School of Physics
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Laser cooling and Atom optics

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Links to VCE Physics

Laser cooling:

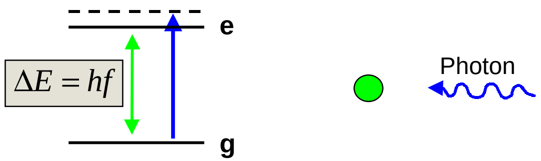
- **atoms have discrete energy levels**
- **photons have momentum**
- **momentum is conserved**
- **energy is conserved**
- **atoms have wave-like characteristics (BEC, atom lasers)**

Atom optics:

- **wave-like nature of matter: very *small* de Broglie wavelength**
- **nano-lithography**

Atoms and lasers: absorption

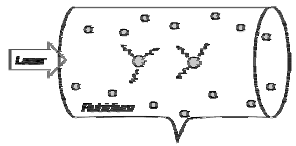
- Consider an atom, minding its own business
- The atom has two discrete (quantised) energy levels, **g** (ground) and **e** (excited) separated by energy ΔE



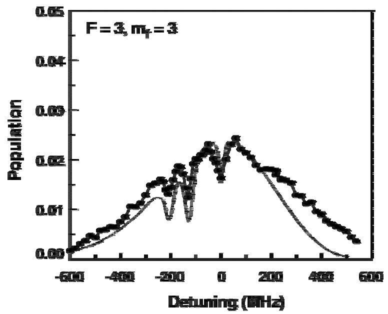
- Along comes a photon from a laser
- The atom is choosy: it ignores the photon unless the frequency f is just right: $\Delta E = hf$

Absorption: research!

- Measure absorption of the laser *vs.* frequency:

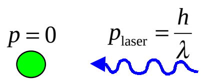


- Real atoms = many levels
- Calculation of spectra difficult
- First calculation for realistic atom (many months of computer time)



Photon momentum

- Let’s return to our hapless atom and the intruding photon
- The atom is at rest; the photon has momentum $p = \frac{h}{\lambda}$



- After the photon is absorbed...

Photon momentum

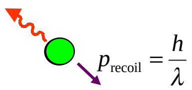
- Let’s return to our hapless atom and the intruding photon
- The atom is at rest; the photon has momentum $p = \frac{h}{\lambda}$

- Conservation of momentum: after the photon is absorbed, the atom (in state **e**) has the momentum, and hence velocity:

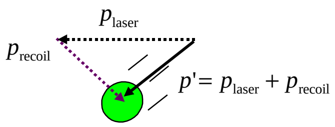
$$v = \frac{p}{m} = \frac{h}{m\lambda}$$

Spontaneous decay

- After some time (Uncertainty Principle), the atom decays, emitting a photon

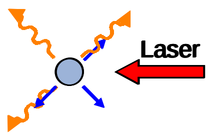


- The decay photon has momentum
- Conservation of momentum: the atom recoils
- Momentum is a vector quantity: atom moves in new direction



Spontaneous decay averages to zero

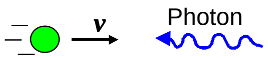
- The spontaneous decays are in random directions
- The recoil kicks average to zero



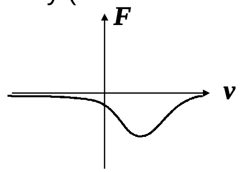
- Many absorption/emission cycles
- Every absorption = one momentum kick in direction of laser
- Net effect: laser pushes atom
- Called *radiation pressure* or *spontaneous force*
- Basis of laser cooling
- Decay time ~ nanoseconds, so acceleration ~ 10^5 to 10^6 m/s^2 !

Doppler shift

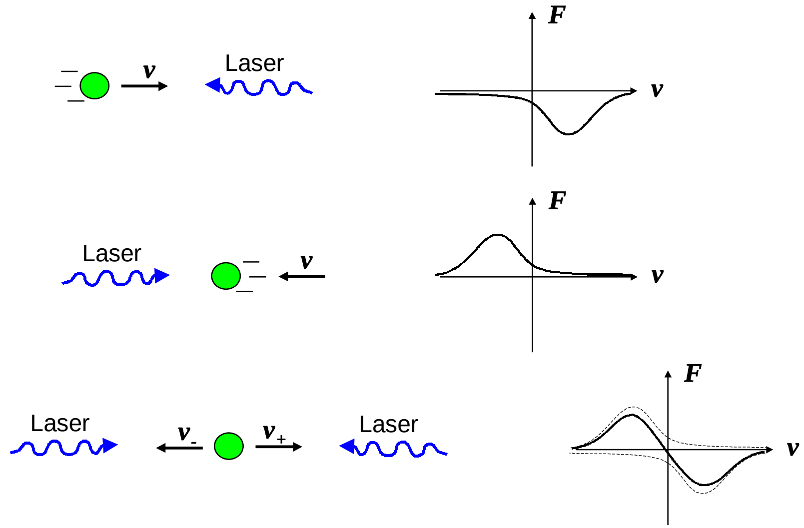
- If atom is moving along laser direction, it sees a Doppler-shifted frequency $f' = f + \frac{v}{\lambda}$



