hat{a}_x^\dagger\hat{a}_x + \hat{a}_y^\dagger\hat{a}_y + \hat{I}\right)$$

$$\omega_c = qB/m$$

$$4qa = m\omega_z^2$$

$$\Omega^2 = \left(\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}\right)$$

$$\hat{a}_\pm = \frac{\hat{a}_x \mp i\hat{a}_y}{\sqrt{2}}$$

$$\hat{a}_x = \sqrt{\frac{m\Omega}{2\hbar}}\hat{x} + \frac{i}{\sqrt{2m\hbar\Omega}}\hat{p}_x$$

$$\hat{N}_- = \hat{a}_-^\dagger\hat{a}_-. \qquad \hat{N}_+ = \hat{a}_+^\dagger\hat{a}_+$$

$$\hat{a}_y = \sqrt{\frac{m\Omega}{2\hbar}}\hat{y} + \frac{i}{\sqrt{2m\hbar\Omega}}\hat{p}_y.$$

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Piéger des particules charges : Pièges de Penning

$$\hat{H} = \hat{H}_{xy} + \hat{H}_z - \frac{\omega_c}{2}\hat{L}_z$$

$$\hat{H}_z = \frac{\hat{p}_z^2}{2m} + \frac{1}{2}m\omega_z^2\hat{z}^2$$

$$\hat{H}_{xy} = \hbar\Omega\left(\hat{a}_x^\dagger\hat{a}_x + \hat{a}_y^\dagger\hat{a}_y + \hat{I}\right)$$

$$\omega_c = qB/m$$

$$4qa = m\omega_z^2$$

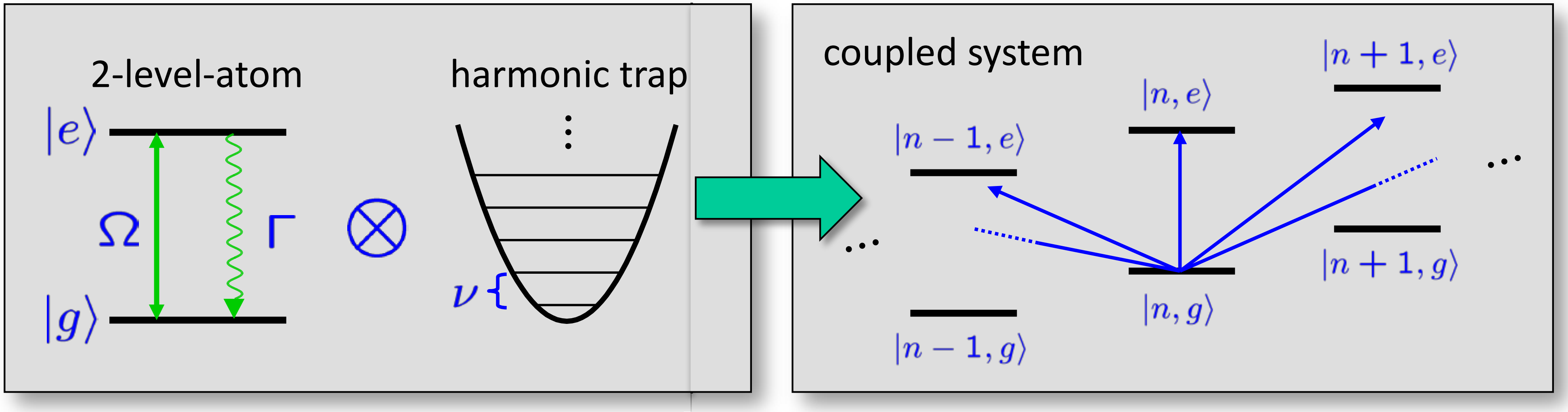
$$\Omega^2 = \left(\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}\right)$$

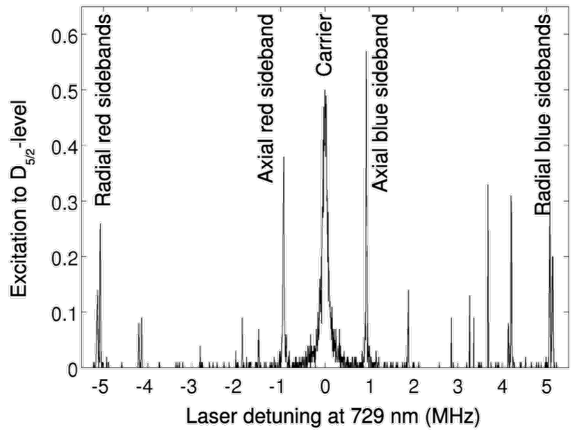
$$\hat{N}_\pm = \hat{a}_\pm^\dagger\hat{a}_\pm = \frac{1}{2}\left(\hat{a}_x^\dagger\hat{a}_x + \hat{a}_y^\dagger\hat{a}_y \pm \frac{\hat{L}_z}{\hbar}\right)$$

$$\hat{H} = \hbar\left(\Omega - \frac{\omega_c}{2}\right)\left(\hat{N}_+ + \frac{\hat{I}}{2}\right) + \hbar\left(\Omega + \frac{\omega_c}{2}\right)\left(\hat{N}_- + \frac{\hat{I}}{2}\right) + \hbar\omega_z\left(\hat{N}_z + \frac{\hat{I}}{2}\right)$$

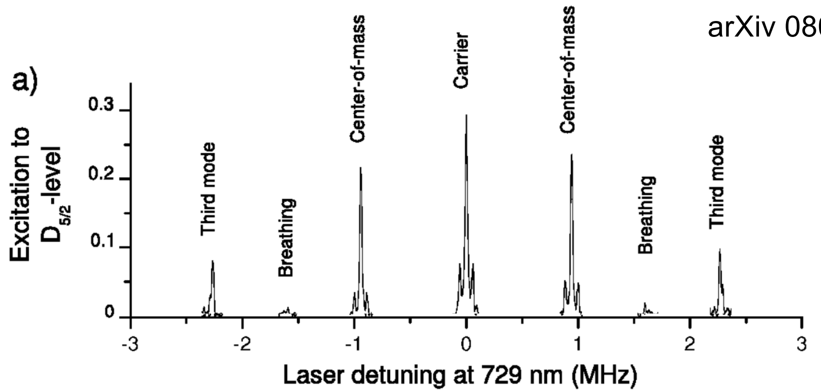
Piéger des ions : système équivalent

Rainer Blatt – Séminaire au Collège de France - 2015





arXiv 0809.4368



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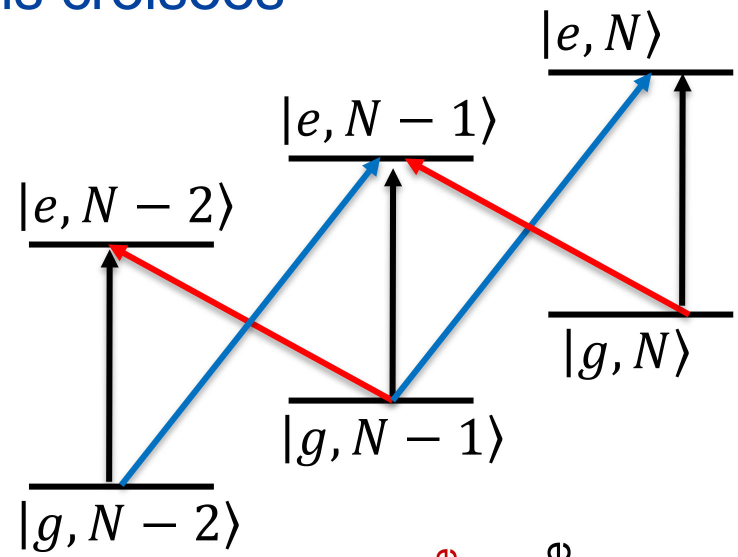
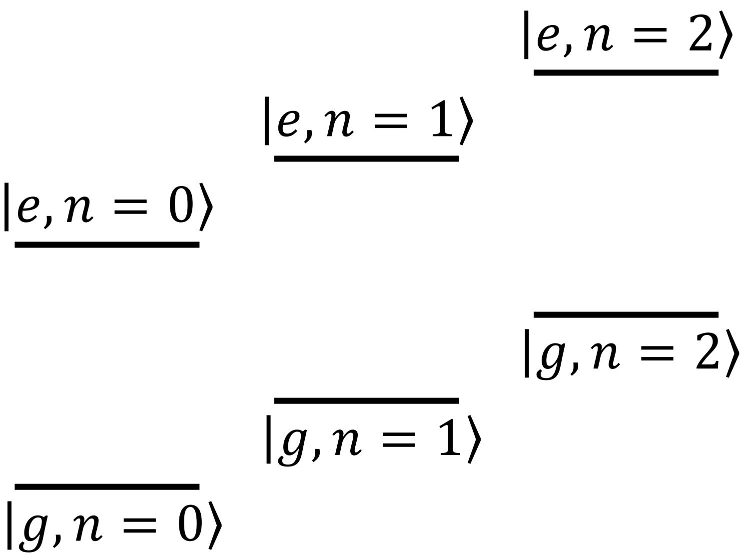
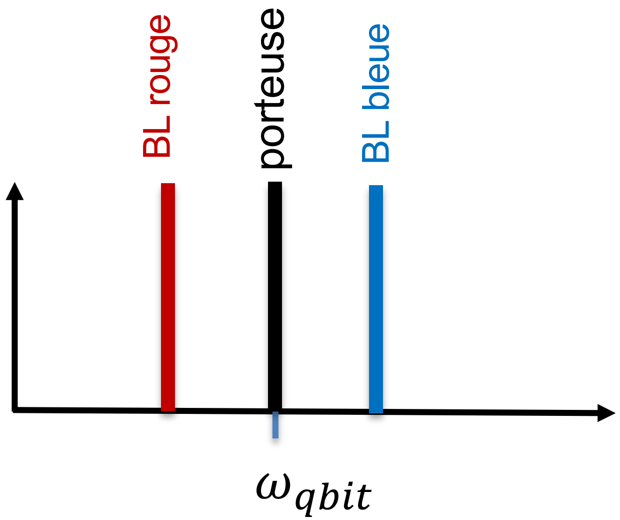
Piéger des ions : transisions croisées



