"Enrico Fermi" Chair
2021/2022

Lectures at Sapienza Università di Roma,
January-May 2022

A History of the Science of Light
From Galileo's telescope to the laser and the quantum information technologies

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Lecture 11. April 7^{th} 2022

Lecture 11: Laser cooling and trapping of neutral atoms

Outline of Lecture

The two kinds of light induced forces: dissipative and reactive force. Orders of magnitude.

Doppler cooling and optical molasses. Temperature limit.

Sub-Doppler cooling: Sisyphus effect.

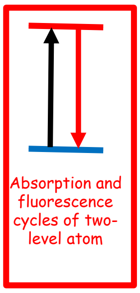
Atomic optics: atomic mirrors, optical tweezers, optical traps for single atoms, optical lattices.

Atomic interferometers: gravimeters.

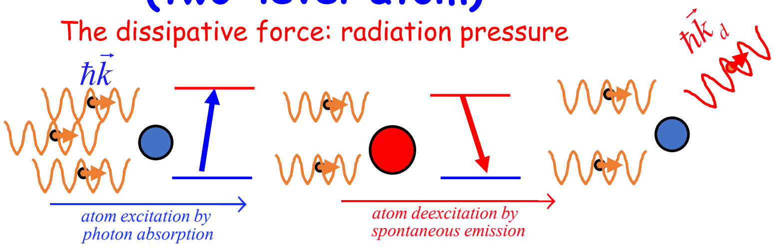
Evaporative cooling, Bose Einstein Condensation and degenerate Fermionic gases.

Ultra cold atomic gases as simulators of condensed matter phenomena.

Qualitative description of radiative forces (two-level atom)



The dissipative force: radiation pressure



Momentum transfer between light and atom:. After each cycle of absorption-emission light scattering, the atomic momentum changes by ,

$$\hbar\Delta\vec{k} = \hbar(\vec{k} - \vec{k}_d)$$

The scattered photon has on average a zero momentum (same probability of emission in opposite directions). After N cycles, the atomic momentum has changed by $N\hbar k$, provided atom has stayed resonant with light (one must account for Doppler effect). The number of cycles per unit time increases with light intensity and saturates to the value $\Gamma/2$ (Γ : natural width of excited state). Hence, the maximum value of the radiation pressure force acting on atom (dissipative force):

$$\vec{F}_D^{(\max)} = \hbar\Gamma\vec{k}/2$$

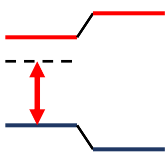
which produces on atom (mass M) the maximum acceleration:

$$a_D^{(\max)} = F_D^{(\max)}/M = \hbar\Gamma k/2M$$

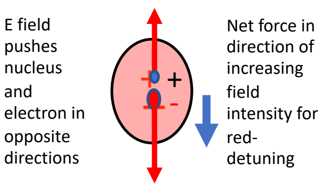
$$= \quad h\Gamma/2M\lambda\left(typically \sim 2\times10^6\, m/s^2\right)$$

Qualitative description of radiative forces (continued)

Reactive force (dipolar force)



A non resonant field induces on atom's ground state a *light-shift* proportional to the light intensity and hence a force proportional to the gradient of the light intensity. For a red-shifted light beam (figure) , the ground state light shift is negative and the force pushes atom towards high fields (opposite sign for blue shifted beam, pushing atom toward low fields)



Equivalent interpretation: the light electric field E induces on atom a dipole proportional to E, separating the positive charge of the nucleus from the barycentre of the negative electron distribution. In a field gradient, the opposite charges are submitted to forces of opposite sign and different amplitudes, resulting in a net force acting on atom. The average net force varies as E^2. Its sign depends on the sign of the detuning between the light and the atomic transition.

At resonance, the reactive force vanishes while the dissipative force is maximum. The reactive force saturates for light intensities much larger than the dissipative force (see next page)

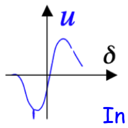
Theory of radiative forces (atom at rest: V=0)

Monochromatic laser field
$$\vec{E}_L(\vec{r},t) = \vec{e}_L \mathsf{E}_L(\vec{r})\cos\left[\omega_L t + \phi(\vec{r})\right]$$
polarisation ($\vec{e}_L$), amplitude (E_L), phase (ϕ)

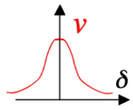
Atom-laser interaction
$$V_{AL} = -\vec{D}.\vec{E}_L(\vec{r},t) \qquad \Omega_R(\vec{r}) = -\mathsf{E}_L(\vec{r})\vec{D}_{eg}.\vec{e}_L/\hbar$$
Atomic dipole operator (matrix element D_{eg}) — Rabi frequency

Average light Force
$$\vec{\mathsf{F}}(\vec{r},t) = \vec{\nabla}\vec{D}.\vec{E}_L(\vec{r},t) = \sum_{i=x,y,z}\langle D_i\rangle \vec{\nabla}E_{Li}(\vec{r},t)$$
Phase and amplitude gradients

Induced steady state dipole (solution of Bloch equations)



$$\langle\vec{D}\rangle = 2\vec{D}_{eg}\left[u\cos(\omega_L t+\phi) - v\sin(\omega_L t+\phi)\right]$$
$$\delta = \omega_L - \omega_a$$



In phase dipole (reactive force)
$$u = \frac{2\delta\Omega}{\Gamma^2 + 2\Omega^2 + 4\delta^2}$$

In quadrature dipole (dissipative force)
$$v = \frac{\Gamma\Omega}{\Gamma^2 + 2\Omega^2 + 4\delta^2}$$

)

Theory of radiative forces (continued)

$$\vec{\mathsf{F}}(\vec{r},t) = \sum_{i=x,y,z}\langle D_i\rangle \vec{\nabla}E_{Li}(r,t) = \vec{\mathsf{F}}_R(\vec{r},t) + \vec{\mathsf{F}}_D(\vec{r},t)$$

Gradients of amplitude and phase give rise to reactive and dissipative forces respectively

Gradient of phase = $-\vec{k}$ (for plane wave)

$$\vec{F}_D = E_L v D_{eg}\vec{\nabla}\phi = -\hbar\Omega v\vec{\nabla}\phi = -\hbar\frac{\Gamma\Omega^2}{\Gamma^2 + 2\Omega^2 + 4\delta^2}\vec{\nabla}\phi = \hbar k\frac{\Gamma\Omega^2}{\Gamma^2 + 2\Omega^2 + 4\delta^2}$$

The dissipative force, maximum at resonance, saturates at *hΓk/2*. This is the radiation pressure force. It is proportional to the dipole in quadrature with the field and to the gradient of the field phase (wave vector for a plane wave).

$$\vec{F}_R = -\hbar u\vec{\nabla}\Omega = -\frac{\hbar\delta}{\Gamma^2 + 2\Omega^2 + 4\delta^2}\vec{\nabla}(\Omega^2)$$

Attractive force towards high fields for $\delta<0$, towards low fields for $\delta>0$.