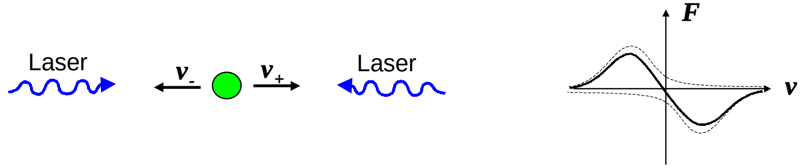
- Absorption probability, and therefore force, depends on frequency and hence on velocity
- If laser is detuned *below* atomic resonance, then:
  - atoms moving towards laser see higher frequency (closer to resonance)
  - hence stronger force

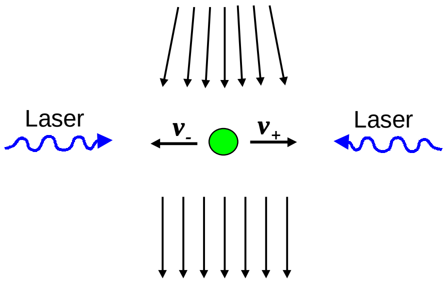


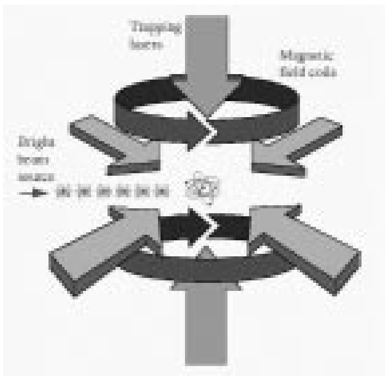
Optical molasses



Laser cooling of atoms







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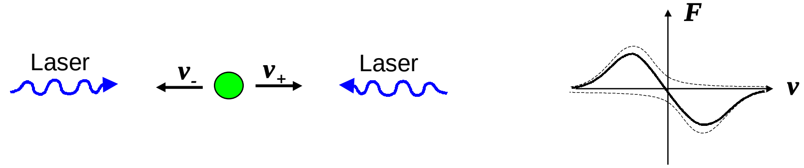
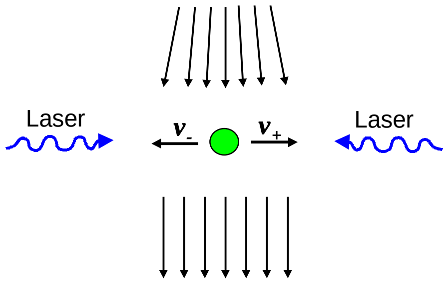
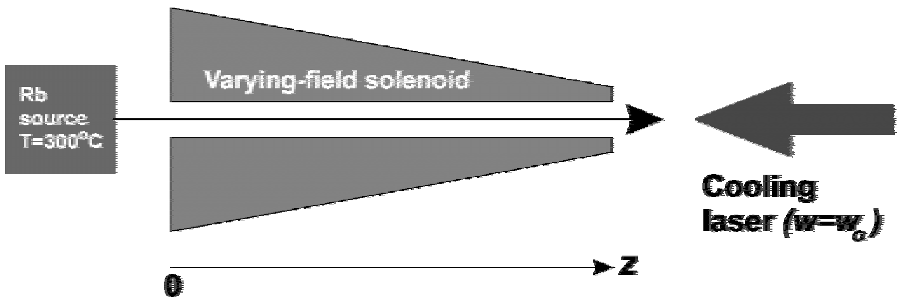