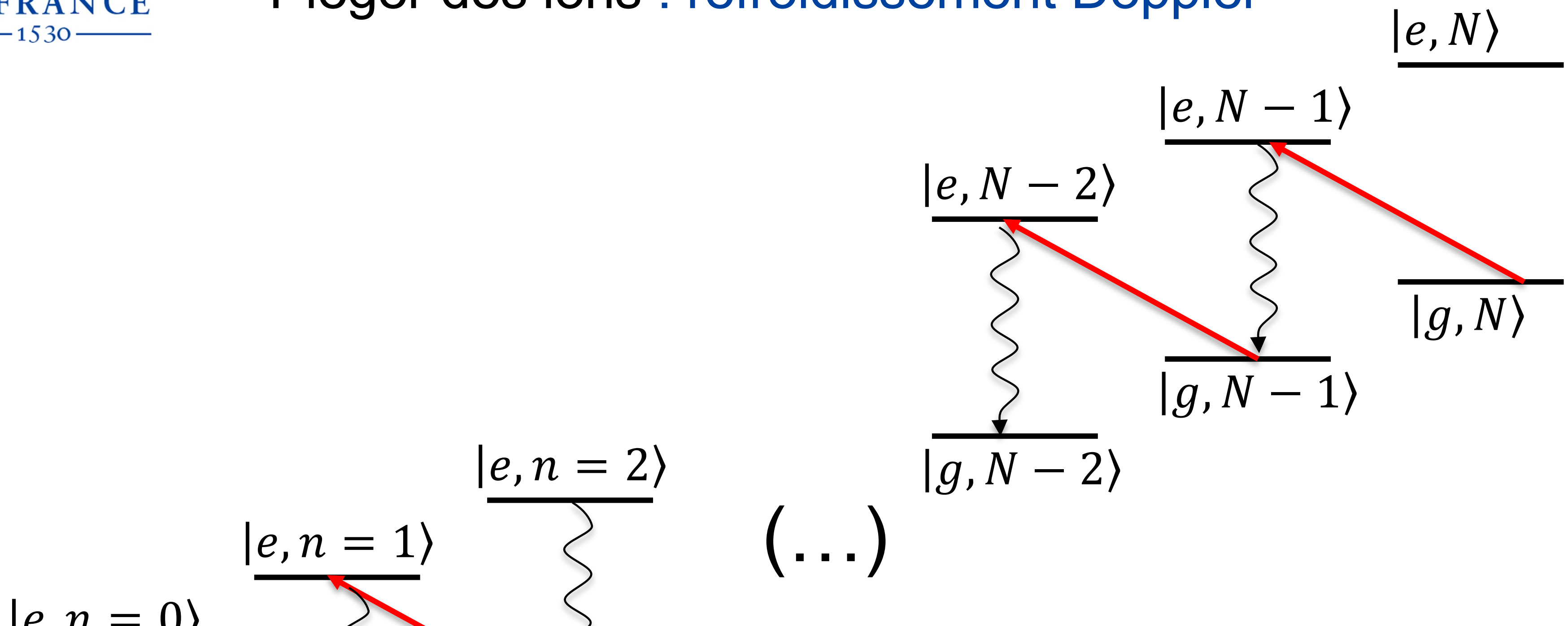


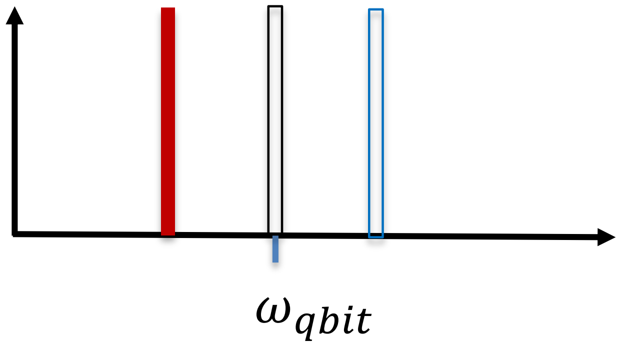
$(\ldots)$



BL = bande latérale

Piéger des ions : refroidissement Doppler





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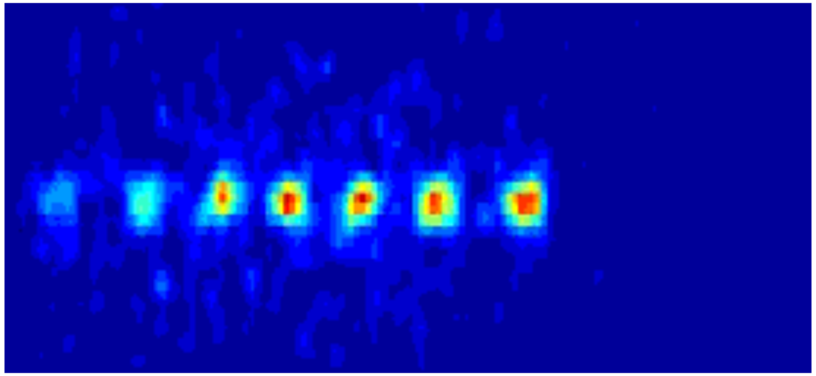
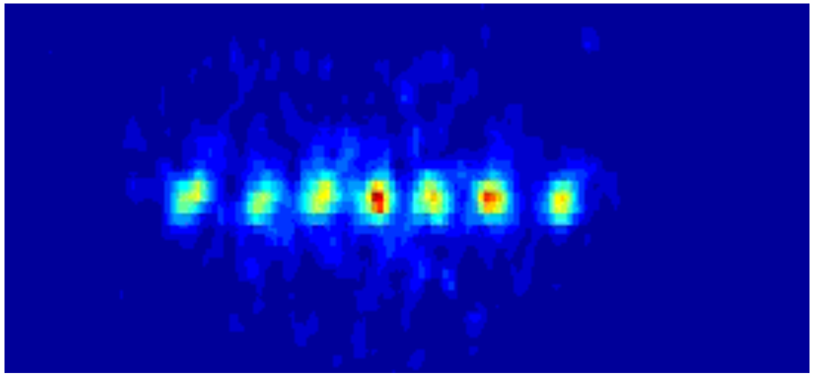
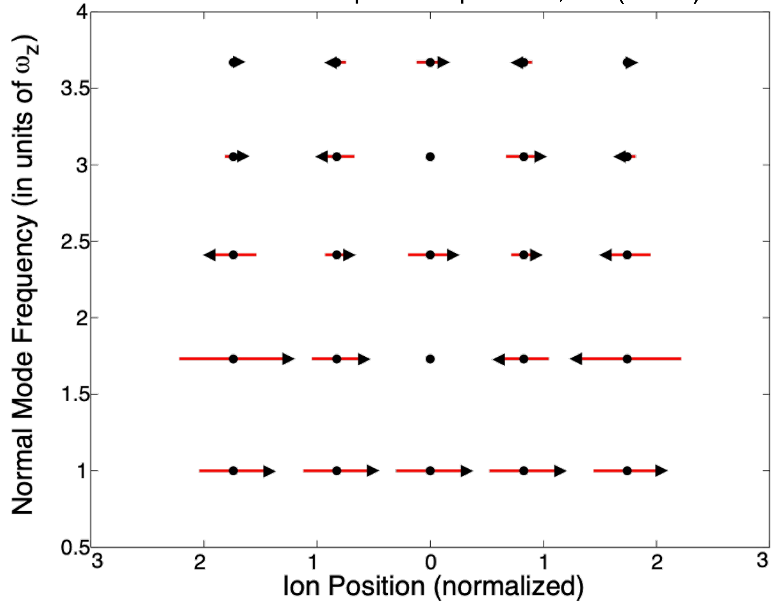
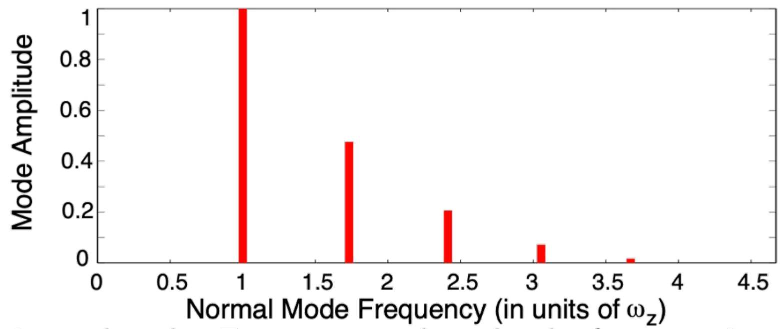
Ions piégés : contrôle du movement





Optics Express 3, 89 (1998)





Courtoisie de Tracy Northrup - Innsbruck

Choix des transitions et contrôle

- Un système physique évolutif avec des qubits bien caractérisés
- Une capacité de mesure spécifique aux qubits
- La capacité d'initialiser l'état des qubits

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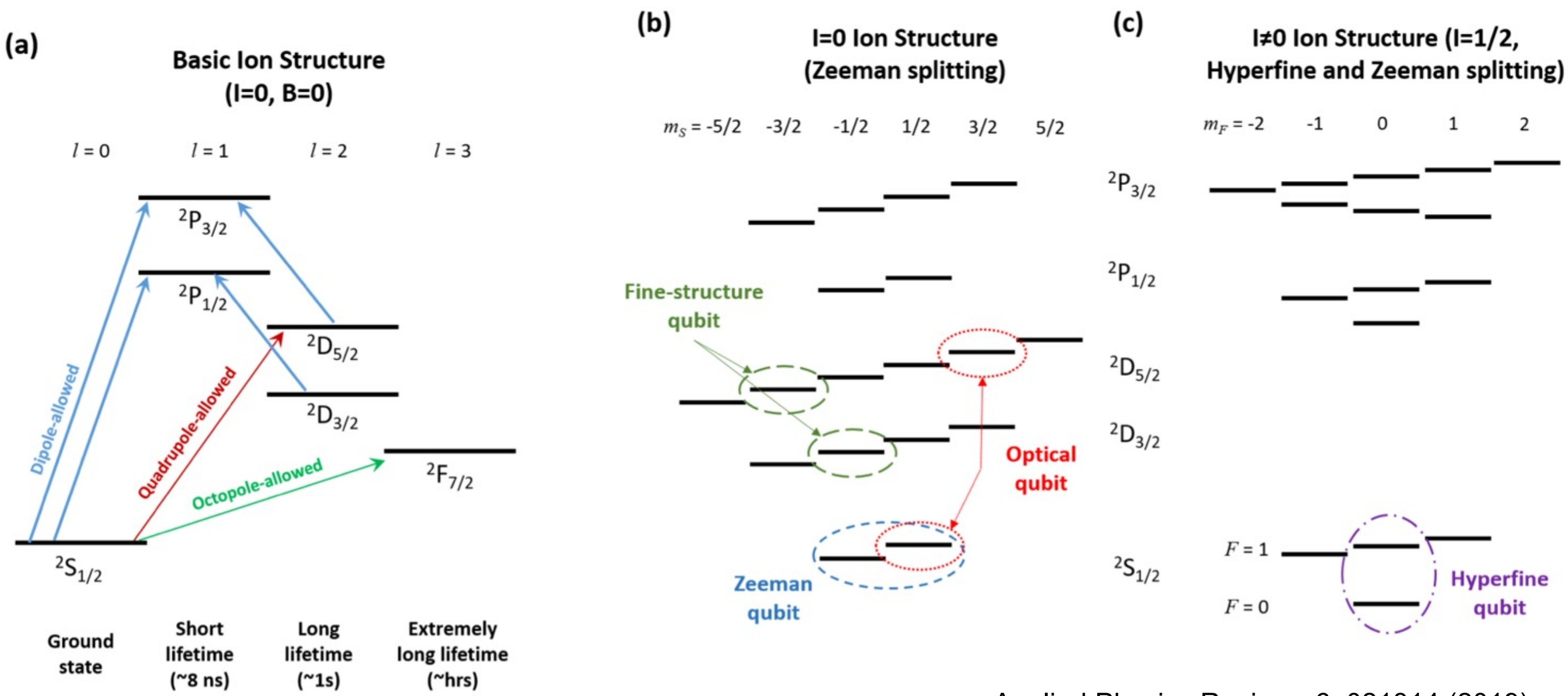
Ions piégés : deux principaux types de qubits:

Qubits optiques

Basés sur transitions optiques interdites
Ca+, Sr+, Ba+, Ra+, (Yb+, Hg+) etc.

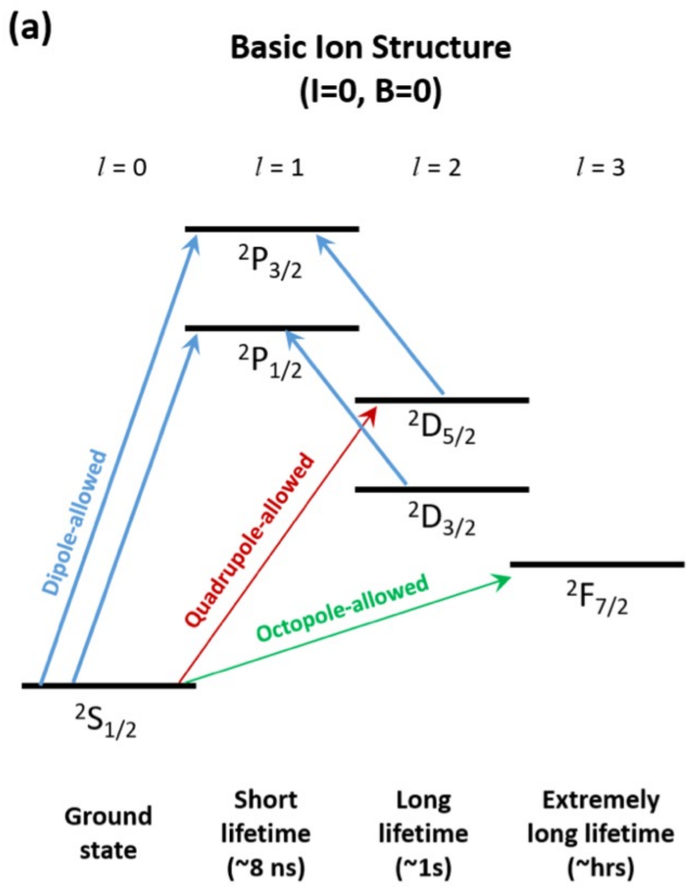
Qubits micro-ondes

Basés sur des états zeeman ou hyperfins
Ca+, Sr+, Ba+, Ra+, (Yb+, Hg+) etc.



Applied Physics Reviews 6, 021314 (2019)

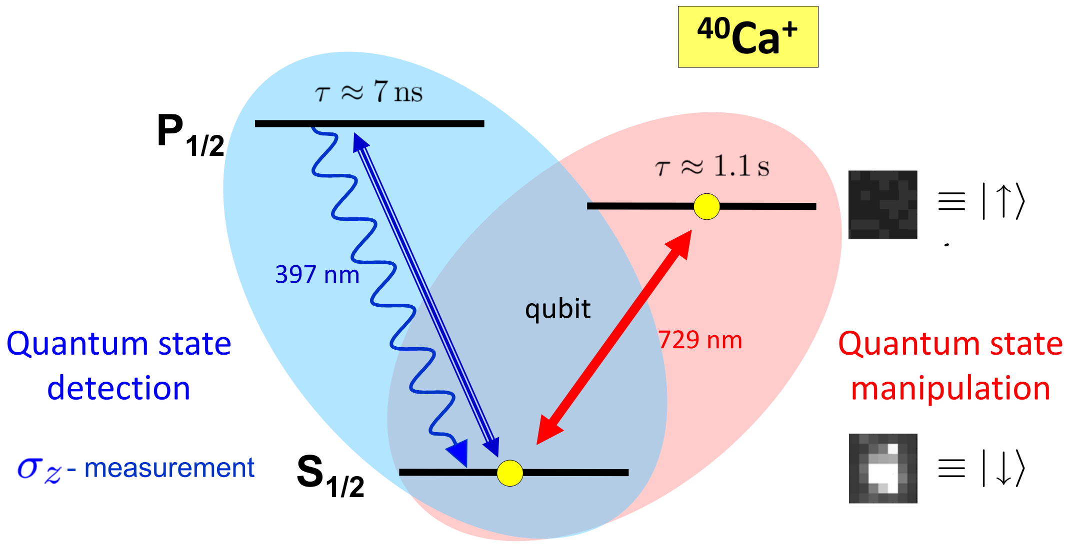
Encodage de l'information : Qubit « optiques »



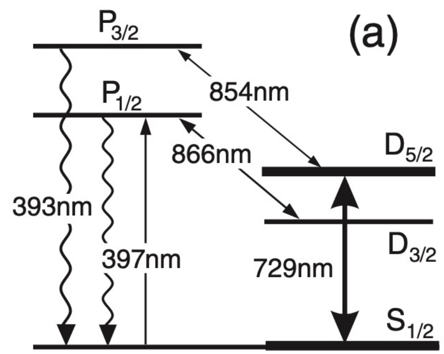
- Pas de champ magnétique appliqué
- Noyau de spin nul
- Transition optiques aux échelles de temps très différentes

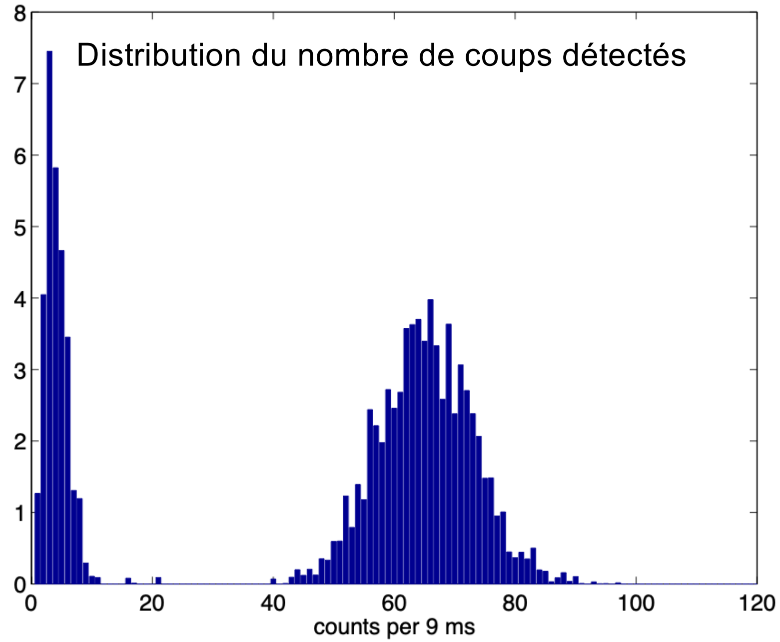
Applied Physics Reviews 6, 021314 (2019)

Qubit optiques : mesure de l'état



Pr. Blatt – Séminaire au Collège de France - 2015

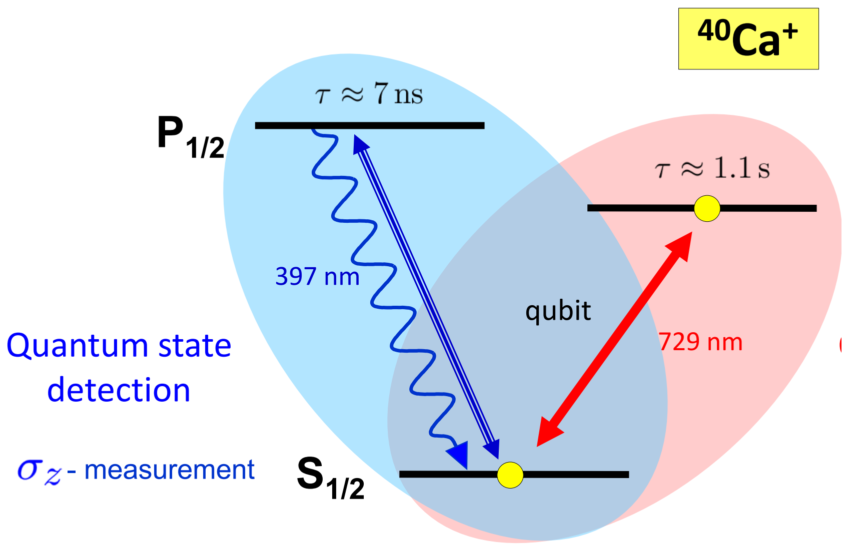




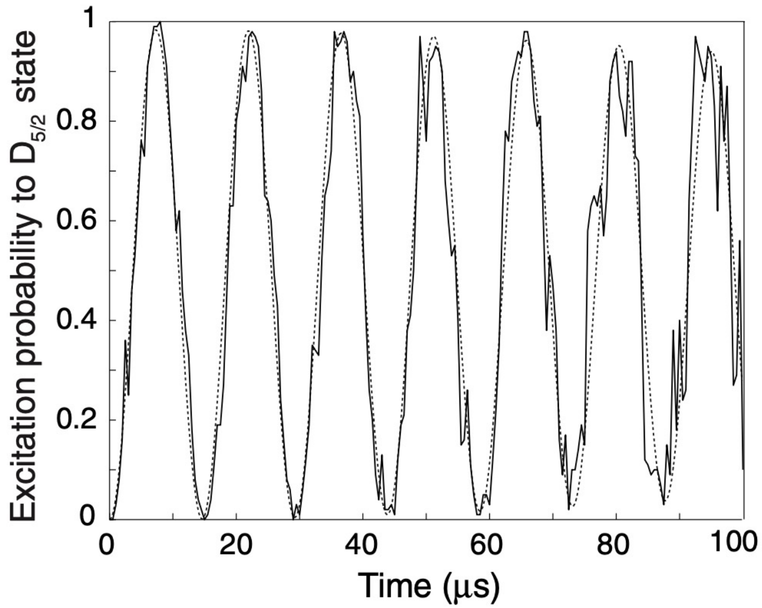
C.F. Roos dissertation, Groupe Pr. Blatt, 2000