The reactive force, zero at resonance, is proportional to the in-phase dipole and to the gradient of light intensity. *For $|\delta| \gg \Gamma,\Omega$, it increases with light intensity as $\nabla(E^2)/\delta$. and does not saturate (until atom perturbation theory breaks down).* ***This force is a light shift effect.***

Laser cooling of atomic beam by counter-propagating laser

Atom at resonance if: $\omega_L = \omega_{eg} - kv(t)$

If resonance condition is maintained during deceleration:

$$v(t) = v_0 - a_D^{max} t$$

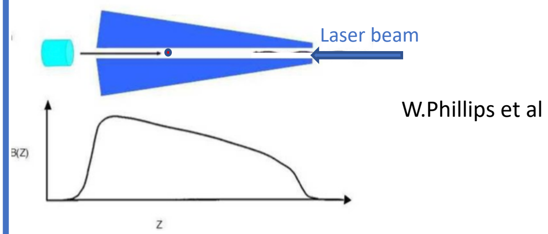
Braking time:

$$t_{stop} = \frac{v_0}{a_D^{max}} \sim \frac{500 m/s}{2\times10^6 m/s^2} \sim 2\times10^{-4} s$$

Braking distance:

$$z - z_0 = v_0 t_{stop} - \frac{a_D^{max} t_{stop}^2}{2} = 0.6m$$

How to keep atom at resonance during braking: Zeeman slower



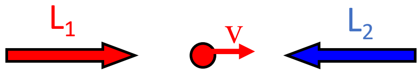
W.Phillips et al

Zeeman shift in a spatially varying magnetic field compensates Doppler shift (solenoid with number of coils decreasing from left to right)

Optical molasses (two-level atom)

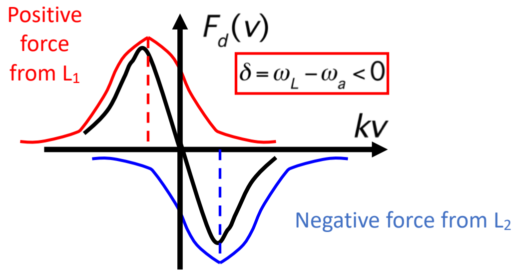
1D cooling in a standing wave of weak intensity (two-level atom and δ < 0)

Dissipative radiative force depends on the atom-field detuning δ in the atom reference frame (Doppler effect).



$\delta_1 = \delta - kv$ $\delta_2 = \delta + kv$

Atom with v > 0 gets closer to resonance and is pushed stronger by L_2 than by L_1 and inversely: the force is always opposed to velocity (friction)

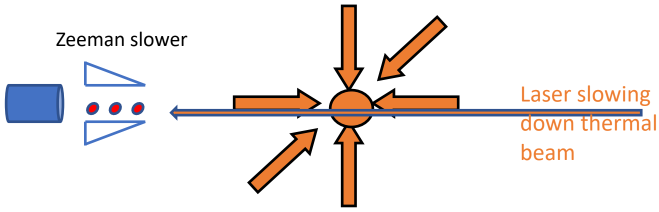


Friction force is dispersive. It is maximal for $\delta = -\Gamma/2$, slowing down atoms with velocity $|v| < \Gamma/k$ in characteristic time τ, .

$$F_d(v) \approx -\alpha v \qquad \alpha = \frac{M_a}{\tau} = -\frac{\hbar\Gamma k^2\Omega^2\delta}{(\delta^2+\Gamma^2/4)^2} \qquad (\Omega < \Gamma, |\delta|)$$

Order of magnitude for $\delta = -\Gamma/2$ and $\Omega^2 = \Gamma^2/10$ $\quad \tau_{opt} \approx \frac{5M_a}{\hbar k^2} : 100\mu s \quad (\Omega^2 : \Gamma^2/10; Rubidium)$

3D Optical molasses



Pairs of red shifted laser beams in three spatial directions: slow atoms emerging from Zeeman slower are braked in three dimensions

S.Chu et al

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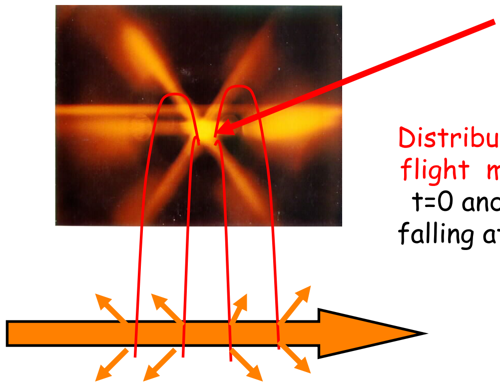


Fluorescence of about one billion atoms moving slowly as if immersed in a viscous medium (force opposed to velocity in 3D)

Distribution of velocities determined by time of flight measurement: molasses is switched of at t=0 and one measures the arrival time of free falling atoms in a laser beam below the molasses

Temperature of the order of 1 microkelvin, a hundred times smaller than expected!

Expected Doppler limit of molasses temperature: fluctuation-dissipation theorem (Einstein 1905)

The average kinetic energy of atoms is damped by the laser friction force in the molasses (dissipation):

$$\frac{d\langle E_c\rangle}{dt} = -2\frac{\langle E_c\rangle}{\tau_m} \quad ; \quad \tau_m \approx \frac{5M}{\hbar k^2}$$

The kinetic energy is increased by the fluctuations of the atomic momentum produced by the random atomic recoil after spontaneous emission in each absorption-emission cycle (Brownian motion in momentum space):

$$\frac{d\langle E_c\rangle_{fluctuation}}{dt} = \Gamma \times \frac{\hbar^2 k^2}{2M}$$

Kinetic energy at equilibrium: $\frac{2\langle E_c\rangle}{\tau_m} \approx \Gamma\frac{\hbar^2 k^2}{2M} \rightarrow \langle E_c\rangle = \Gamma\hbar^2 k^2 \tau_m / 4M \approx \hbar\Gamma$

Predicted temperature is 100 time larger than observed! A good experimental surprise