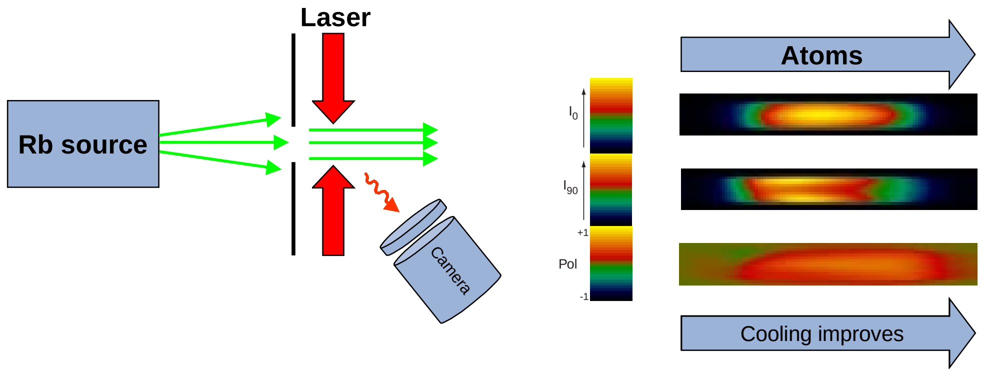
3D molasses?

- Not so simple!
- Atoms leaving normal atomic sources have v ~ 1000 m/s
- Way too fast for Doppler cooling (peaks at ~ 5 m/s)
- Need clever idea – of Nobel prize-winning proportions!



Laser cooling: research!

- New approach to explore cooling processes
- Look at spontaneous decay photons
- Measure polarisation: provides information on cooling



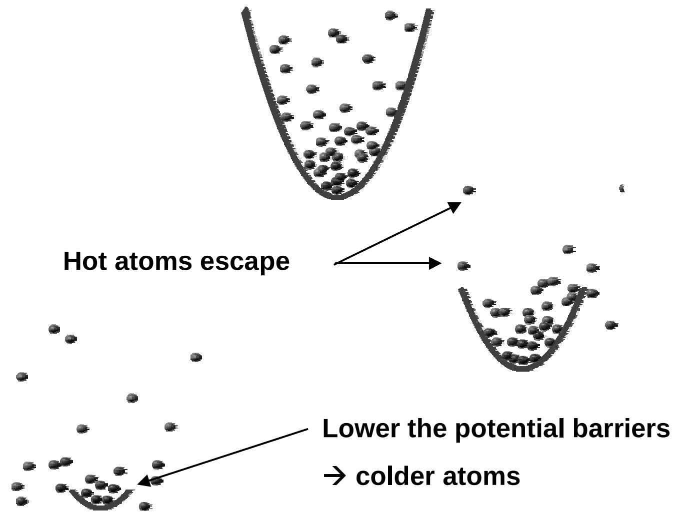
Laser cooling: the ultimate

- Laser cooling reaches micro-Kelvin temperatures
- Evaporative cooling (like air conditioning!) reaches nano-Kelvin
- Atomic momentum then very small, hence wavelength large:

$$p = \frac{h}{\lambda} \quad \text{so} \quad \lambda = \frac{h}{p}$$

- Cold atoms have macroscopic wavelike characteristics
- Wavelength greater than atomic separation...
  - → Bose-Einstein condensation (BEC)
  - → atoms condense into common quantum state
  - → basis for "atom lasers", i.e. coherent atoms

Colder and colder: evaporative cooling



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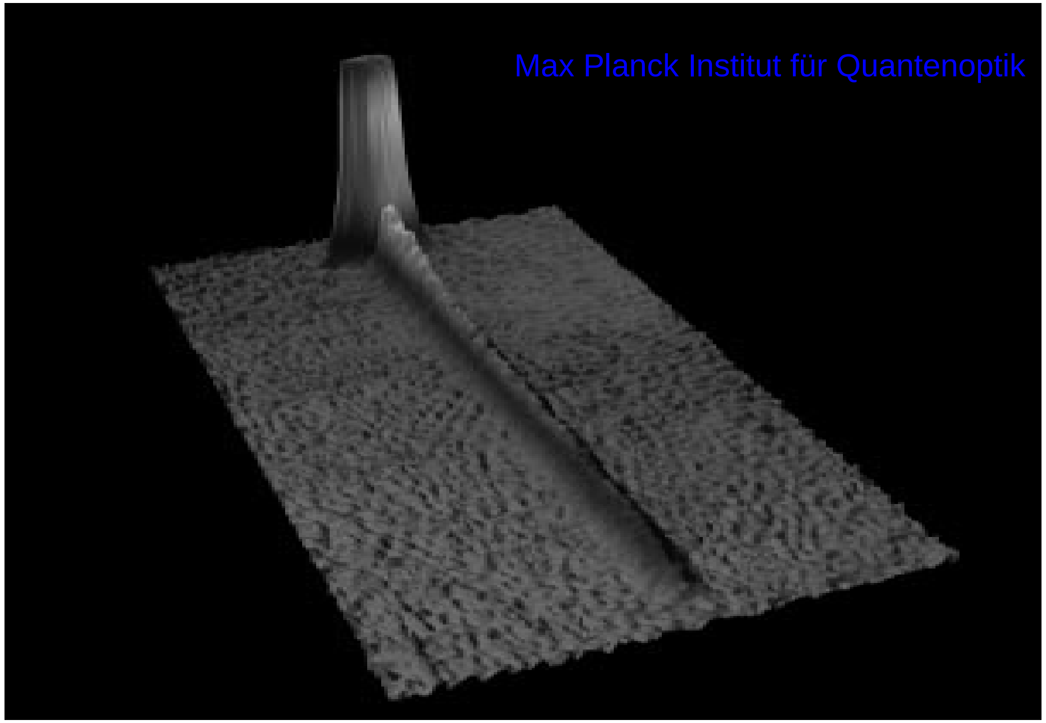