COLLÈGE DE FRANCE 1530

Qubit optiques : porte à 1 qubit

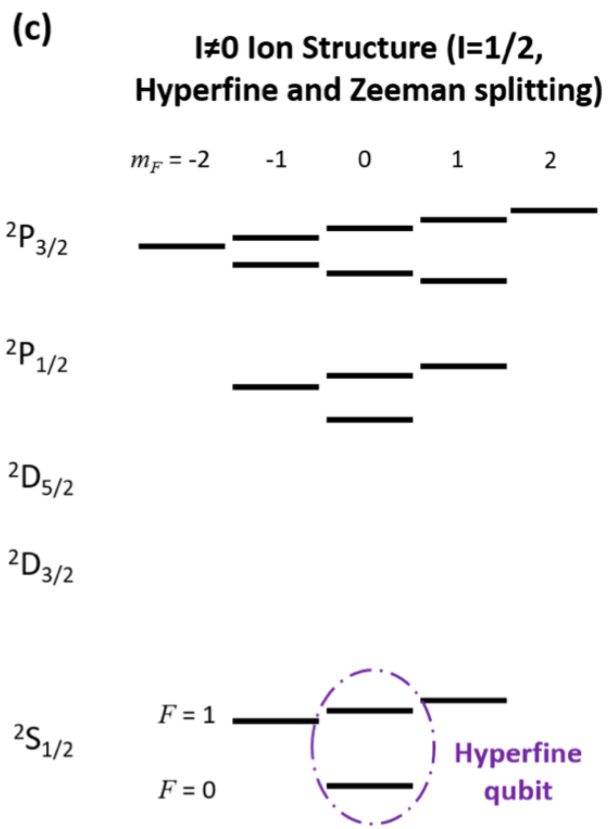


Pr. Blatt – Séminaire au Collège de France - 2015



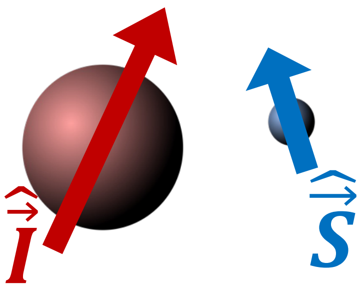
J. Phys. B: At. Mol. Opt. Phys. 36 623

Qubit micro-onde : transition horloge



Applied Physics Reviews 6, 021314 (2019)

- Champ magnétique appliqué
- Noyau de spin non-nul
- Qbits défini par les états de couplage hyperfin



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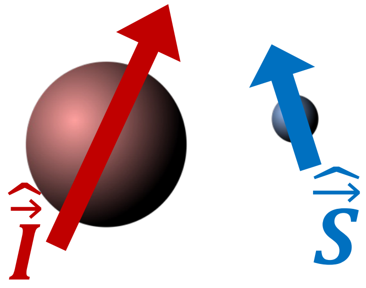
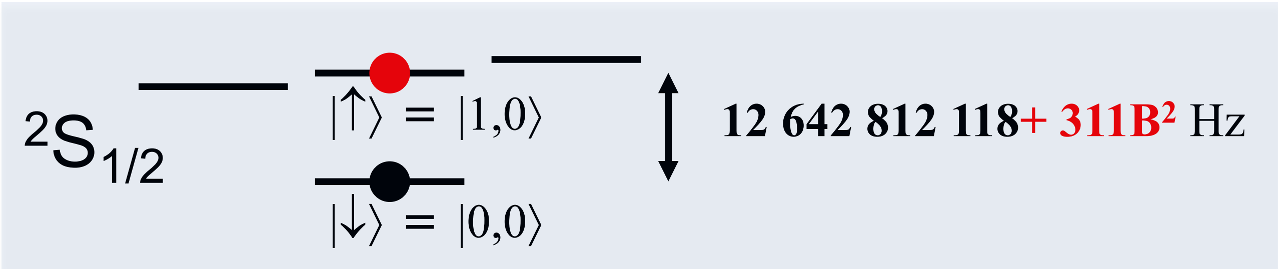
Transitions « horloges » : couplage spins electron-noyau



$$\hat{H} \propto \hat{\vec{S}} \cdot \hat{\vec{I}}$$

Ytterbium $^{171}Yb^{+}$



Spin total : $\hat{\vec{J}} = \hat{\vec{S}} + \hat{\vec{I}}$

$$\left|\hat{\vec{J}}\right|^2 = \left|\hat{\vec{S}} + \hat{\vec{I}}\right|^2 = \left|\hat{\vec{S}}\right|^2 + \left|\hat{\vec{I}}\right|^2 + 2\,\hat{\vec{S}}\,.\,\hat{\vec{I}}$$

Parenthèse : addition de spins

On peut diagonaliser simultanément $\hat{I}^2$, $\hat{S}^2$, $\hat{J}^2$ et $\hat{J}_z$:

$$\hat{I}^2 \,|i,s,j,m\rangle = \hbar^2 i(i+1)\,|i,s,j,m\rangle$$

$$\hat{S}^2 \,|i,s,j,m\rangle = \hbar^2 s(s+1)\,|i,s,j,m\rangle = 3/4\hbar^2\,|i,s,j,m\rangle$$

$$\hat{J}^2 \,|i,s,j,m\rangle = \hbar^2 j(j+1)\,|i,s,j,m\rangle$$

$$\hat{J}_z \,|i,s,j,m\rangle = \hbar m\,|i,s,j,m\rangle\,.$$

$$j \in \{|j-1/2|,\ldots,|j+1/2|\}.$$

$$\hat{H}_{\text{hyperfin}} = A\,\hat{\vec{S}}\cdot\hat{\vec{I}} = \frac{A}{2}\left(\hat{\vec{J}}^2 - \hat{\vec{S}}^2 - \hat{\vec{I}}^2\right)$$

$$\hat{H}_{\text{hyperfin}}\,|i,s,j,m\rangle = \frac{A}{2}\Big[j(j+1) - s(s+1) - i(i+1)\Big]\hbar^2\,|i,s,j,m\rangle$$

$$s = \frac{1}{2} \quad\Rightarrow\quad s(s+1) = \frac{3}{4} \qquad j \in \left\{i-\frac{1}{2},\ i+\frac{1}{2}\right\}.$$

$$E_{i,j} = \frac{A\hbar^2}{2}\left[j(j+1) - i(i+1) - \frac{3}{4}\right]$$

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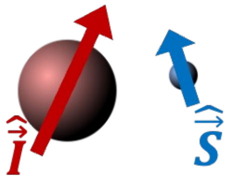
Transitions « horloges » : couplage spins electron-noyau



$$E_{i,j} = \frac{A\hbar^2}{2}\left[j(j+1) - i(i+1) - \frac{3}{4}\right]$$

Cas $I = \frac{1}{2}$

Singulet ($j = 0$) :

$$|0,0\rangle = \frac{|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle}{\sqrt{2}}.$$

Triplet ($j = 1$) :

$$|1,1\rangle = |\uparrow\uparrow\rangle\,, \qquad |1,0\rangle = \frac{|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle}{\sqrt{2}}, \qquad |1,-1\rangle = |\downarrow\downarrow\rangle$$

$^2S_{1/2}$

$$E_{j=1} = \frac{A}{4}$$

$$E_{j=0} = -\frac{3A}{4}$$

couplage spins electron-noyau

$$\hat{W} = -\hat{\boldsymbol{\mu}} \cdot \boldsymbol{B}.$$

$$\hat{W} = -\gamma_e\,\hat{S}_z\,B - \cancel{\gamma_n\,\hat{I}_z}\,B,$$

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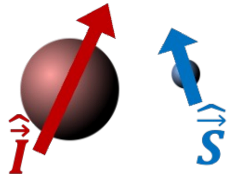


Transitions « horloges » : Sensibilité au champ magnétique

$$\hat{H} = \hat{H}_{\mathrm{HF}} + \hat{W}$$

$$\hat{H}_{\mathrm{HF}} = A\,\hat{\vec{S}}\cdot\hat{\vec{I}}, \qquad \hat{W} = -\gamma_e\,\hat{S}_z\,B$$

- ω_{HF} : fréquence hyperfine,
- $\omega_B \propto B$: couplage Zeeman

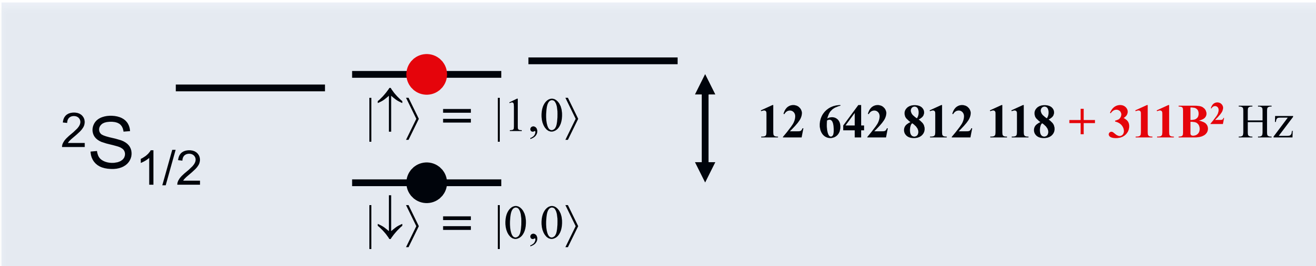
Dans la base $|1,1\rangle\,,\ |1,-1\rangle\,,\ |1,0\rangle\,,\ |0,0\rangle$

$$\hat{H} = \hbar\begin{pmatrix} \omega_{\mathrm{HF}}+\omega_B/2 & 0 & 0 & 0 \\ 0 & \omega_{\mathrm{HF}}-\omega_B/2 & 0 & 0 \\ 0 & 0 & \omega_{\mathrm{HF}} & \omega_B/2 \\ 0 & 0 & \omega_B/2 & 0 \end{pmatrix}$$

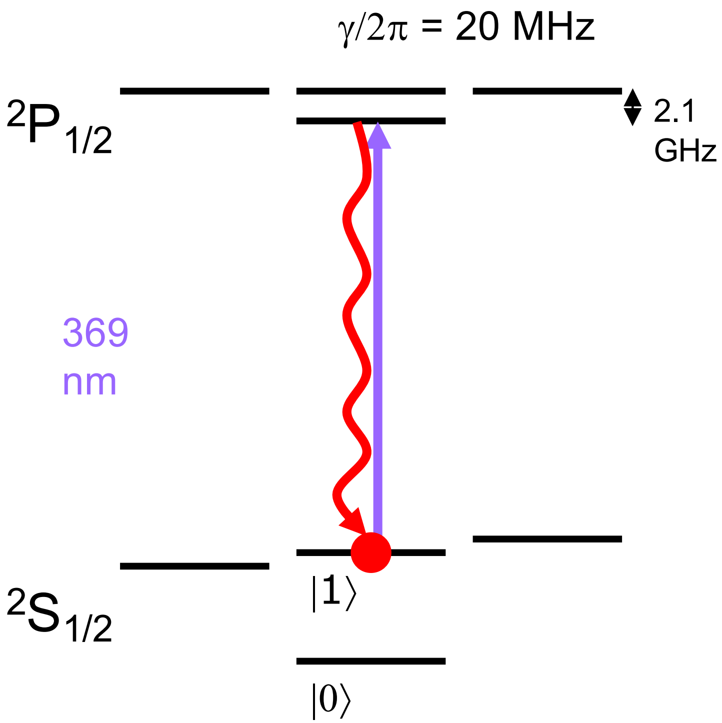
Limite champ faible $(\omega_B \ll \omega_{\mathrm{HF}})$:

$$E_\pm = \frac{\hbar}{2}\left(\omega_{\mathrm{HF}} \pm \sqrt{\omega_{\mathrm{HF}}^2+\omega_B^2}\right)$$

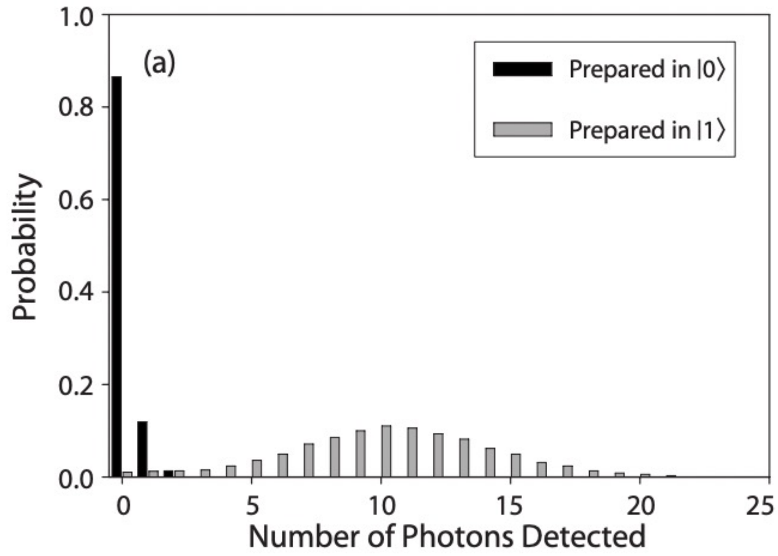
$$E_+ \simeq \hbar\left(\omega_{\mathrm{HF}} + \frac{\omega_B^2}{2\omega_{\mathrm{HF}}}\right), \qquad E_- \simeq -\hbar\frac{\omega_B^2}{2\omega_{\mathrm{HF}}}$$



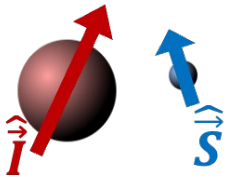
Transitions « horloges » : lecture du qubit