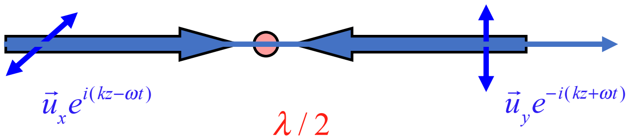
Doppler limited temperature: $T_{Doppler} = \hbar\Gamma / k_B \; (240\mu K \;\; for\; Na; 140\; \mu K \;\; for\; Rb)$

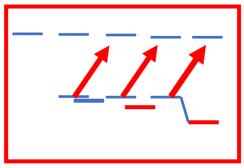
Doppler limited velocity: $v_{Doppler} \sim \sqrt{2\hbar\Gamma / M} \sim 0.3 m/s$

Sub-Doppler cooling of an atom with ground state degeneracy: Sisyphus effect

Counterpropagating light beams with orthogonal linear polarizations

Dephasing between the u_x and u_y polarizations: $\varphi_x - \varphi_y = 2kz$



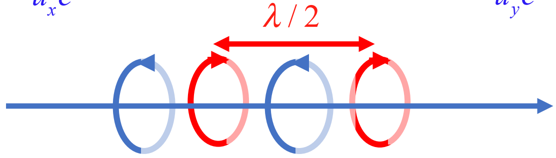


Red-detuned σ_+ light shifts down m=+1 ground state and leaves m=-1 state almost unshifted

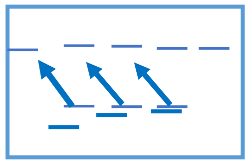
σ_+ polarization:

$$\varphi_x - \varphi_y = \frac{\pi}{2} + 2n\pi$$

$$z_+ = \frac{\pi}{4k} + n\frac{\pi}{k} = \frac{\lambda}{8} + n\frac{\lambda}{2}$$



Light polarized alternatively in σ_+ and σ_- with a $\lambda/2$ periodicity and constant average intensity. Between circular polarizations, polarization is linear at 45°.



Red-detuned σ_- light shifts down the m=-1 state and leaves m=+1 state almost unshifted

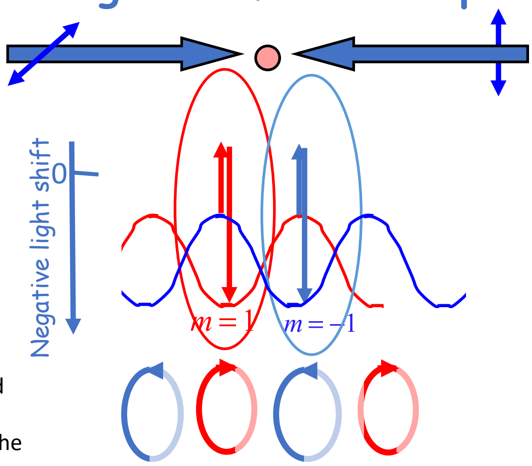
σ_- polarization:

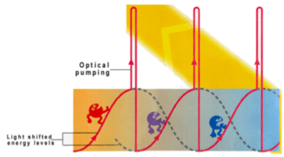
$$z_- = z_+ + \frac{\lambda}{4}$$

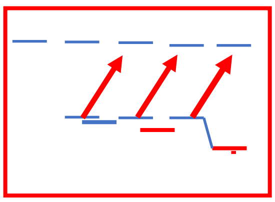
Light shifts of m=1 and m=-1 states are spatially modulated along Oz, with periodicity $\lambda/2$. Maximum of m=+1 shift corresponds to minimum for m=-1 shift

Sisyphus effect: σ_+ and σ_- optical pumping in modulated light-shift landscape

C.Cohen-Tannoudji and J.Dalibard

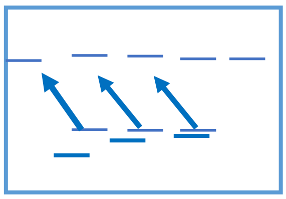






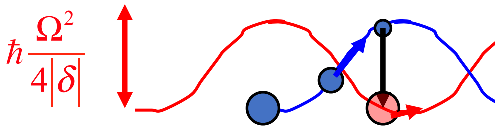
When atom reaches a σ_+ polarized position , it is at the top of a potential barrier for m=-1 and at the bottom of a valley for m=+1. The light pumps it from m=-1 towards m=+1: atom at top of potential hill is brought back to the bottom of a valley.

Atom then climbs potential in m=+1 state until it reaches the next σ_- polarized zone: it is then pumped back to the m=-1 state and loses the potential energy it had gained over its $\lambda/4$ travel.



The correlated periodic spatial variations of the light shifts and the σ_+ /σ_- optical pumping processes force atom to continuously climb potential hills and exhaust its kinetic energy very efficiently. Hence the name :**Sisyphus cooling.**

Limit of sub-Doppler cooling



Sisyphus cooling stops when atom has not enough kinetic energy to climb potential well:

$$k_B T_{Sisyphus} \sim \hbar \frac{\Omega^2}{4|\delta|}$$

Sisyphus cooling is more efficient than Doppler cooling. The correlation between the dissipative optical pumping (cycles of photon absorption and spontaneous emission) and the braking due to the reactive force leads to temperatures which can be two orders of magnitude smaller than that of the Doppler cooling limit.Comparing $T_{Sisyphus}$ with $T_{Doppler}$ we find:

$$\frac{T_{Sisyphus}}{T_{Doppler}} = \frac{\Omega^2}{4|\delta|\Gamma} \sim \frac{Ground\ state\ light\ shift / \hbar}{Excited\ state\ line\ width} \sim 10^{-2}$$

This ratio between the ground state light shift and the excited state natural line width is achieved with realistic values of Ω and δ:

$$\Omega \sim \Gamma \sim |\delta| / 25$$

$T_{Sisyphus}$ cannot be decreased indefinitely by decreasing the light intensity and Ω.