Atom optics

- Treat light as particles (photons)
- Optics is all about controlling light, i.e. photons
- Change particles: electron optics, neutron optics, atom optics
- Advantages? YES!
  - Heavy, therefore wavelength small, therefore nano-focus
- How do we control atoms? They are:
  - large
  - massive
  - neutral
- Use static electromagnetic fields, or **near-resonant lasers**

Dipole force

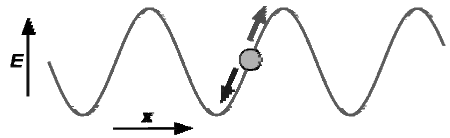
- Tune laser close to atomic resonance
- Atoms become dipoles
- Feel force due to electric part of eletromagnetic laser field

Red detuning: in phase

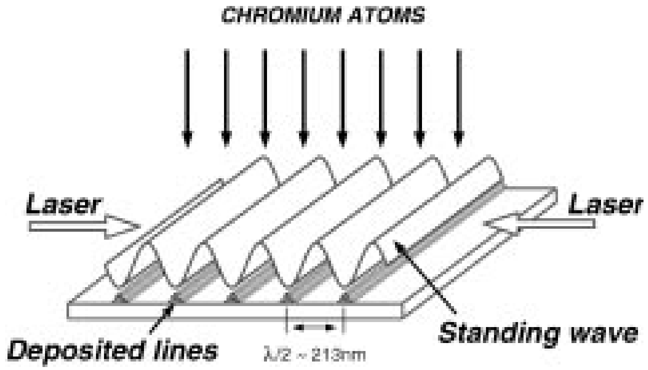
force towards high intensity regions

Blue detuning: anti-phase

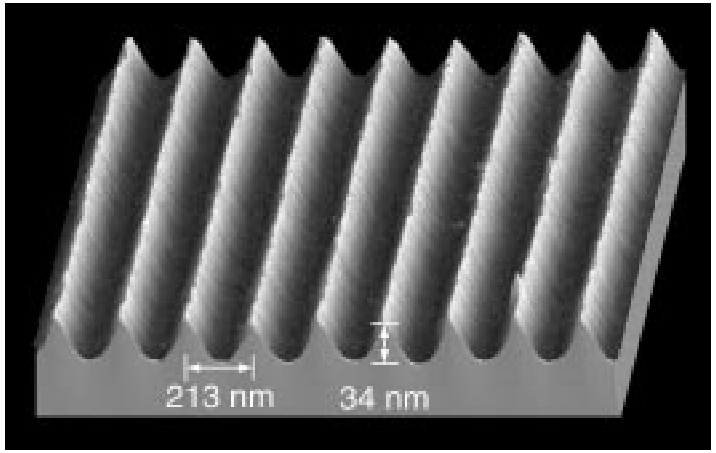
force towards low intensity regions

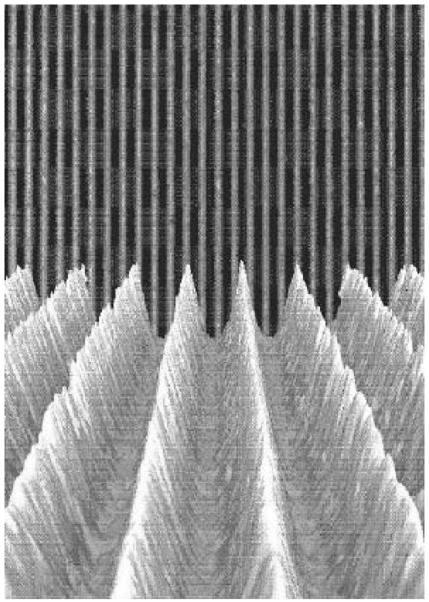


Nanofocusing atoms



Nanofocusing atoms

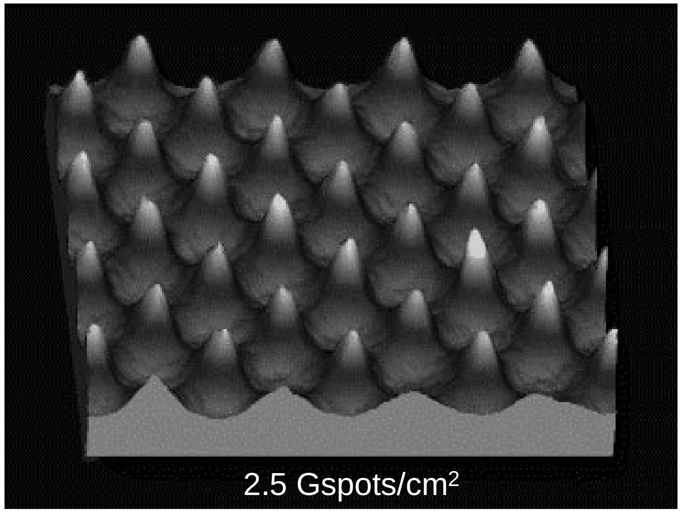




- Blue backdrop shows large-range regularity
- Perspective shows detailed view of chromium lines
- Spacing 212.78nm
- Width ~65nm: now down to ~20nm
- Height ~30nm, 100nm demonstrated

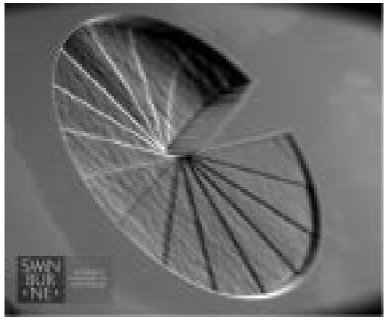