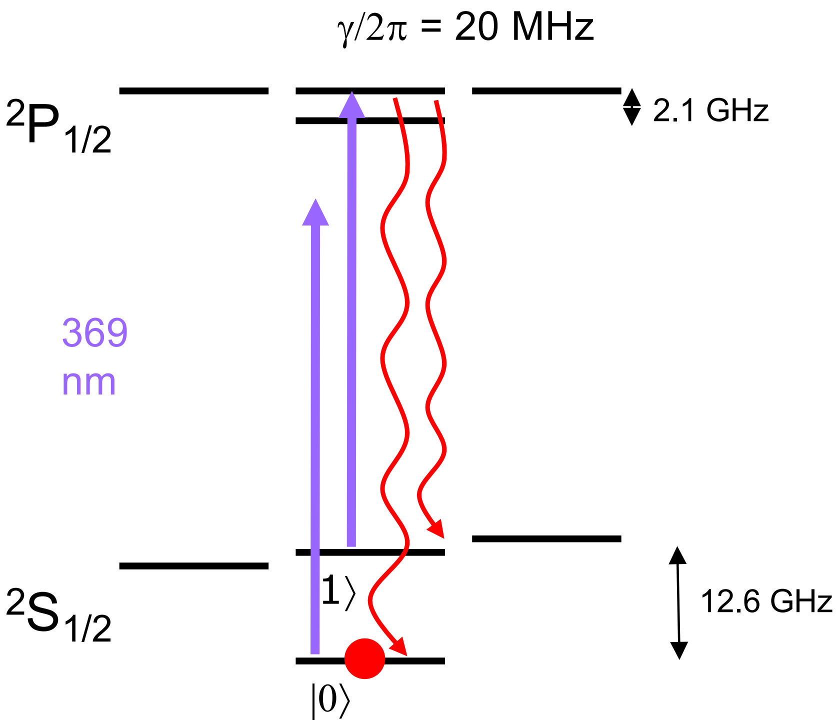


Phys. Rev. A 76, 052314 2007

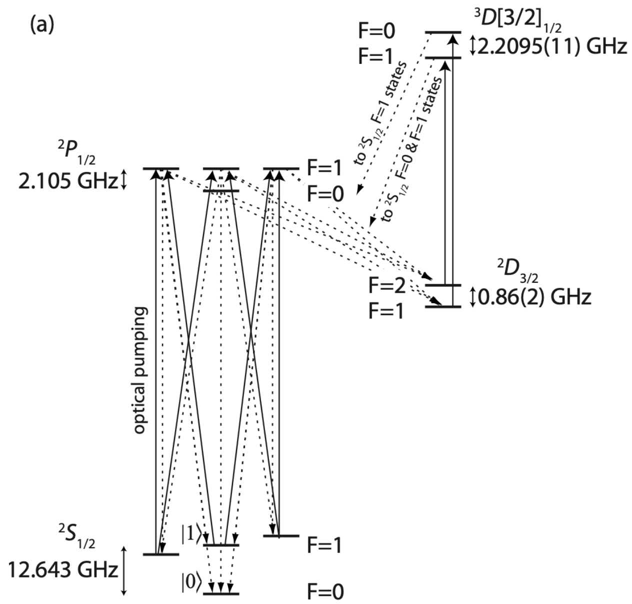


Transitions « horloges » : initialisation du qubit



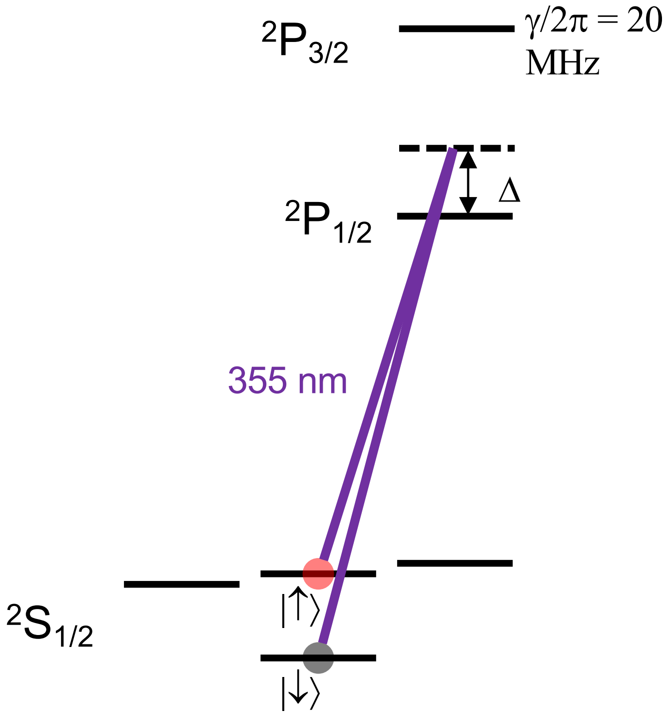


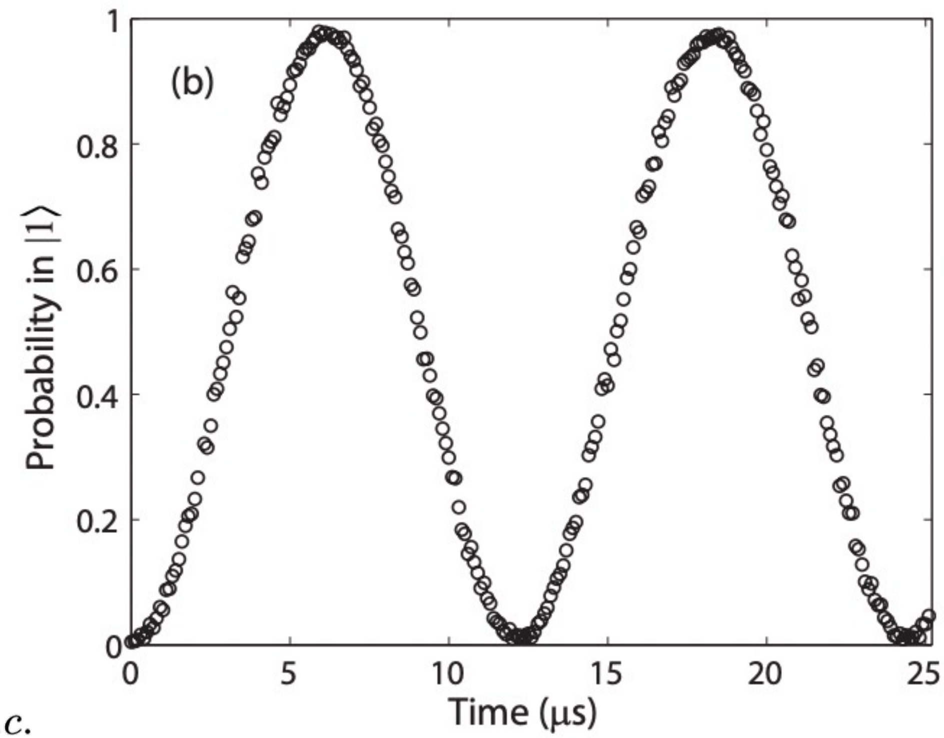
Phys. Rev. A 76, 052314 2007



Transitions « horloges » : manipulation du qubit

Phys. Rev. A 76, 052314 2007





$$\hat{H}_{\text{int}} = -\hat{\vec{d}} \cdot \vec{E}(t) \qquad \vec{E}(t) = \vec{E}_1 e^{-i\omega_1 t} + \vec{E}_2 e^{-i\omega_2 t} + c.c.$$

$$\hat{H}_{\text{eff}} = \hbar\Omega_{\text{Raman}} e^{i(\omega_2-\omega_1)t+i\varphi} |\uparrow\rangle\langle\downarrow| + h.c.$$

$$\Omega_{\text{Raman}} \sim \frac{\Omega_1\Omega_2}{2\Delta}$$

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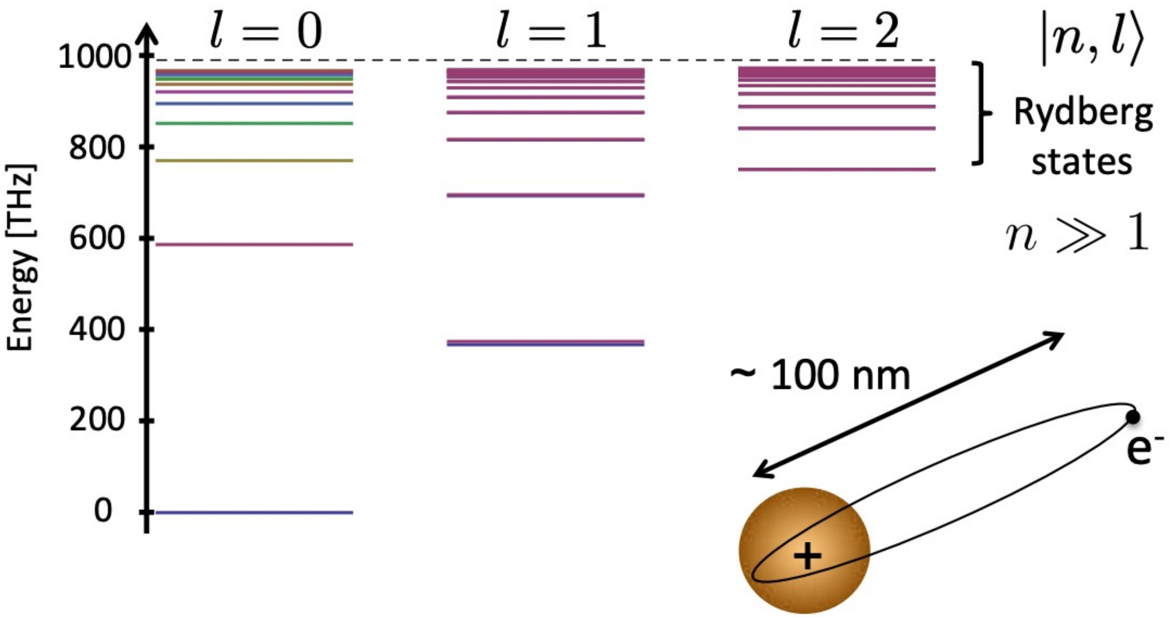
Qubit à base d'ions : zoologie

Applied Physics Reviews 6, 021314 (2019)

Ion	m (amu)	I	$\lambda_{1/2}$,$\lambda_{3/2}$,λ_D (nm)	γ_D (s^{-1})	$\omega_F/2\pi$ (THz)	Qubits	FOFI, B_0 (mT)	Gates
Be^+	9	3/2	313, 313, N.A.	N.A.	0.198	H	11.94	R, M
Mg^+	25	5/2	280, 280, N.A.	N.A.	2.75	H	10.9	R, M
	24	0	"	"	"	*		R
Ca^+	40	0	397, 393, 729	0.855	6.68	Z, F, O		R, O
	43	7/2	"	"	"	H, O	14.61	R, M
Sr^+	87	9/2	422, 408, 674	2.90	24.0			
	88	0	"	"	"	O		O, R
Cd^+	111	1/2	226, 214, N.A.	N.A.	74.4	H	(Clock)	R
	112,114	0	"	"	"	*		R
Ba^+	133†	1/2	493‡, 455, 1762	0.0286	50.7	H, O	(Clock)	
	137	3/2	"	"	"	H, O	(Clock)	
	138	0	"	"	"	O		R
Yb^+	171	1/2	369‡, 329, 411	139	99.8	H	(Clock)	R, M
	172, 174	0	"	"	"	O		

Atomes neutres : niveaux d'énergie pertinents

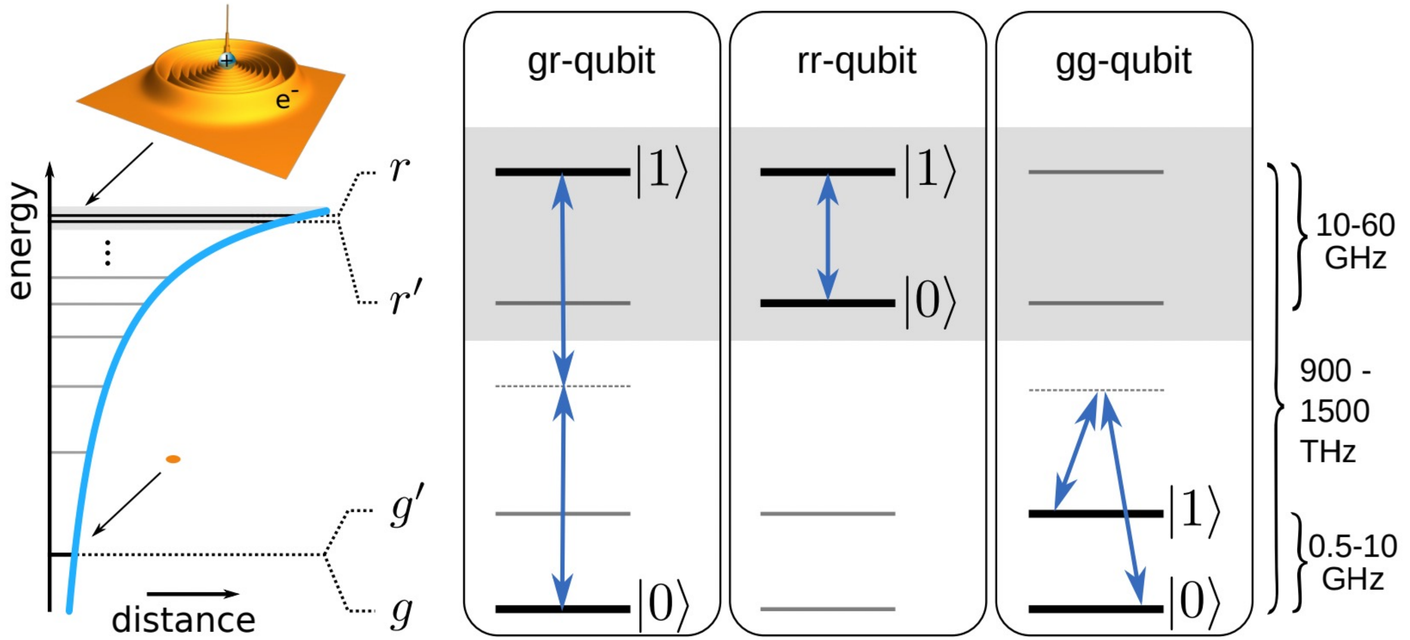
A. Browaeys – Séminaire au Collège de France - 2015



Etats de Rydberg :
Temps de vie long : n> 60 , $\tau > 100\ \mu s$
Grande sensibilité au champ électrique $\alpha \propto n^7$

Atomes neutres : encodage qubit

AVS Quantum Sci. 3, 023501 (2021)