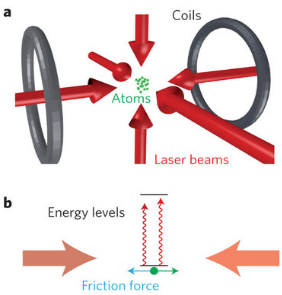
We have neglected in this analysis the recoil energy of the atom when it emits a spontaneous emission photon. The temperature corresponding to this minimal energy is:

$$T_{recoil} \sim \frac{\hbar^2 k_L^2}{2 M k_B} \sim 10^{-6} K \quad (for\ Rb)$$

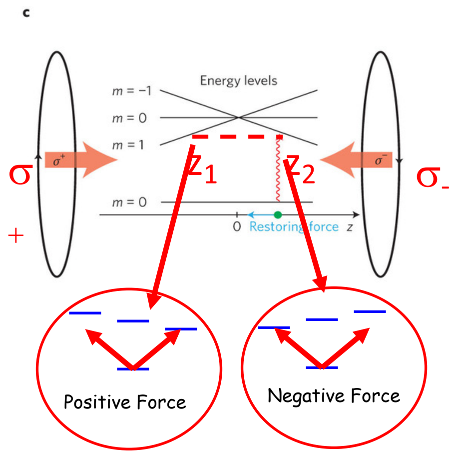
Neutral atom traps

J.Dalibard

Dissipative magneto-optical-trap (MOT). Transition J=0→J=1



The MOT maintains indefinitely atoms suspended in the Earth gravitational field



Combination of $\sigma_+ - \sigma_-$ polarized counterpropagating red-shifted beams with magnetic field gradient realized by pairs of coils fed with currents in opposite directions, creating a magnetic field gradient with zero field at r=0. Zeeman effect compensates the laser detuning at z_1 and z_2

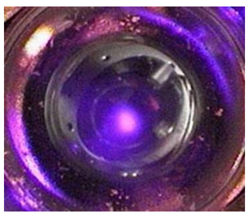
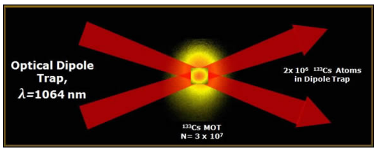


Image of a Calcium MOT (NIST)

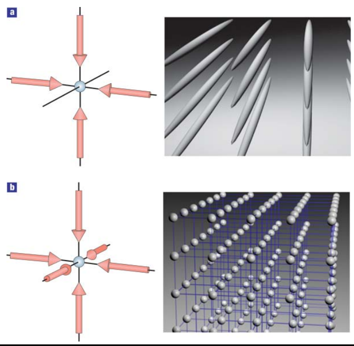
a position-dependent force adds-up to the friction force of the molasses : at z_1, the radiation pressure of the σ_+ beam is larger than that of the σ_- beam (the opposite happens at z_2).

Dipolar optical traps

Non resonant light far detuned on red side with high light intensity: atoms are attracted towards high fields by the dipolar force derivating from the light-shift potential.



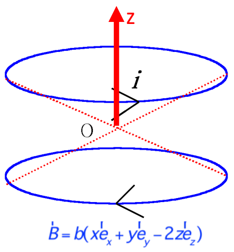
Single trap: atomic optical tweezer



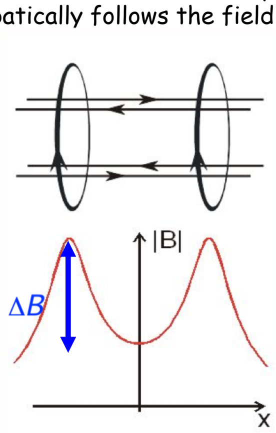
1D, 2D or 3D optical lattices made by intersecting interfering intense laser beams. Zero or one atom per lattice site. Systems simulate condensed matter situations. A very rich physics

Magnetic trap for neutral atoms

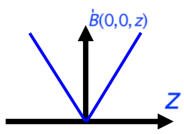
Laser cooled atoms can be trapped "in the dark" by a magnetic field gradient acting on their magnetic moments. Conservative traps without perturbations of atoms by light. The atoms are in states attracted towards low fields at center of trap (low field seekers). The magnetic moment of atoms adiabatically follows the field direction as atom moves.



Traps able to confine atoms with temperatures in the hundred μK range



Joffe-Pritchard Trap



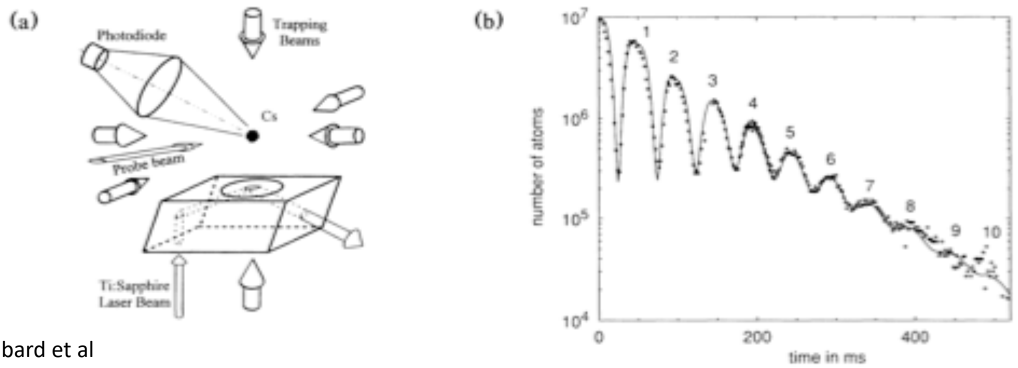
Quadripolar trap with anti-Helmholtz coils

$$T_{max} : \mu_B.\Delta B / k_B \approx 60 \mu K / Gauss$$

Atom Optics

Cold atom mirror

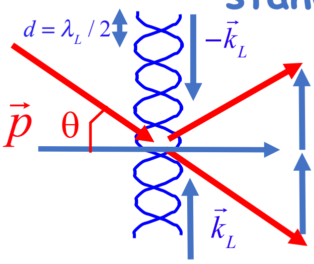
Matter wave experiments taking advantage of the large de Broglie wavelength of cold atoms



J.Dalibard et al

Cold atoms bounce on an atomic mirror realized by an evanescent wave emerging from a glass parallelepiped. The blue-detuned laser beam repels the Cesium atoms released from a MOT at time t=0: the atoms fall towards the mirror, then bounce back and are detected by their fluorescence when they cross a resonant probe laser beam. Several successive bounces are detected. This is an atomic trampoline or an "atom cavity" closed at bottom by the atomic mirror and at top by gravity.