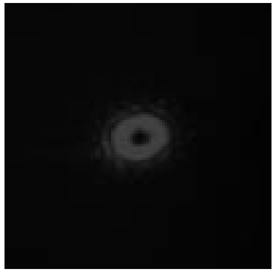
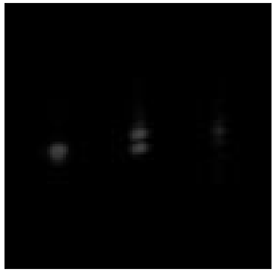
NIST United States Department of Commerce
National Institute of Standards & Technology

Two orthogonal standing waves

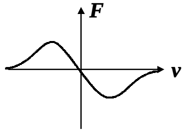


Arbitrary patterns?

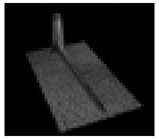
- Atoms pushed along gradients in light intensity
- Shape laser field appropriately to get complex patterns
- Use *computer generated holograms (CGH)*
- CGH converts normal laser into complex shape

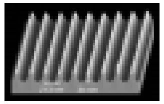
Summary



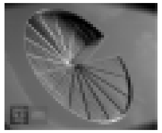
Photon momentum: laser cooling



Wavelike particles: atom lasers

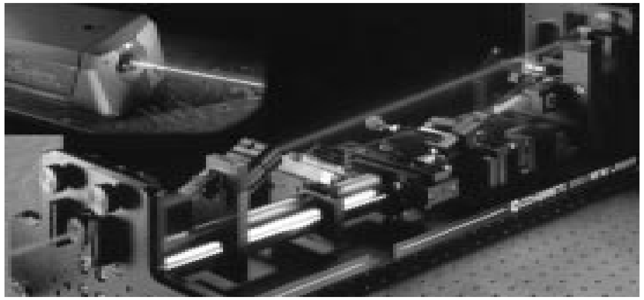


Optics with atoms: nanofocusing



Light fields from holograms

Single frequency laser: $350,000



- **Up to 2 watts CW**
- **Linewidth 500kHz**
- **Tuneable from 400nm to 1100nm**
- **Uses 100kW electrical input ($15 per hour!)**
- **Cost $350,000**

Single frequency laser: $5000

- **50 milliwatts CW**
- **Linewidth 1MHz**
- **Tuneable from 770nm to 790nm**
  (further with different diodes)
- **Uses a few watts**
- **Cost $5,000**