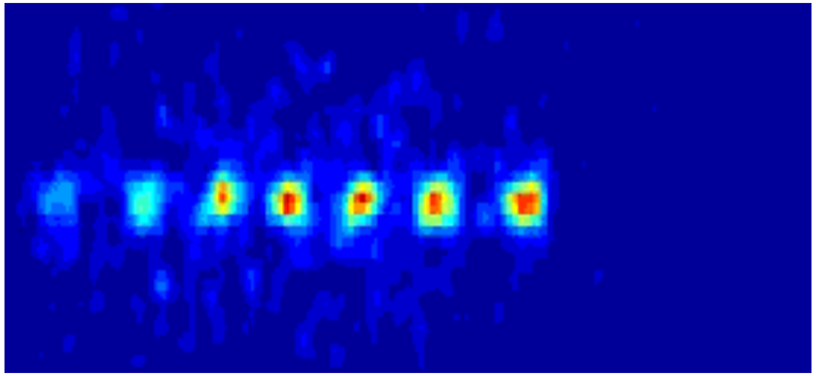


Portes logiques à deux qubits

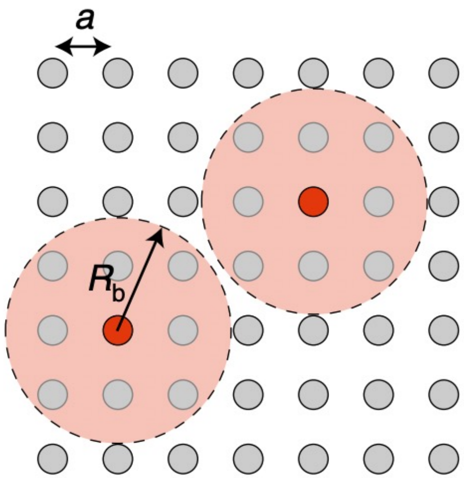
- Un ensemble « universel » de portes quantiques

Ions et atomes : portes à deux qubits

Courtoisie de Tracy Northrup - Innsbruck



Intrication médiée par le mouvement



Nature Physics 16, 132 (2020)

Intrication par les états de Rydberg

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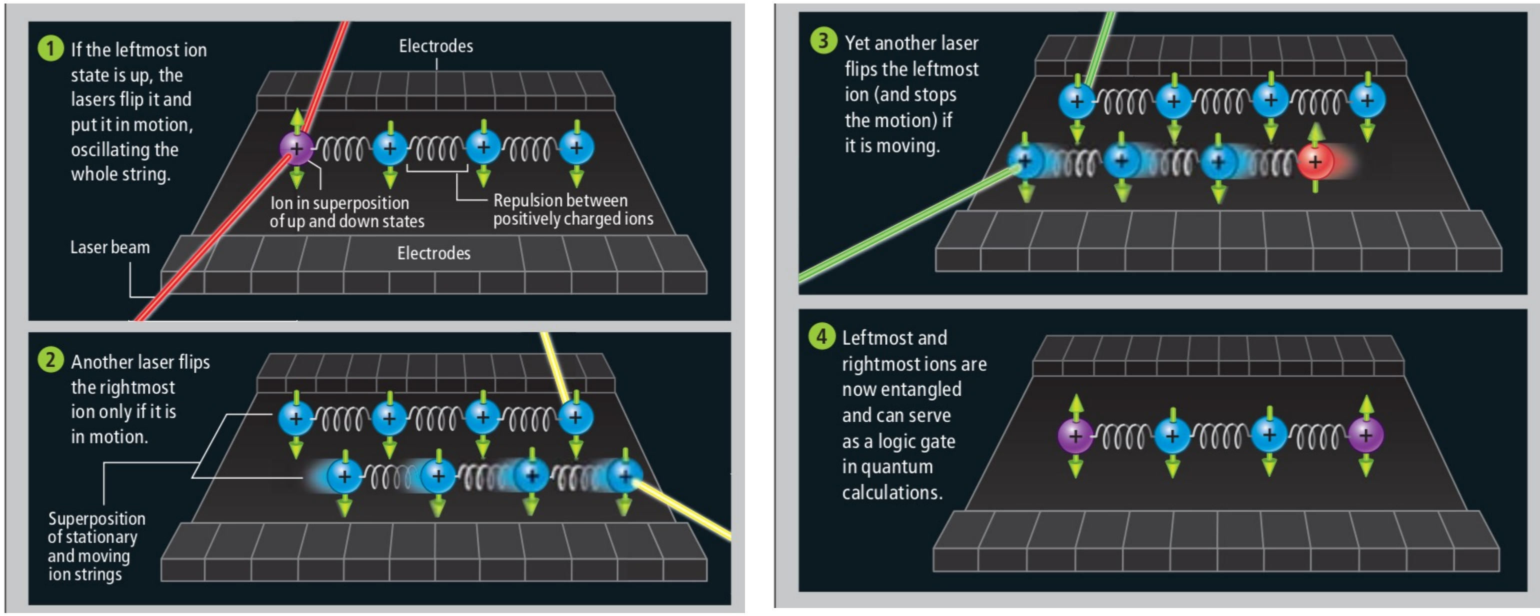
Intriquer deux ions : porte Cirac-Zoller

VOLUME 74, NUMBER 20 PHYSICAL REVIEW LETTERS 15 MAY 1995

Quantum Computations with Cold Trapped Ions

J. I. Cirac and P. Zoller*
Institut für Theoretische Physik, Universiät Innsbruck, Technikerstrasse 25, A-6020 Innsbruck, Austria
(Received 30 November 1994)

A quantum computer can be implemented with cold ions confined in a linear trap and interacting with laser beams. Quantum gates involving any pair, triplet, or subset of ions can be realized by coupling the ions through the collective quantized motion. In this system decoherence is negligible, and the measurement (readout of the quantum register) can be carried out with a high efficiency.



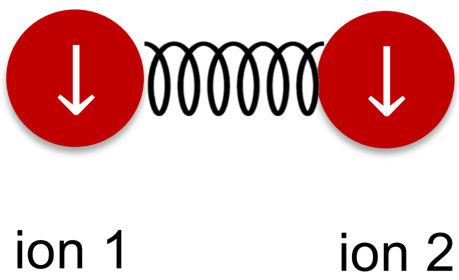
Intriquer deux ions : porte Cirac-Zoller

Etats utiles

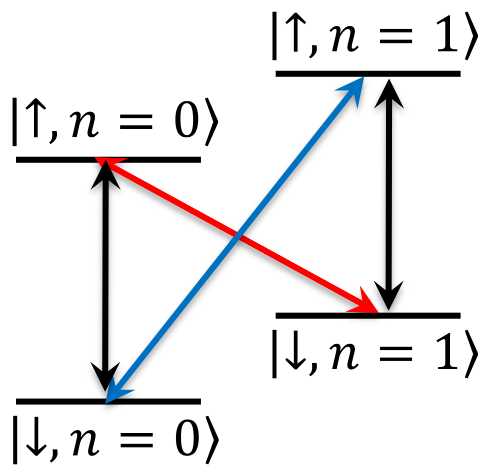
- Ion 1 : qubit interne $|\downarrow\rangle_1\, , |\uparrow\rangle_1$
- Ion 2 : qubit interne $|\downarrow\rangle_2\, , |\uparrow\rangle_2$
- Mouvement (mode commun) : $|0\rangle\, , |1\rangle$

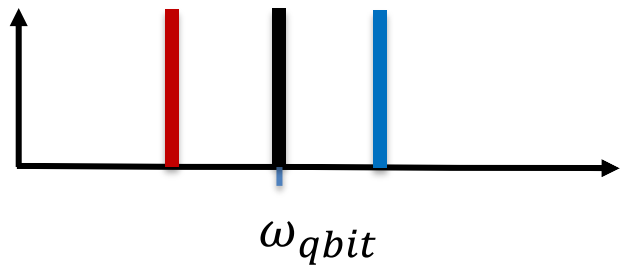
Etat de départ

$$|\downarrow\rangle_1\, |\downarrow\rangle_2\, |0\rangle \equiv |\downarrow\downarrow\rangle\, |0\rangle\, .$$



Lasers de contrôle

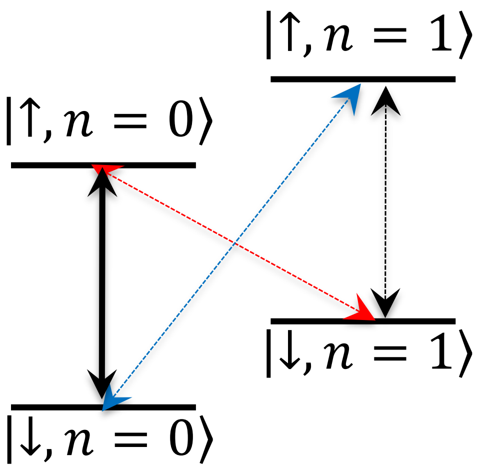


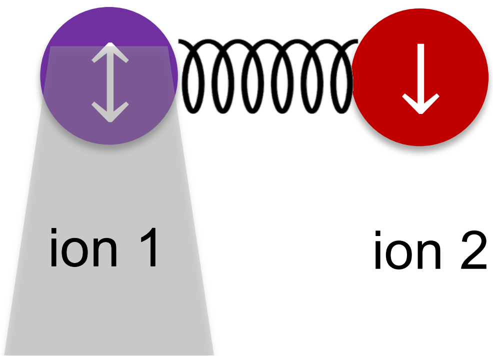


Intriquer deux ions : porte Cirac-Zoller

Etape 1 : on met l'ion 1 dans une superposition

$$|\downarrow\rangle_1 \xrightarrow{\pi/2} \frac{|\downarrow\rangle_1 + |\uparrow\rangle_1}{\sqrt{2}}.$$





Etat final

$$|\psi_0\rangle = \frac{|\downarrow\downarrow\rangle\,|0\rangle + |\uparrow\downarrow\rangle\,|0\rangle}{\sqrt{2}}$$

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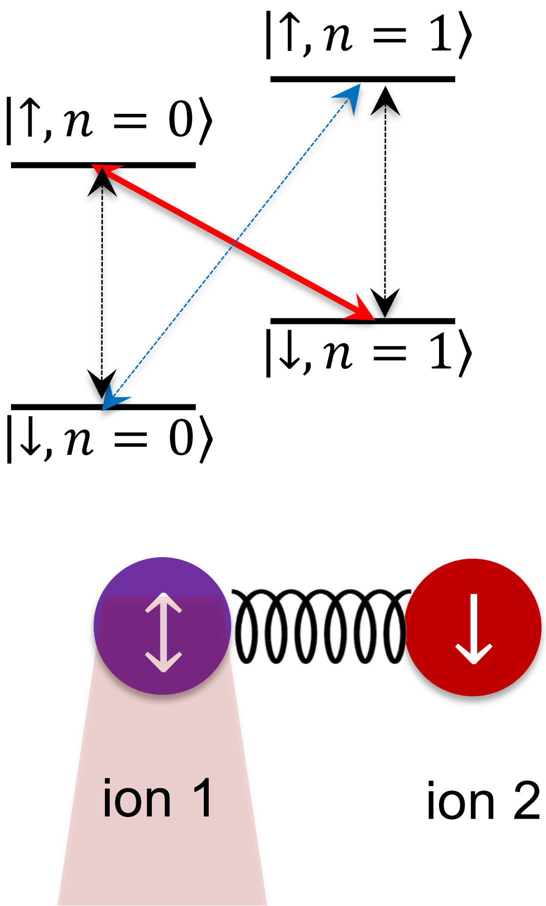
Intriquer deux ions : porte Cirac-Zoller

$$|\psi_0\rangle = \frac{|\downarrow\downarrow\rangle\,|0\rangle + |\uparrow\downarrow\rangle\,|0\rangle}{\sqrt{2}}$$

Etape 2 : si ion 1 est ↑ on le met en mouvement

$$|\uparrow\rangle_1\,|0\rangle \longrightarrow |\downarrow\rangle_1\,|1\rangle$$



Etat final

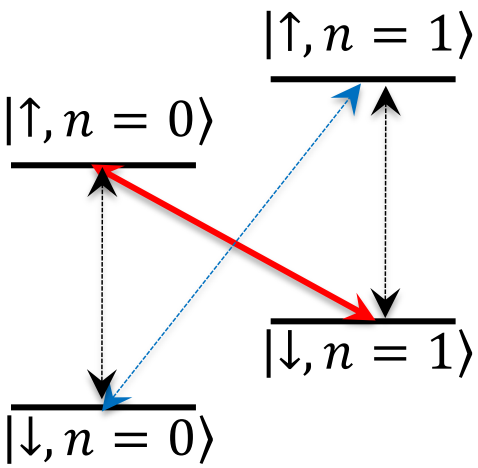
$$|\psi_1\rangle = |\downarrow\downarrow\rangle\,\frac{|0\rangle + |1\rangle}{\sqrt{2}}$$

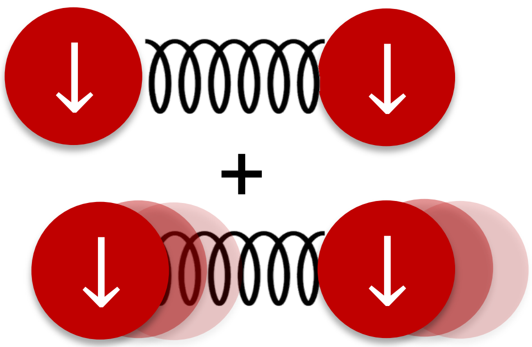
Intriquer deux ions : porte Cirac-Zoller

$$|\psi_0\rangle = \frac{|\downarrow\downarrow\rangle\,|0\rangle + |\uparrow\downarrow\rangle\,|0\rangle}{\sqrt{2}}$$

Etape 2 : si ion 1 est ↑ on le met en mouvement

$$|\uparrow\rangle_1\,|0\rangle \longrightarrow |\downarrow\rangle_1\,|1\rangle$$





Etat final

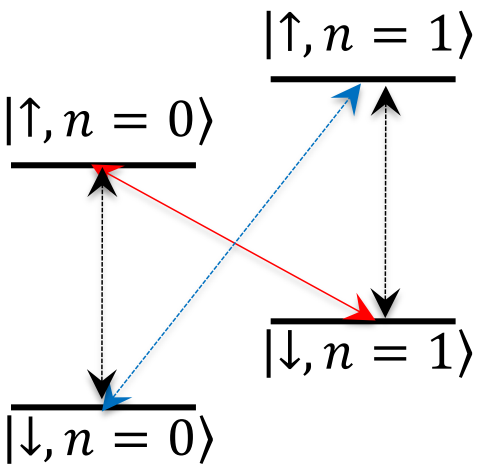
$$|\psi_1\rangle = |\downarrow\downarrow\rangle\,\frac{|0\rangle + |1\rangle}{\sqrt{2}}$$

Intriquer deux ions : porte Cirac-Zoller

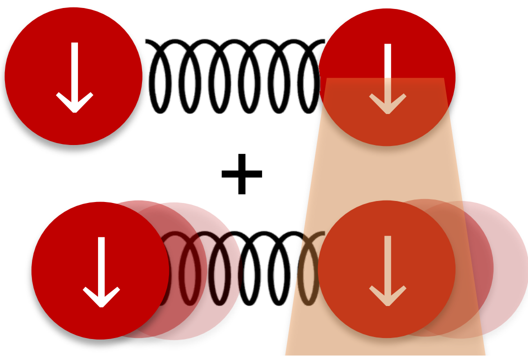
$$|\psi_1\rangle = |\downarrow\downarrow\rangle \frac{|0\rangle + |1\rangle}{\sqrt{2}}$$