Bragg scattering of atomic de Broglie wave by Laser standing wave: an atom beam splitter



A two-level atom (states g,e) with momentum p impinges on a light standing wave consisting of two interfering laser beams with opposite wave vectors $+k_L$ and $-k_L$. The incidence angle of the atom is θ. The light presents nodes and antinodes with a spatial periodicity $d=\pi/k_L = \lambda_L/2$ (λ_L : laser wavelength). Consider the process by which the atom in level g absorbs a photon from the k_L wave and emits by stimulated emission a photon in the $-k_L$ wave:

$$|g,\vec{p}\rangle \xrightarrow{\text{absorption of } k_L \text{ photon}} |e,\vec{p}+\hbar\vec{k}_L\rangle \xrightarrow[-k_L \text{ photon}]{\text{stimulated emission of}} |g,\vec{p}+2\hbar\vec{k}_L\rangle$$

The photon number has not changed (one photon has been transferred from one beam to the other) and the atom is back in g. Conservation of energy requires that the impinging and final atom momentum have same value:

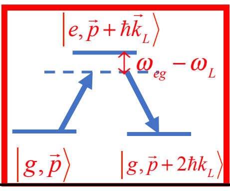
$p = |\vec{p}+2\hbar\vec{k}_L|$ which is satisfied if: $p\sin\theta = \hbar k_L$

This condition can also be written as:

$$MV\sin\theta = h/\lambda_L \quad or \quad \sin\theta = \lambda_{dB}/\lambda_L = \lambda_{dB}/2d$$

where λ_{dB} is the wavelength of the matter wave of the atom (mass M, velocity V).

Same condition as for X ray scattering: the laser beams form a grating scattering the matter wave at the Bragg angle. The roles of light and matter are inverted! In the process the $|e,p+\hbar k_L\rangle$ state is only virtually excited because the laser is non-resonant with atom ($\omega_{eg} > \omega_L$). The atom-light system evolves coherently. If light is applied for $\pi/2$ pulse, one prepares state



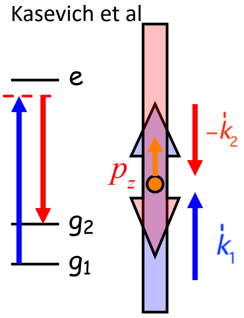
$$|g\rangle\left(|\vec{p}\rangle + e^{i\varphi}|\vec{p}+2\hbar\vec{k}_L\rangle\right)/\sqrt{2}$$

Atom exits in 2 directions at once:

This is an atom beam-splitter!

Inelastic Bragg scattering with bi-color counterpropagating lasers: beam splitter entangles internal & external atom states

S.Chu et al
Kasevich et al



Consider now two vertical counterpropagating laser beams with slightly different colors (wave vectors k_1 and $-k_2$) and a three level atom falling in the light beam along Oz (1 dimension situation). The atom has two ground states levels g_1 and g_2 and one excited state e and the laser frequencies satisfy the condition:

$$\omega_1 - \omega_2 = c(k_1 - k_2) = \omega_{g_2 g_1}$$

By absorbing a photon from the k_1 laser beam and emitting a photon in the k_2 one, the atom evolves from state $|g_1, p_z\rangle$ to the state $|g_2, p_z + h(k_1+k_2)\rangle$ (a Raman process). If the lasers are applied for a time corresponding to a $\pi/2$ Raman pulse of the coherent evolution, the atom ends up in state:

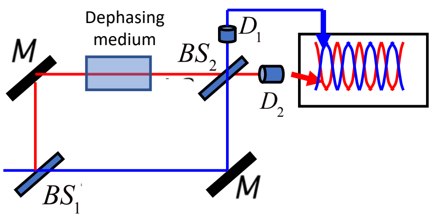
$$\left(|g_1, p_z\rangle + e^{i\varphi}|g_2, p_z + \hbar(k_1+k_2)\rangle\right)/\sqrt{2}$$

The atomic beam splitter now entangles the internal state of the atom with its external motional state. In practice, the impinging atomic state is a wave packet with a dispersion Δp_z of momentum along Oz, extending spatially over $\Delta z = \hbar/\Delta p_z$. The outgoing atom is prepared in a superposition of two atomic wave packets associated to different internal states g_1 and g_2, whose centers separate at speed $\hbar(k_1+k_2)/M$. The phase of the superposition is determined by the adjustable relative phases of the counterpropagating lasers.

If the Raman lasers are applied for a twice longer time (π Raman pulse), the two atomic states are exchanged:

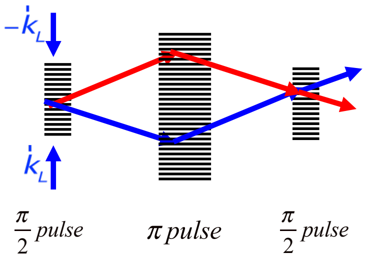
$$|g_1, p_z\rangle \xrightarrow[\pi\ Raman\ pulse]{} |g_2, p_z + \hbar(k_1+k_2)\rangle \,;\, |g_2, p_z + \hbar(k_1+k_2)\rangle \xrightarrow[\pi\ Raman\ pulse]{} -|g_1, p_z\rangle$$

Atomic interferometry

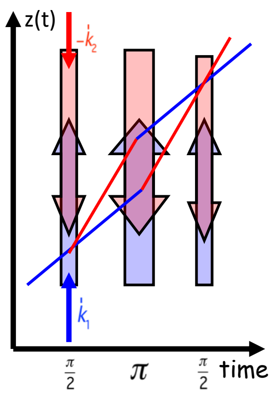


Comparing photon and atom interferometers:

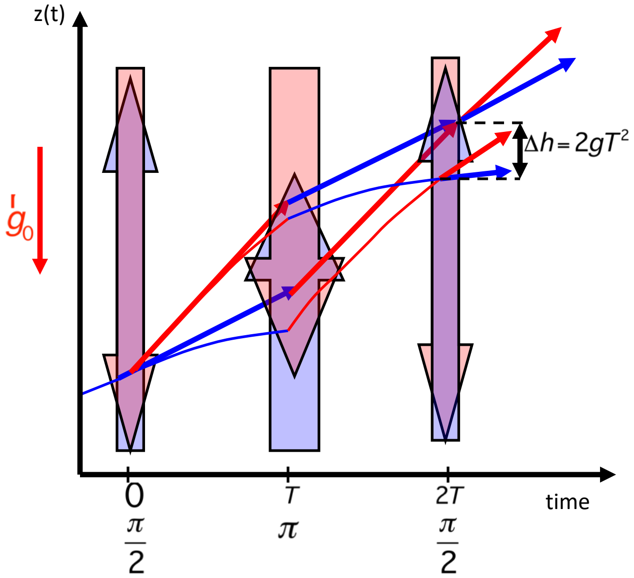
In an optical Mach Zehnder interferometer, the photon trajectory is split into two pathes by a beam splitter (BS_1). The pathes are folded by two mirrors (M) before being recombined by a second beam splitter (BS_2). The outputs of BS_2 are recorded by two detectors (D_1, D_2). The quantum phase between the two pathes is modified either by interposing a medium with refractive index in one path or by moving a mirror. When the phase difference is scanned, fringes with opposite phases are detected by D_1 and D_2.



