Paths of Discovery
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OPTICAL METHODS. A SIMPLE WAY TO INTERROGATE AND TO MANIPULATE ATOMS[1]

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OPTICAL METHODS

By letting atoms interact with resonant light, one can
- prepare atoms in interesting states
- detect their presence in these states
- control their various degrees of freedom: spin, position, velocity.

This opens new possibilities, provides new situations, allowing one to explore new fields of research.

Good examples for understanding
- how basic research is making progress
- how important applications emerge, most of the time in an unexpected way, from this progress.

A FEW CHARACTERISTICS OF ATOMIC STATES

1. Atoms have an internal angular momentum J 

They are like 'spinning tops'.

The projection J_z of J along the z-axis is quantized

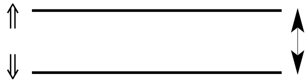
$J_z = M\hbar$ $\hbar = h/2\pi$ h: Planck constant

M: magnetic quantum number, integer of half-integer

For example, for a 'spin 1/2' atom, two possible values of M:

$M = +1/2$ Spin up ⇑ $M = -1/2$ Spin down ⇓

In a static magnetic field B, the 2 spin states have opposite magnetic energies proportional to B



Energy splitting ΔE proportional to B

$\Delta E = h\nu_z$

Magnetic resonance: transitions between the 2 spin states induced by a radiofrequency wave with frequency ν_z.

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[1] The text below is a transcription of the slides presented during the Symposium.

2. Atoms have a linear momentum P
   $P = mv$ m: mass of the atom v: velocity

A FEW CHARACTERISTICS OF PHOTONS

Photons are the light quanta associated with a light beam.

1. Photons have an angular momentum J
   J_z depends on the light polarization.
   Right circular polarization (σ_+) relative to the z-axis: $J_z = +\hbar$
   Left circular polarization (σ_-) relative to the z-axis: $J_z = -\hbar$
   Linear polarization (π) parallel to the z-axis: $J_z = 0$

2. Photons have a linear momentum P
   $P = h\nu/c$ ν: frequency of light c: velocity of light

BASIC CONSERVATION LAWS

The total angular momentum and the total linear momentum of the atom + photon system are conserved when the atom absorbs or emits a photon.

One can thus transfer angular and linear momentum from photons to atoms, which gives the possibility.

- to polarize the atoms, by preparing them in a given spin state
- to detect (through the polarization of the emitted or absorbed light) in what spin state they are
- to change their velocity.

Using conservation laws in atom-photon interactions for

- manipulating the angular momentum of atoms
  Optical pumping
- reducing their velocity
  Laser cooling and trapping

OPTICAL PUMPING

At room temperatures and in low magnetic fields the various atomic spin states are nearly equally populated. Very weak spin polarization.

By transferring angular momentum from polarized photons to atoms, one can achieve large spin polarization and easily detect magnetic resonance signals (due to a tranfer between 2 unequally populated spin states induced by a resonant RF field) in dilute gaseous atomic media

High sensitivity High resolution

Examples of new investigations stimulated by these methods

- multiple photon transitions
- light shifts
- identification of relaxation mechanisms.

A. Kastler

J. Brossel

RADIATIVE FORCES

In a fluorescence cycle (absorption of one photon followed by the spontaneous emission of a photon), the velocity change of the atom due to the transfer of linear momentum of the absorbed photon is equal to $\delta v = h\nu/mc$, on the order of 10^{-2} m/s. The duration of a cycle is limited by the time τ spent by the atom in the excited state before falling back to the ground state by spontaneous emission (radiative lifetime of the order of 10^{-8} s). In a resonant laser beam, the atom can undergo $1/\tau = 10^8$ cycles/s. The velocity change per second, i.e. the acceleration or the deceleration of the atom, can thus be on the order of

$$10^{-2} \times 10^8 \,\mathrm{m/s^2} = 10^6 \,\mathrm{m/s^2} = 10^5 g$$

An atom in a resonant laser beam thus feels huge radiative forces which can be used to reduce its velocity (cooling) and to confine it in a small spatial zone (trapping).

ULTRACOLD ATOMS

Samples of about 10^8 atoms with temperatures on the order of a few 10^{-6} K and with velocities on the order of 1 cm/s can now be currently obtained. At room temperatures ($T = 300\,K$), atomic velocities are on the order of 1 km/s.

Why are ultracold atoms interesting?

– Low velocities provide long interaction times and consequently allow very precise measurements.

High resolution spectroscopy Frequency standards

– Low velocities provide large de Broglie wavelengths (proportional to 1/v) and thus make it easier to observe the wave nature of atomic motion

– Interference between de Broglie waves

– Bose Einstein condensation: a macroscopic number of atoms with the same wave function.

EXAMPLES OF APPLICATIONS

– Magnetometers and masers with optically pumped atoms

– MRI of the lung with optically pumped He^3 atoms

– Atomic clocks with ultracold atoms reaching a relative frequency stability and an accuracy of a few 10^{-16}

– Atom lithography

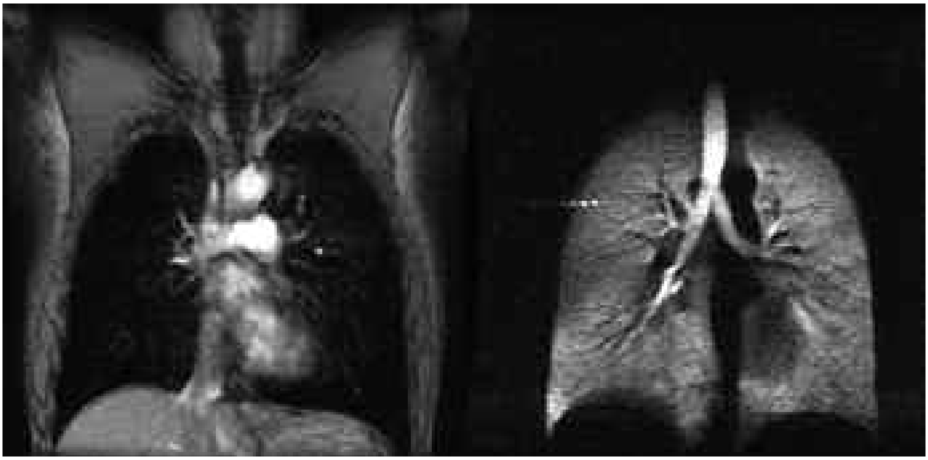
– Atomic gradiometers and gyrometers with de Broglie waves

– Atom lasers: coherent beams of atoms de Broglie waves extracted from a Bose Einstein condensate

– Quantum information using a Bose Einstein condensate trapped in an optical lattice.

Most of these applications were not planned in advance and introduce discontinuous changes in the technology.

MRI IMAGES OF THE HUMAN CHEST



Proton-MRI ^{3}He-MRI

G.A. Johnson, L. Hedlund, J. MacFall, Physics World, November 1998 and references therein.

CONCLUSION