Etape 3 : si ion 2 est ↑ et en mouvement, on le retourne

$$|\downarrow\rangle_2 |1\rangle \longrightarrow |\uparrow\rangle_2 |1\rangle$$



En pratique : 3 impulsions et un état auxiliaire

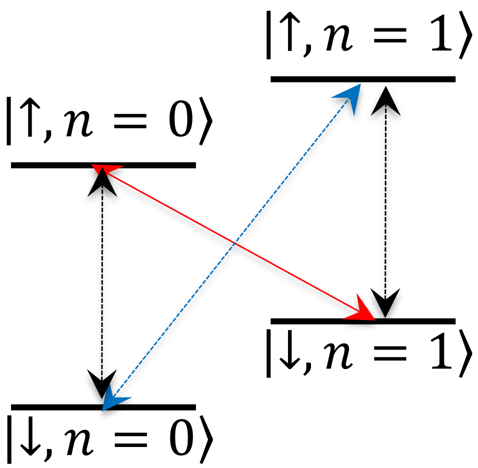


Intriquer deux ions : porte Cirac-Zoller

$$|\psi_1\rangle = |\downarrow\downarrow\rangle \, \frac{|0\rangle + |1\rangle}{\sqrt{2}}$$

Etape 3 : si ion 2 est ↓ et en mouvement, on le retourne

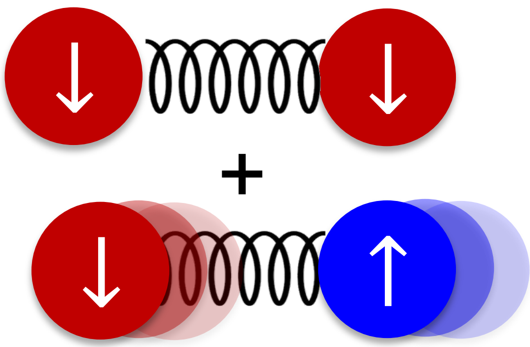
$$|\downarrow\rangle_2 \, |1\rangle \longrightarrow |\uparrow\rangle_2 \, |1\rangle$$



En pratique : 3 impulsions et un état auxiliaire

Etat final

$$|\psi_2\rangle = \frac{|\downarrow\downarrow\rangle \, |0\rangle + |\downarrow\uparrow\rangle \, |1\rangle}{\sqrt{2}}$$

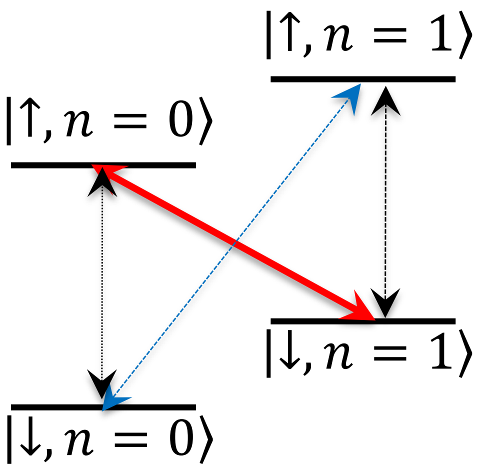


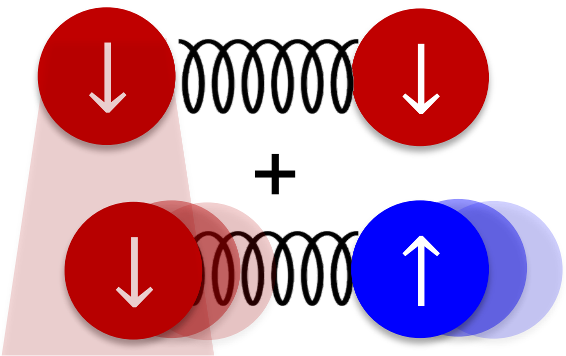
Intriquer deux ions : porte Cirac-Zoller

$$|\psi_2\rangle = \frac{|\downarrow\downarrow\rangle\,|0\rangle + |\downarrow\uparrow\rangle\,|1\rangle}{\sqrt{2}}$$

Etape 4 : si ion 2 est ↑ et en movement, on le retourne

$$|\downarrow\rangle_1\,|1\rangle \longrightarrow |\uparrow\rangle_1\,|0\rangle$$





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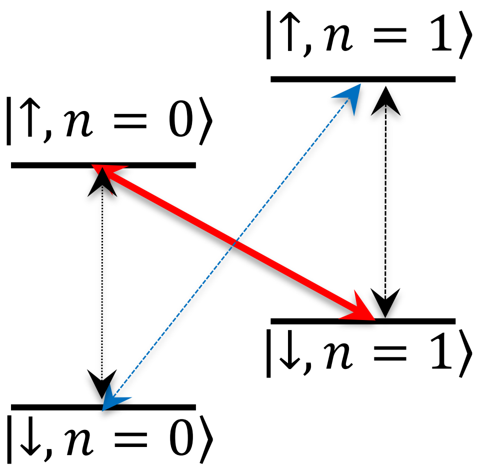
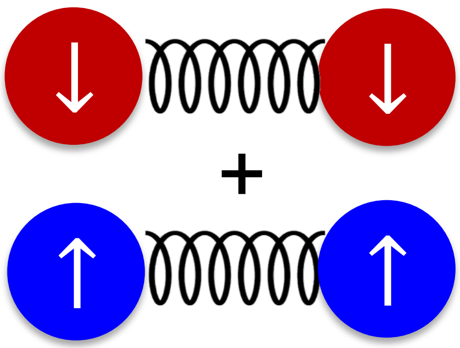
Intriquer deux ions : porte Cirac-Zoller

$$|\psi_2\rangle = \frac{|\downarrow\downarrow\rangle\,|0\rangle + |\downarrow\uparrow\rangle\,|1\rangle}{\sqrt{2}}$$

Etape 4 : si ion 2 est ↑ et en movement, on le retourne

$$|\downarrow\rangle_1\,|1\rangle \longrightarrow |\uparrow\rangle_1\,|0\rangle$$

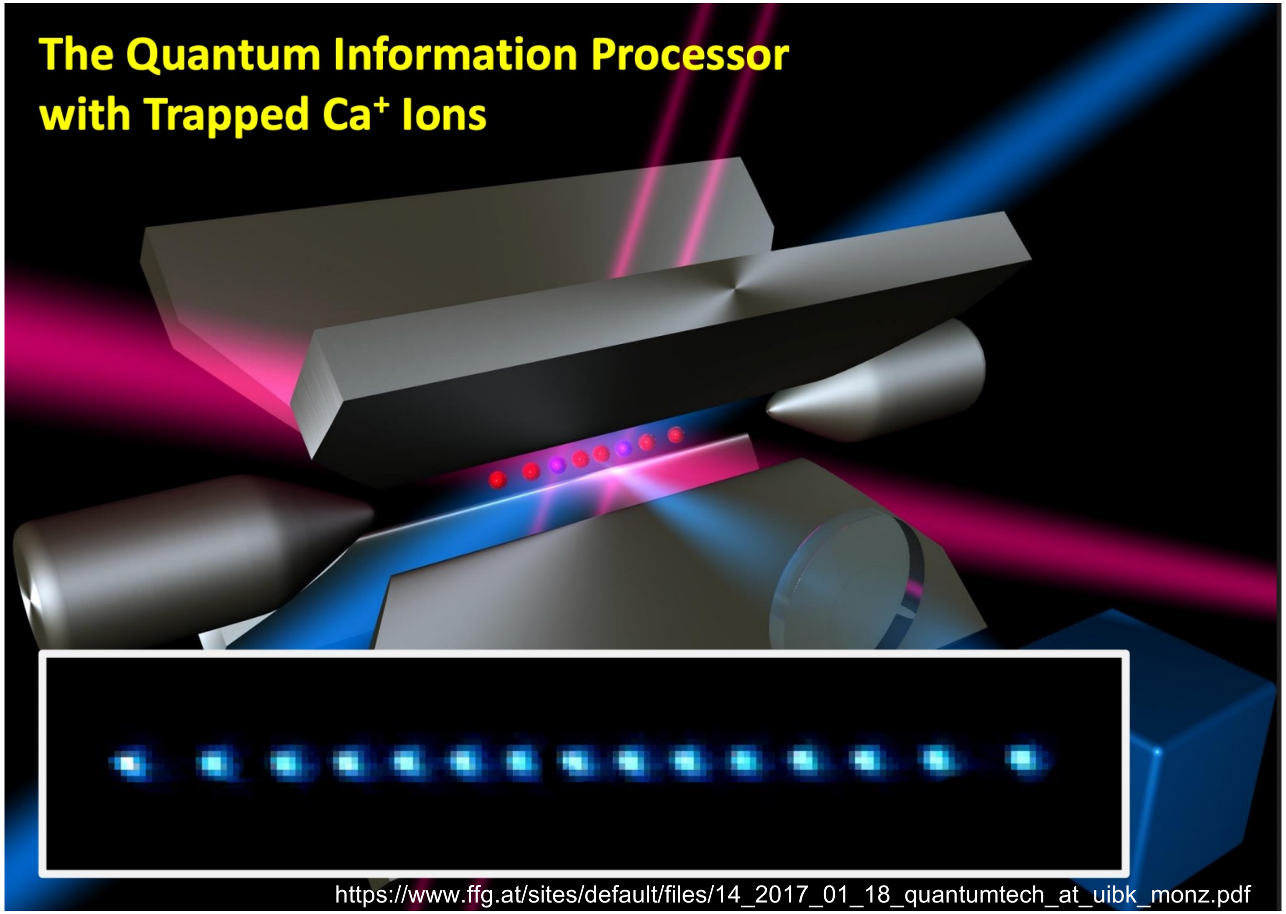




Etat final

$$|\psi_3\rangle = \frac{|\downarrow\downarrow\rangle + |\uparrow\uparrow\rangle}{\sqrt{2}} \otimes |0\rangle$$

Architecture processeur quantique : ions



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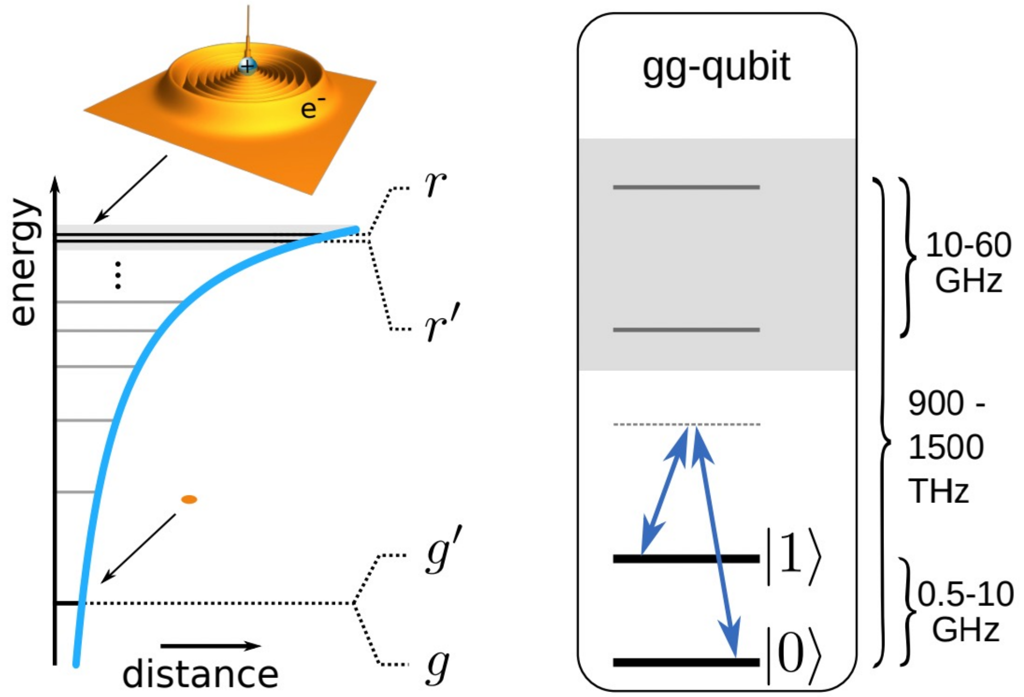
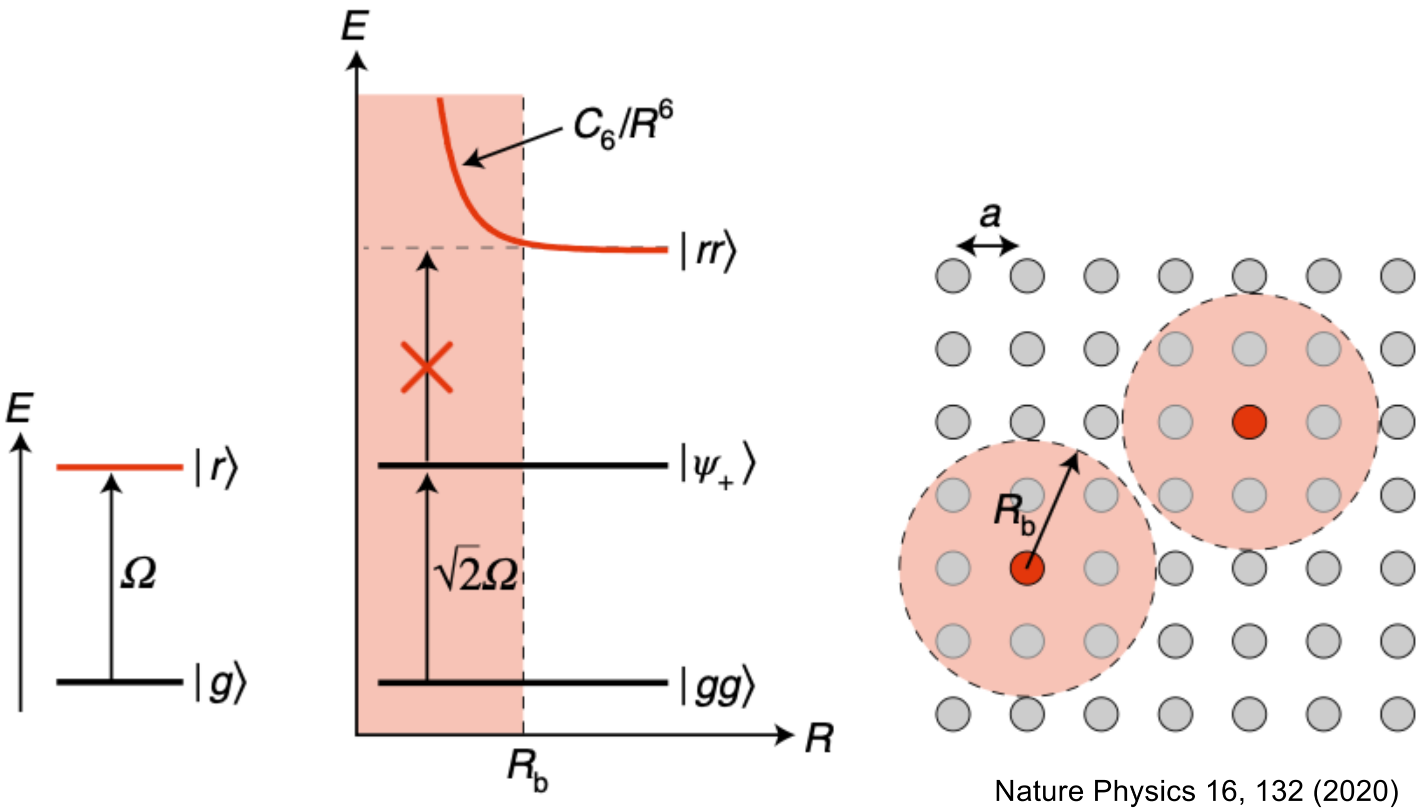
Intriquer 2 atomes : interaction dans les états de Rydberg