In the atomic interferometer, the pairs of counterpropagating bi-color vertical lasers play the roles of beam splitters ($\pi/2$ Raman pulse) and of mirrors (π Raman pulses) The atom trajectories may be in two D (left figure) or in 1D (vertical beam (right figure). The beam-splitter $\pi/2$ pulses separate the spatial wave functions of the atom and the mirror π pulses exchange the atomic momenta and the atomic internal state. The atom is detected after the third pulse in state g_1 or g_2. Fringes are produced by variation of gravitational or rotational acceleration (next pages).



Atomic gravimeter



Bold straight lines: atom altitude versus time in free falling frame

$$z_{atom\ frame}(2T) = z_0 + 2\frac{p+\hbar k_L}{M}T$$

Fine parabolic lines: atom altitude versus time in laboratory (laser) frame

$$z_{lab\ frame}(2T) = z_0 + 2\frac{p+\hbar k_L}{M}T - 2g_0T^2$$

Fringe phase : $\Delta\varphi = 2\pi\frac{\Delta h}{\lambda} \rightarrow$

$$\Delta\varphi = k_L\Delta h = 2g_0k_LT^2$$

Typical sensitivity:

$\delta\varphi \approx 5.10^{-3}\,rad\ (100s\ integration\ time)$;

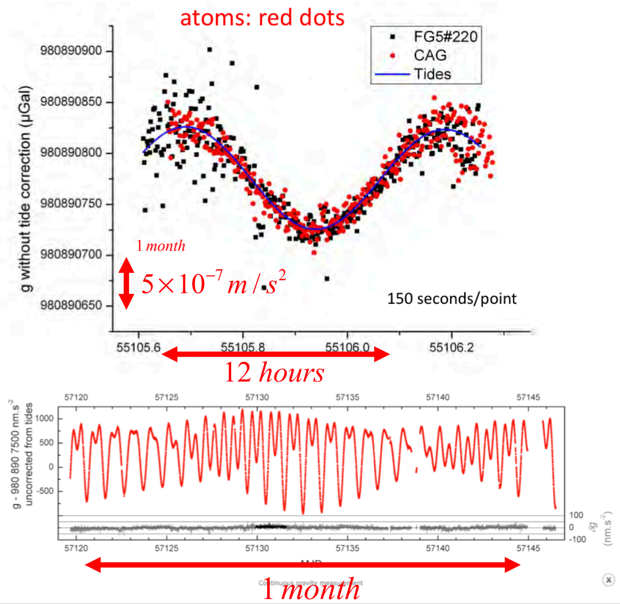
$T = 0.2s$; $k_L = 10^7\,m^{-1}$

$$\delta g = \frac{\delta\varphi}{2k_LT^2}\,m/s^2 \sim 6\times10^{-9}\,m/s^2 \sim 6\times10^{-10}\,g$$

Sensitivity 1/δg is proportional to square of free fall time T^2 and to signal to noise ratio S/N = 1/δφ
(S/N increases like √t where t is the fringe detection averaging time)

Observation of Earth tides with cold atom gravimeter

F. Pereira Dos Santos
A. Landragin



Cold atom gravimeter, Kasevitch group, Stanford University

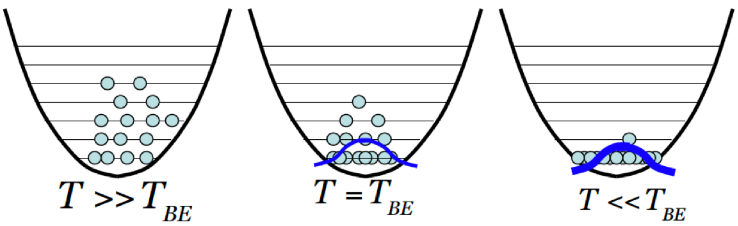
Cold atomic beam falling in a 10 m high tower

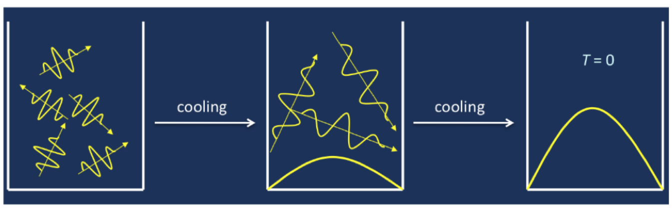
Sensitivity 50 times larger than for a 20 cm free fall distance:

$$\frac{\delta g}{g} \sim 10^{-10} (1\, s\ integration\ time)$$

Bose Einstein condensation of R_b^{85} atoms

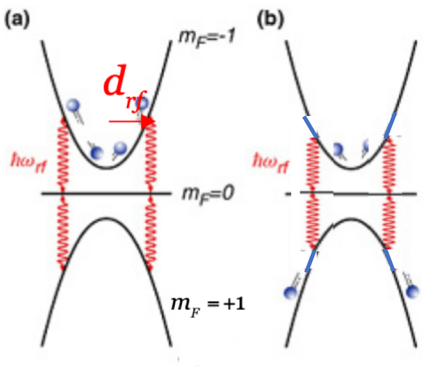
Cold atoms trapped in a MO are transferred to a magnetic trap and cooled to lower temperature by evaporative cooling (see next slide). The goal is to increase the de Broglie wavelength to the point when it becomes of the order of the interatomic distances in the gas. The atoms then collapse in the trap ground state