AVS Quantum Sci. 3, 023501 (2021)

Intriquer 2 atomes : interaction dans les états de Rydberg

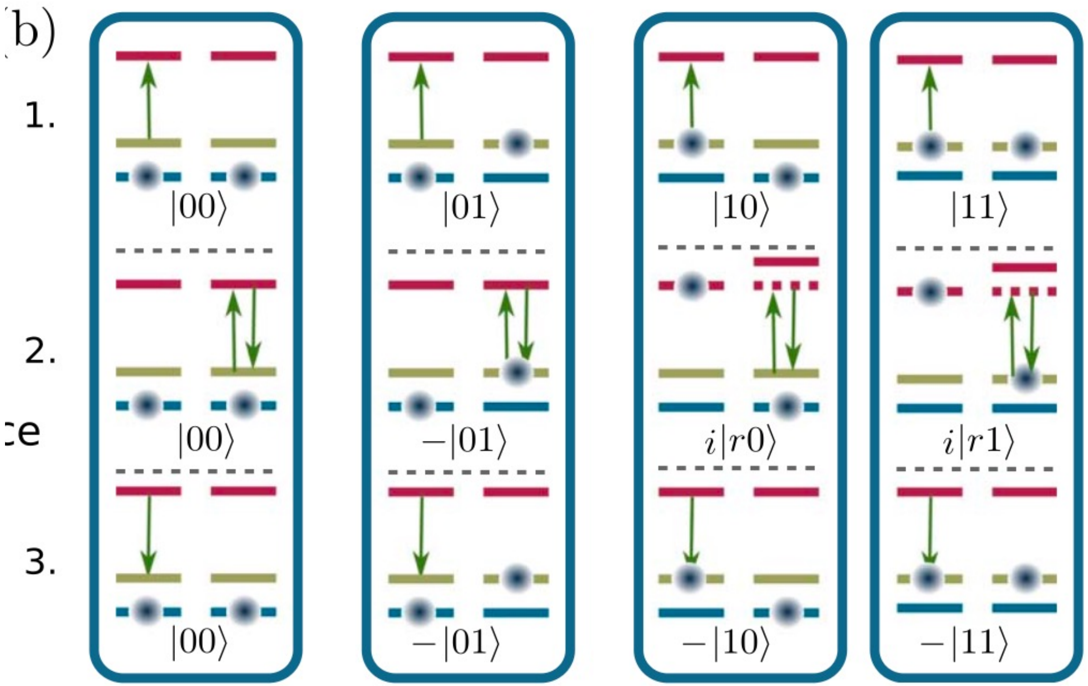


Nature Physics 16, 132 (2020)

Intriquer 2 atomes : interaction dans les états de Rydberg

Porte CZ

$$
\begin{array}{c|cccc}
 & |00\rangle & |01\rangle & |10\rangle & |11\rangle \\
\hline
|00\rangle & 1 & 0 & 0 & 0 \\
|01\rangle & 0 & 1 & 0 & 0 \\
|10\rangle & 0 & 0 & 1 & 0 \\
|11\rangle & 0 & 0 & 0 & -1
\end{array}
$$



J. Phys. B: At. Mol. Opt. Phys. 53 012002

COLLÈGE DE FRANCE 1530

Atomes et ions : d’où vient la décohérence ?

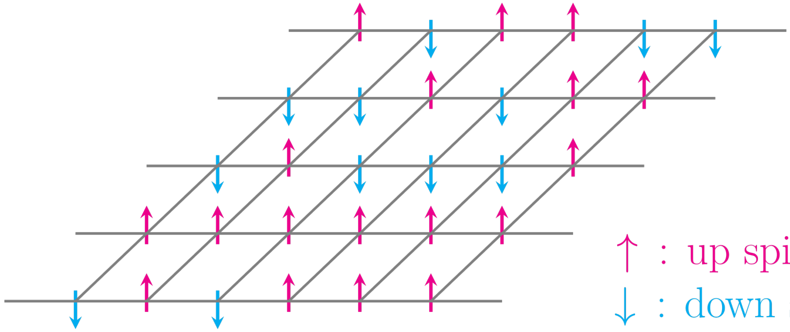
- Sensibilité au champ magnétique :
  - en B^2 : pour qubits hyperfins, atomes neutres et ions (dominant)
  - En $|B|$ pour qubits Zeeman et optiques
- Fluctuation dans le piège optique (effet Stark) pour les atomes neutres
- Temps de vie fini : encodage sur état de Ryberg
- Sensibilité au champ électrique : encodage sur état de Rydberg
- Bruit laser pour qubits optiques à base d’ions

COLLÈGE DE FRANCE
1530

Résultats récents, exemples d'applications

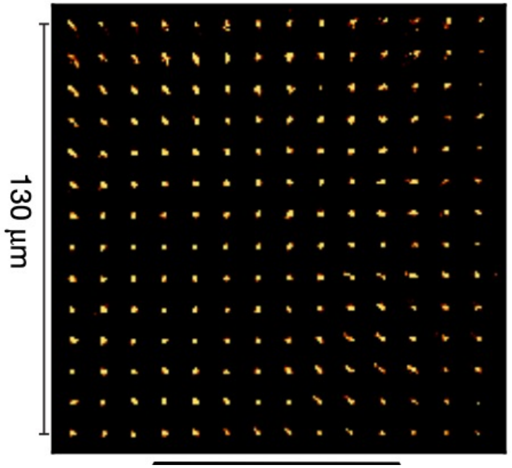
Simulation quantique : atomes de Rydberg

Classe de problèmes : Modèle de Ising

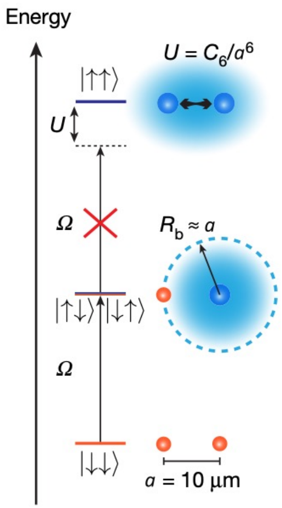


$$\hat{H} = \frac{\hbar\Omega}{2}\sum_i \hat{\sigma}_x^{(i)} - \hbar\delta\sum_i \hat{n}_i + \sum_{i<j} V_{ij}\,\hat{n}_i\hat{n}_j,$$

Nature 595, 233 (2021)



$$|\downarrow\rangle = |g\rangle$$
$$|\uparrow\rangle = |r\rangle$$



Rappel : équations de Bloch optiques (leçon 3)

$$\hat{H}(t) = \frac{\hbar\omega_0}{2}\,\hat{\sigma}^z + \hbar\Omega\cos(\omega_L t)\,\hat{\sigma}^x$$

$$\hat{H}_{\text{tournant}} = \frac{\hbar\Delta}{2}\,\hat{\sigma}^z + \frac{\hbar\Omega}{2}\,\hat{\sigma}^x$$

$$\hat{n} = |r\rangle\langle r| = \frac{1}{2}(\mathbb{I} + \hat{\sigma}^z)$$

Séminaire Pr. Antoine Browaeys

Modèles de Ising : applications en dehors de la physique

Modèle de Ising

$$\hat{H} = \frac{\hbar\Omega}{2}\sum_i \hat{\sigma}_x^{(i)} - \hbar\delta\sum_i \hat{n}_i + \sum_{i<j} V_{ij}\,\hat{n}_i\hat{n}_j,$$

$$x_i = (1 + s_i)/2.$$

(Connectivité arbitraire)

QUBO

(*Quadratic Unconstrained Binary Optimization*) :

$$\min_{\mathbf{x}\in\{01\}^N,} C(\mathbf{x}) = \sum_i Q_{ii}\, x_i + \sum_{i<j} Q_{ij}\, x_i x_j$$

•$x_i \in \{0, 1\}$: variables binaires

•Q: matrice réelle

• **quadratique** : pas de termes d'ordre > 2

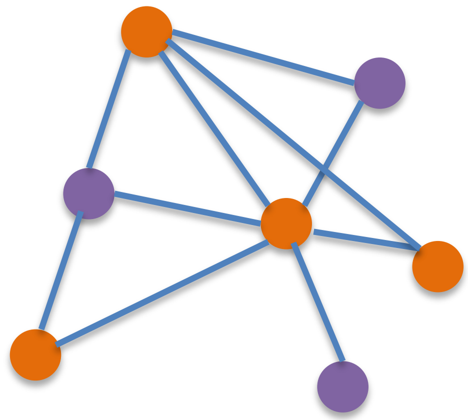
•**unconstrained** : pas de contraintes explicites (elles sont encodées via pénalités)

Exemple: colorier un graphe avec 2 couleurs:

$x_i = 0\ (1)$ orange (bleu)

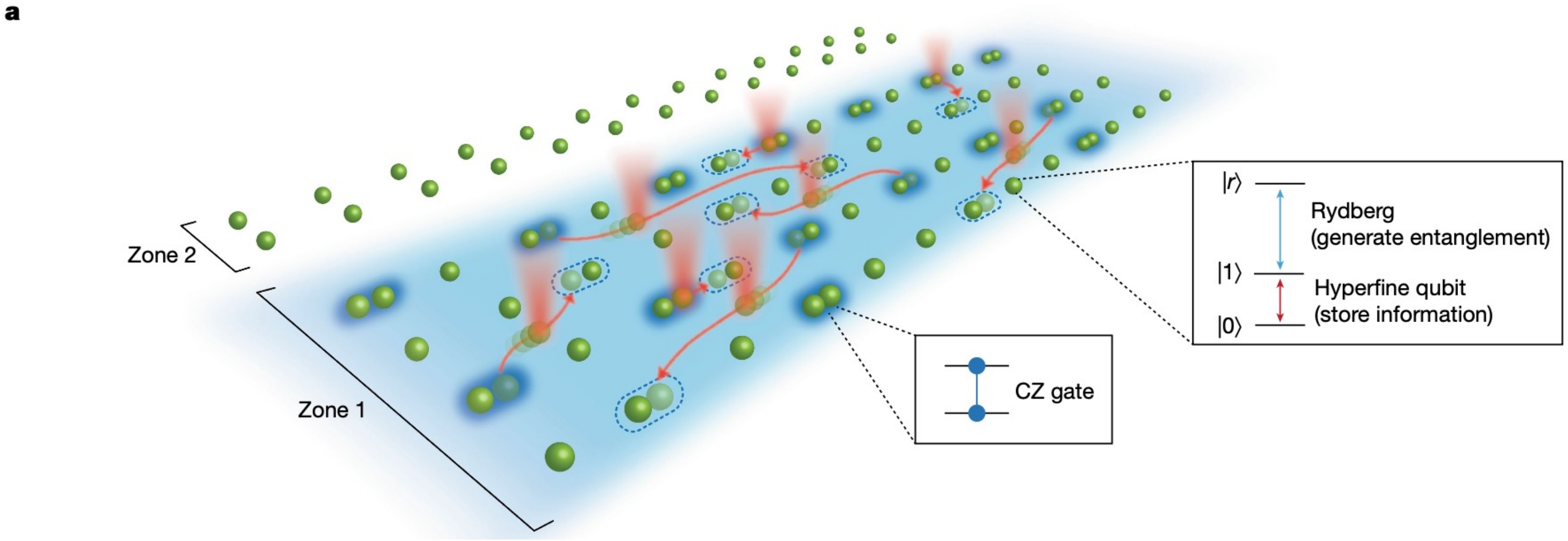
$Q_{ij} = 1\ si\ (i, j)$ connectés

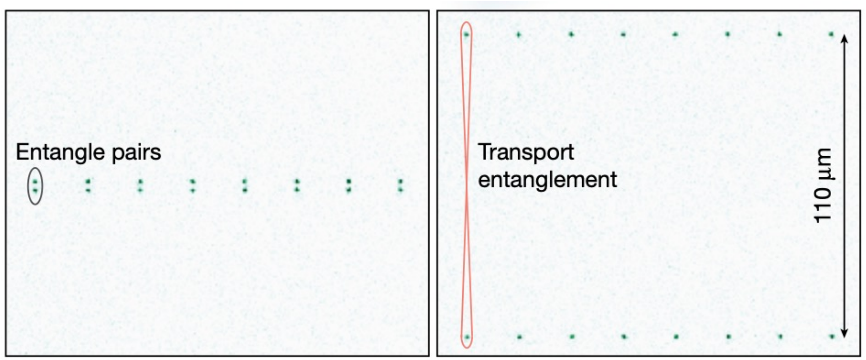
Formulation QUBO : = $\sum_{i<j} Q_{ij}\, x_i x_j + \sum_{i<j} Q_{ij}\,(1 - x_i)(1 - x_j)$

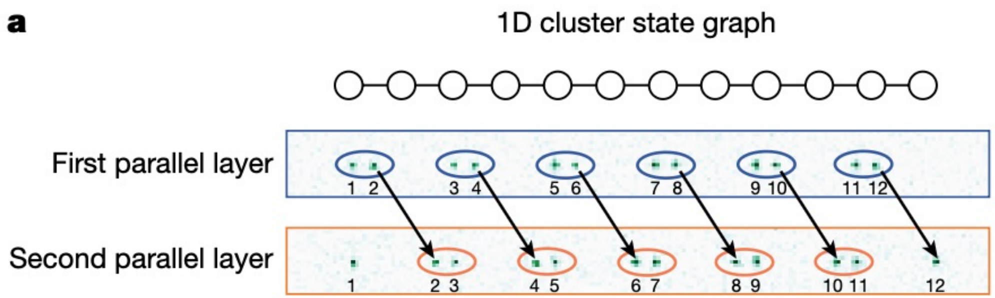


Finances
Logistique
Planning
Optimisation réseaux
IT
…

Processeurs atomiques : portes logiques



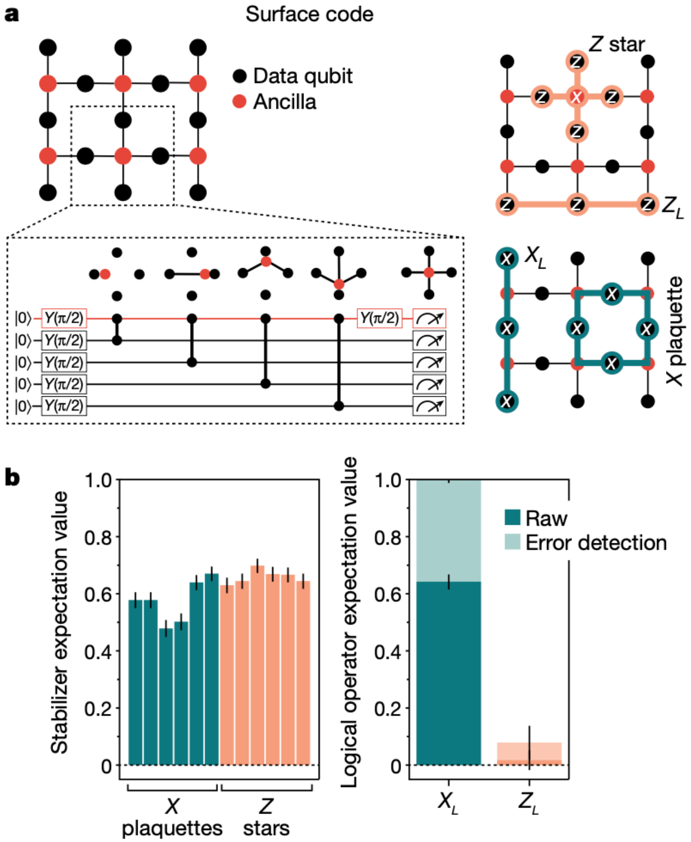




Nature 604, 451 (2022)

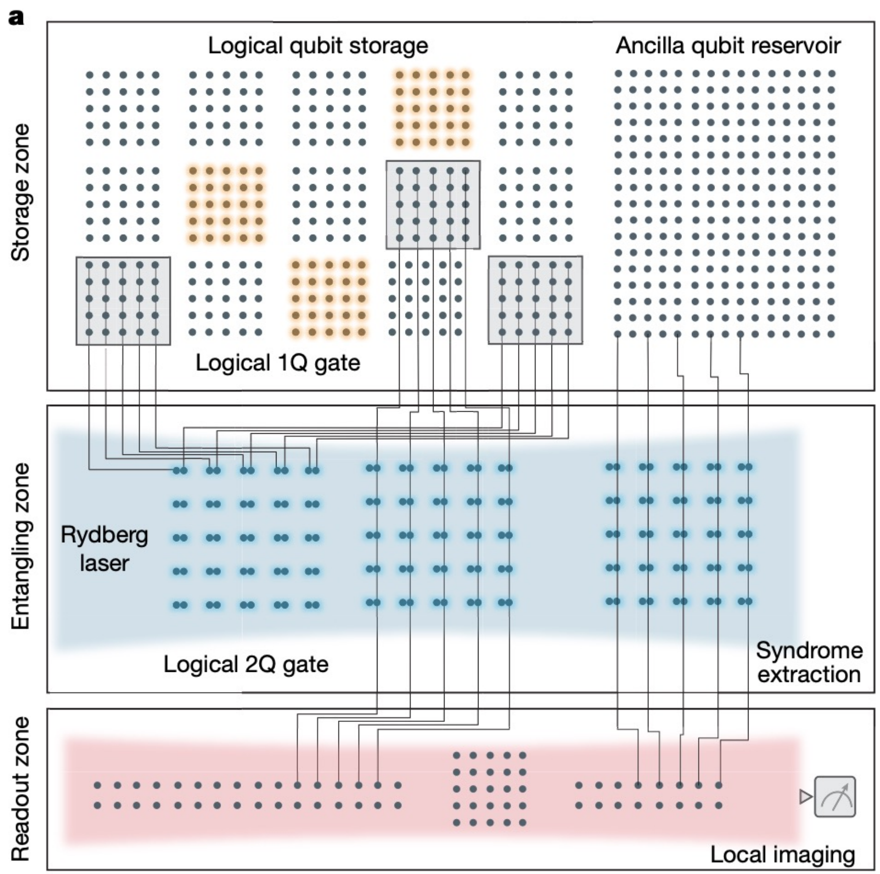
Processeurs atomiques : génération d'états de graphe

Vers le qubit logique



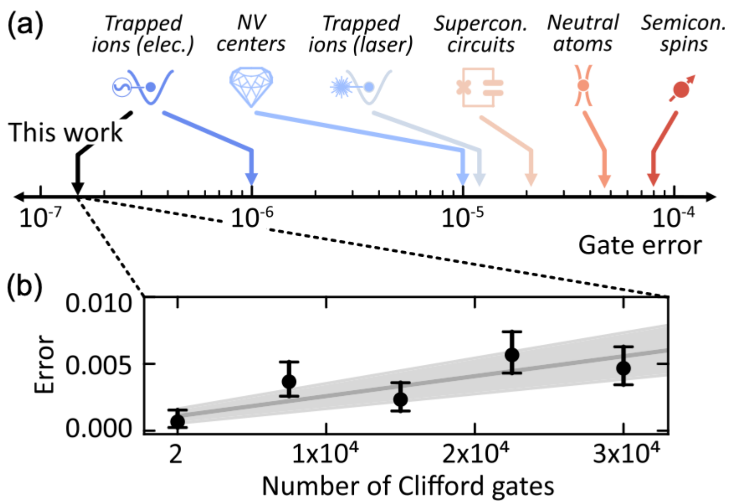
Nature 604, 451 (2022)

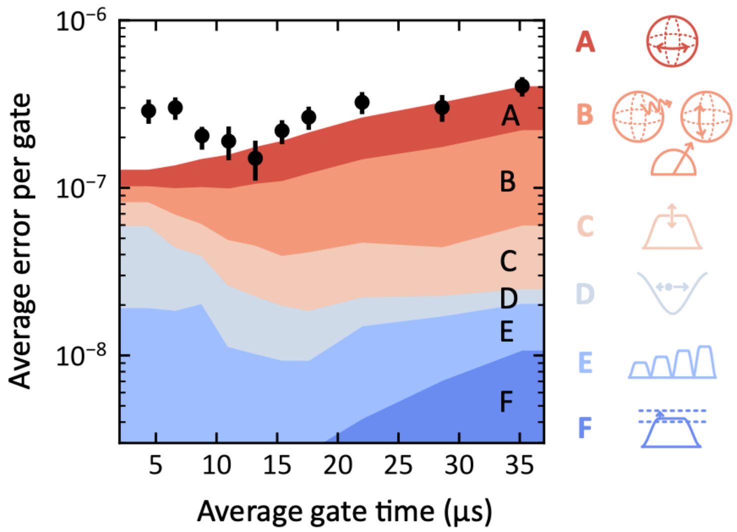
Et la correction d'erreurs



Nature 626, 58–65 (2024)

Processeurs à base d'ion : erreurs record



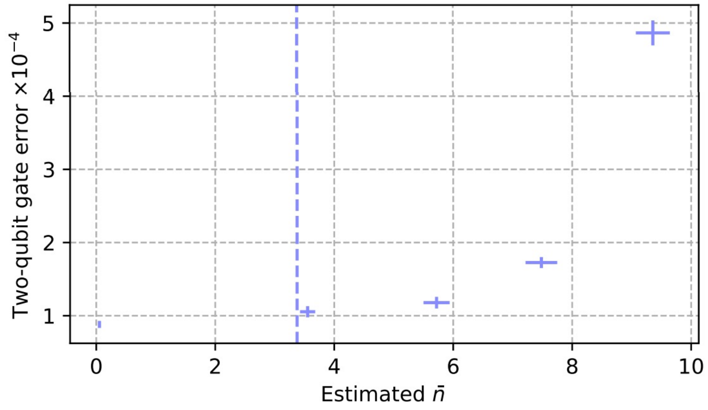


Erreurs record à 1 qubit

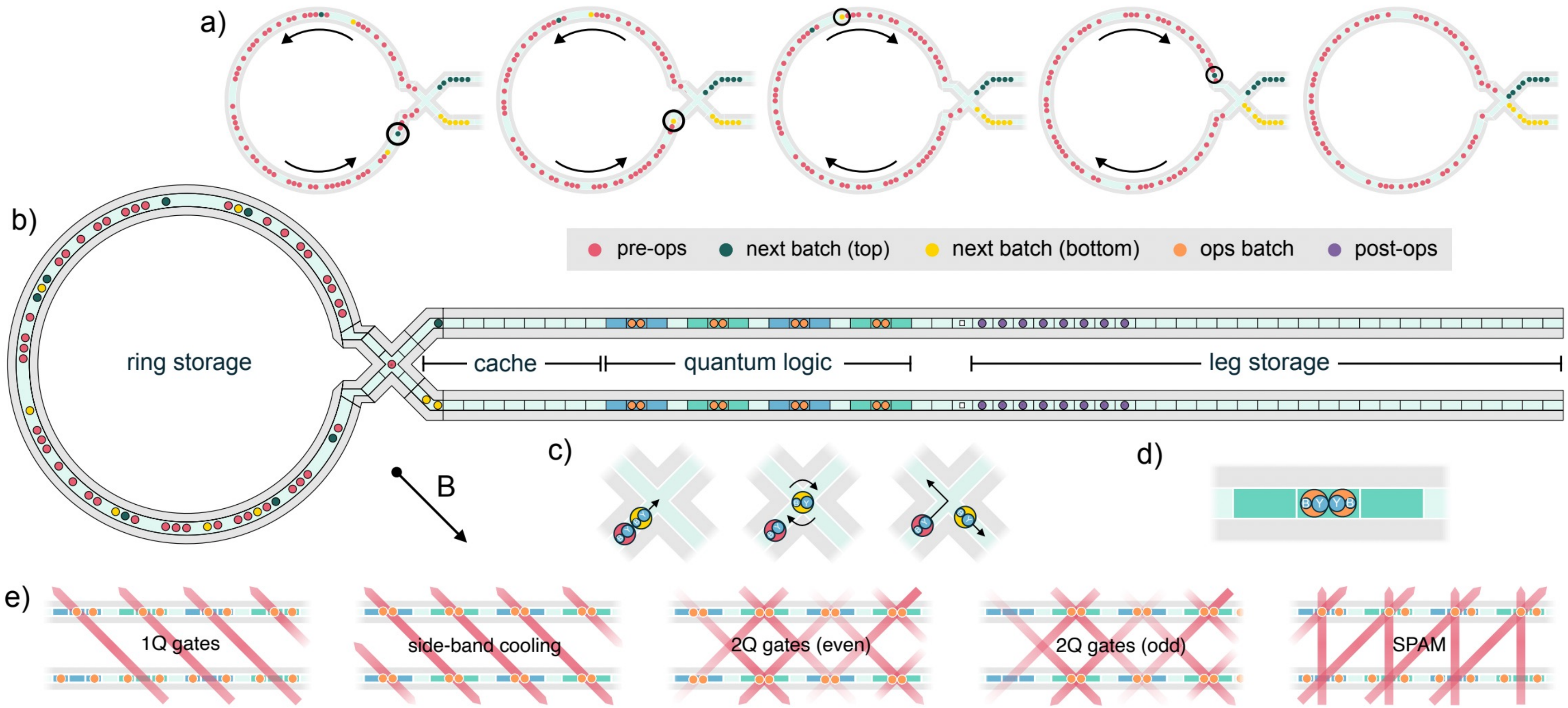
Phys. Rev. Lett. 134, 230601 (2025)

Réduction des erreurs sans refroidissement

arXiv:2510.17286

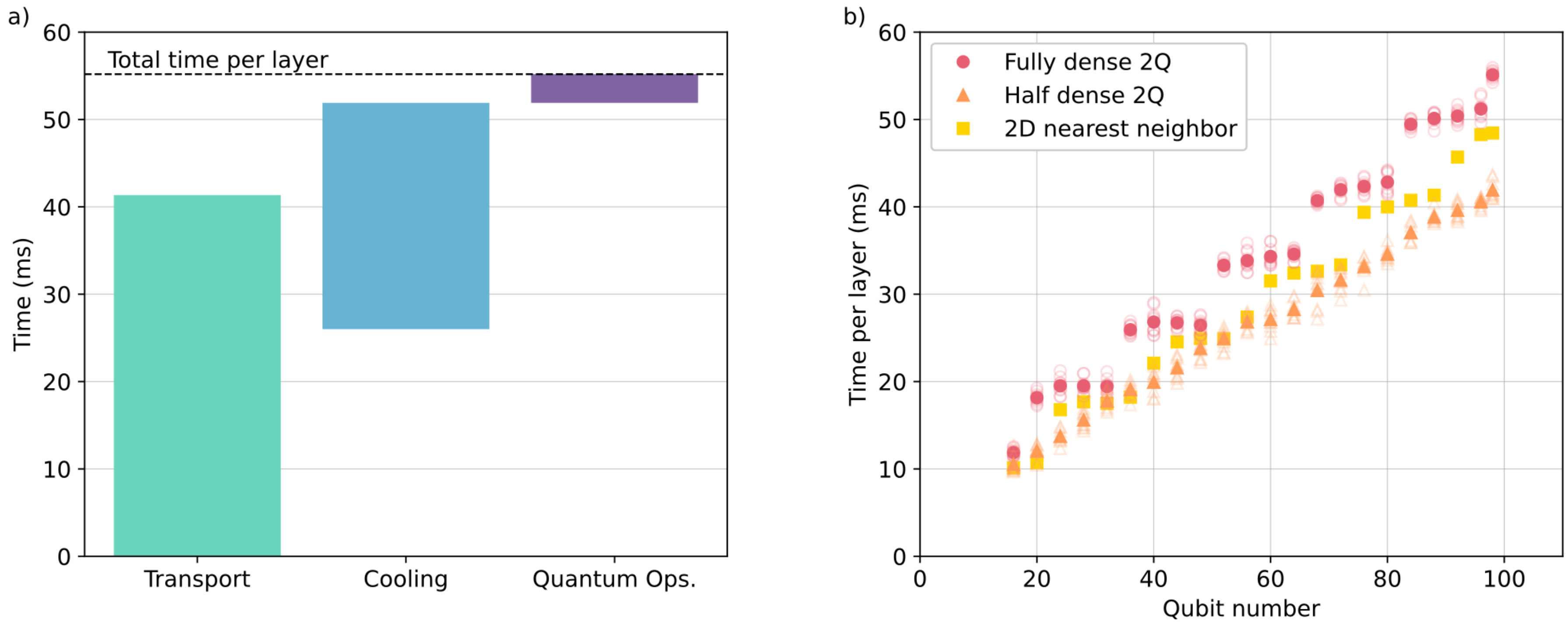


Processeurs à base d'ion : processeur à « CCD »



arXiv:2511.05465

Processeurs à base d'ion : processeur à « CCD »

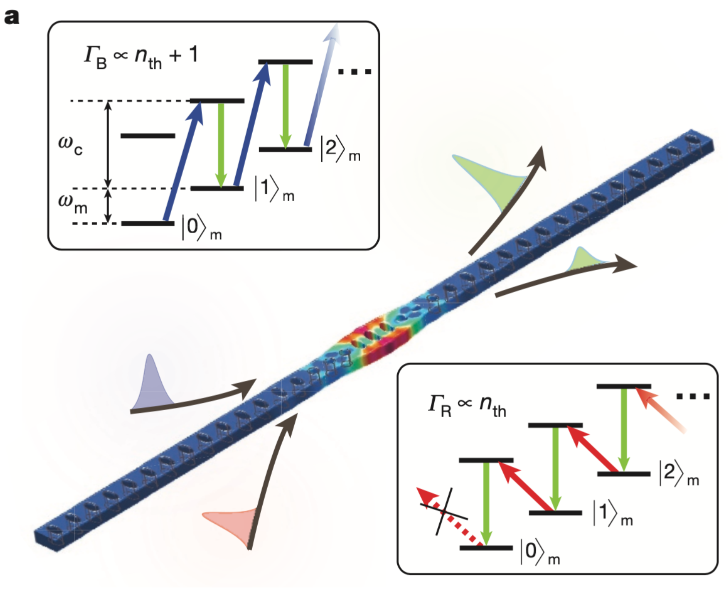


arXiv:2511.05465

Prochaines séances

17 février

Vibrations et technologies quantiques



Nature 530, 313–316 (2016)

24 février

Interfaces quantiques