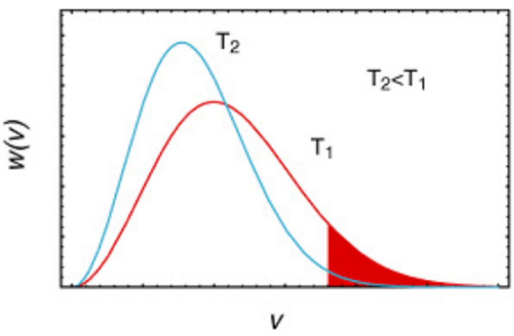




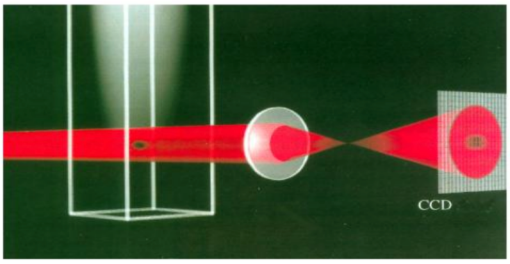
Evaporative cooling

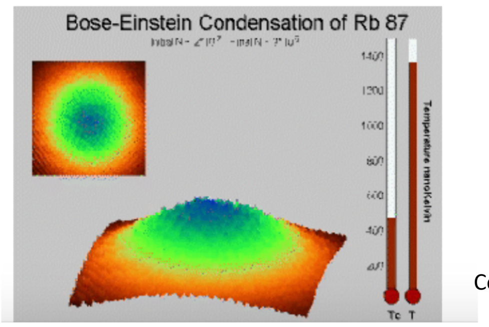
A rf field whose frequency is adjusted to flip the magnetic moment of atoms reaching a preset distance from the trap center is applied to the atoms. These atoms are ejected from the trap. The average temperature of the remaining atoms decreases after thermalization by collisions. The frequency of the rf is adiabatically decreased, which expels colder and colder atoms. The decrease of the temperature must occur faster than that of the BEC threshold temperature which diminishes as the number of atoms in the trap is lowered.



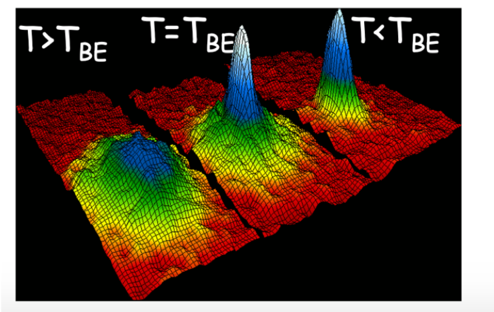


Observing Bose Einstein Condensation



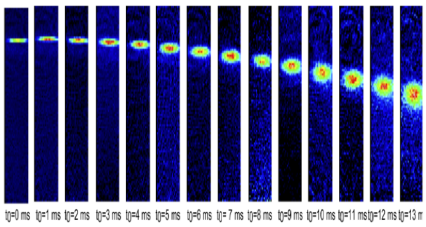


Cornel et al, JILA

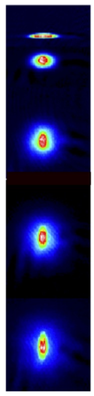


Demonstration of Heisenberg uncertainty relations in the expansion of a Bose-Einstein Condensate

A thermal gas in free fall (atoms relased from trap at a given time and observed by light absorption after a delay)

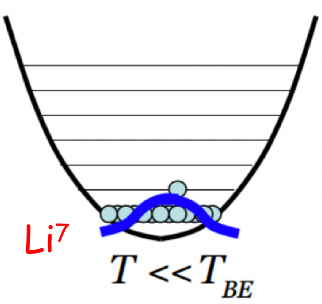


The classical gas expands isotropically: the atomic cloud is spherical

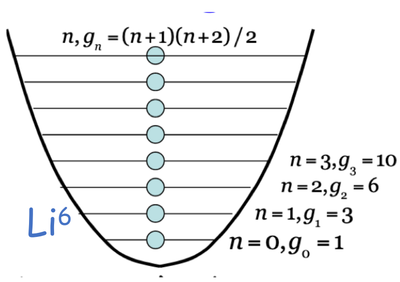


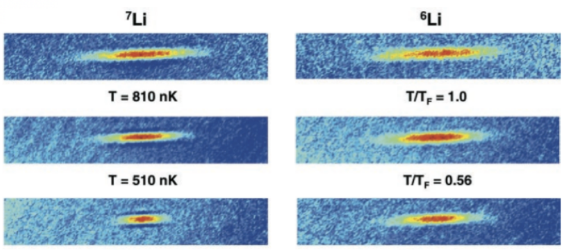
Same experiment performed with a BEC below the threshold temperature: the initial wave function has $\Delta z \ll \Delta x$, hence, according to Heisenberg uncertainty relations $\Delta v_z \gg \Delta v_x$: the free falling cloud expands faster in the vertical direction than in horizontal one: the ellipticity of the cloud gets inverted during fall

Degenerate fermionic quantum gas: trapping and cooling of a mixture of Li^7 (bosons) and Li^6 (fermions) gas



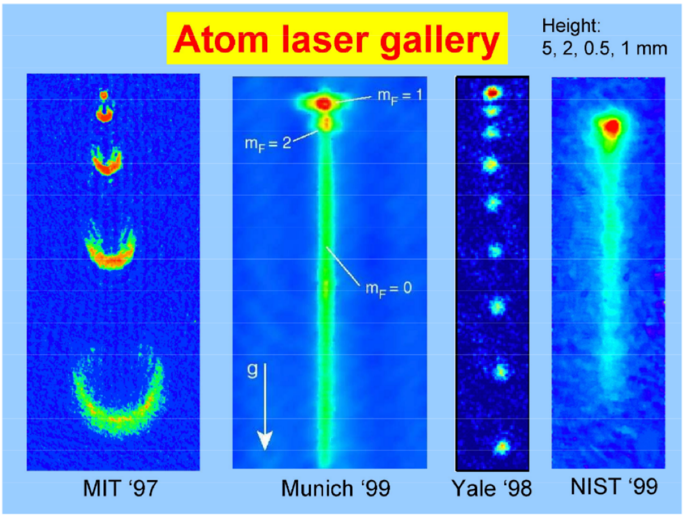
Li^7 bosons are evaporatively cooled and the Li^6 fermionic atoms get cooled by Li^6-Li^7 collisions. When degeneracy is achieved, the bosons are concentrated at trap center while femions occupy a larger volume due to the exclusion principle. The two gases are detected selectively using lasers of slightly different frequencies (isotope shift)





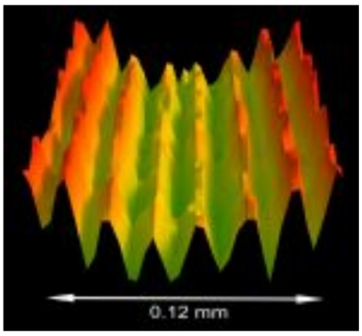
Hulet et al, Houston

Atoms released from a BEC form a beam of coherent matter wave analoguous to a laser (atoms replacing photons)

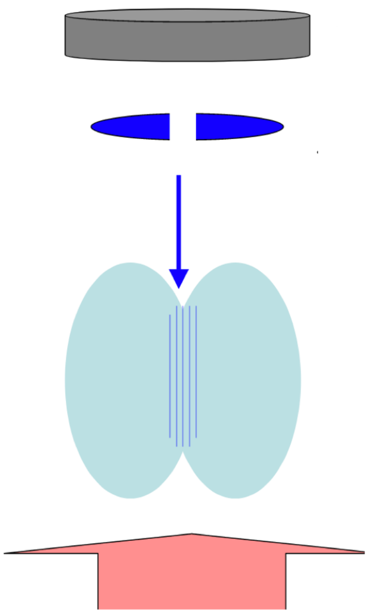


Interference of two independent BECs

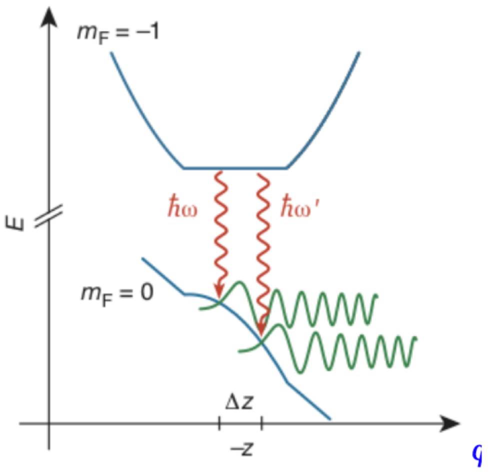
A cigar-shaped BEC is cut in two by a blue-detuned laser beam, then left to expand in free fall. When the two parts overlap, interferences appear in the superposition. The fringes are detected on the top screen by absorption of a probe laser beam. Analogy with the interference of two independent laser beams.



Ketterle et al, MIT

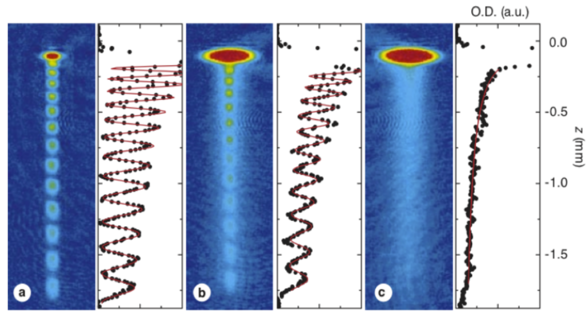


Beating between two atom laser beams



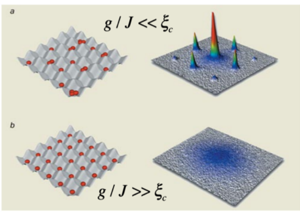
Atoms with v_z=0 velocity are extracted from an atomic trap by two rf pulses of slighly different frequencies, forming two vertical beams falling from altitudes differing by Δz. The two beams have slighly different velocities along Oz, hence different de Broglie wavelengths, resulting in an obervable beating.

The atomic coherence is large for BEC ($T < T_{BEC}$, left figure), decreases at $T = T_{BEC}$ (center) and vanishes for the thermal gas ($T > T_{BEC}$, right). Analogy with the difference between laser and classical light.



I.Bloch et al, Garching

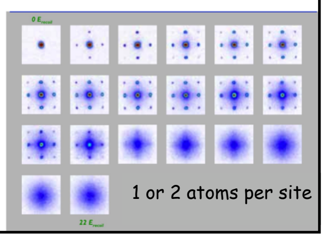
Mott transition in a BEC trapped in an optical lattice



Interfering laser beams form a 3D lattice of potential wells in which a Rb BEC is trapped. Situation analogous to electrons moving in a metallic cristal, with the difference that particles are here bosons and the scale very different (lattice period of the order of μm instead of Angströms, energies of the order of nK instead of hundred K). A phase transition is predicted in such a system. There is a competition between two processes: one is a tunnel effect (characterized by an energy J) which tends to make the atoms hop from well to well with strong correlated fluctuations in the populations of different wells. The other process is a localization mechanism due to repulsive interactions between atoms (characterized by an energy g), which tends to pin-down the atoms in individual wells without fluctuations of the number of particles.

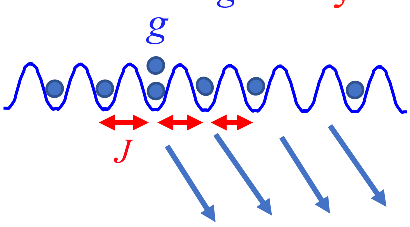
When g/J increases and crosses a critical number ξ, the boson gas in the lattice is predicted to evolve from a superfluid to an insulator. This is called a Mott transition. It has been observed by Greiner et al (2003). They have left the BEC stabilize in a lattice, then released the atoms by suddenly suppressing the lattice and observed after a free flight delay the shadow of the expanded cloud illuminated by a resonant laser.

The resulting images (right figure) correspond from left to right and top to bottom to increasing potential depths of the optical wells. They show a clear interference pattern when J is large (small well depths) which fades away and vanishes when J decreases below threshold (large well depths). This illustrates complementarity: in the superfluid phase, atomic fluctuations make it impossible to know from which well a detected atom is coming, hence there is interference. In insulator phase, the origin of each atom could be in principle determined by inspecting the lattice after atomic detection, hence the lack of interference.



The Mott transition interpreted by complementarity

$g / J \leq \xi$

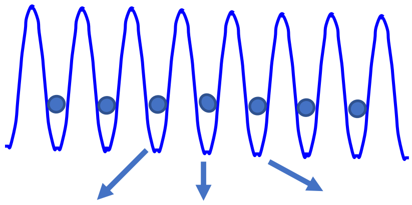


Matter wavelets from different wells interfere: Bragg diffraction in specific directions

Small well depth: tunneling rate J much larger than energetic cost g when 2 atoms repell each other in same well: atoms can hop from well to well:
BEC is superfluid

Interwell fluctuations of number of atoms : impossible to know from which well an atom is coming when lattice is suppressed:
Path indiscernability and interferences

$g / J \geq \xi$



Matter wavelets from different well have no phase correlations: diffraction is diffuse

Large well depth: tunneling rate negligible and the cost of having two atoms in same well big: atoms distribute themselves in different wells,
BEC is an insulator

No fluctuations of well occupation number (here the case when occupation per well is 1): when an atom is detected after lattice release, it is in principle possible to find out where an atom is missing: path discernability and no interference

Concluding remarks

In this lecture, we have studied laser cooling and trapping mechanisms of neutral atoms which have allowed physicists to reach the coldest temperatures ever encountered in the universe, to observe fundamental phenomena and to invent new measuring devices exploiting the properties of matter waves.

In the next lecture, I will describe how laser manipulation methods applied to ions or to neutral atoms are used to build clocks of unprecedented precision and I will discuss some possible applications.