Trapping Neutral Atoms with Electromagnetic Fields

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Neutral atoms have now been trapped in inhomogeneous magnetic fields or laser fields. Densities up to $10^{12}$ atoms/cm$^3$ have been obtained, with storage times of several minutes. The very low temperature of these trapped atoms (below one millikelvin) opens the way to new physical phenomena.

Controlling the motion of charged particles by electromagnetic fields is now a well mastered technique. Its applications range from particle accelerators to the trapping of a single ion, and include the familiar cathode ray tube. The situation is much different for neutral species, as the means of influencing them are so sparse. For example, until 1985, the only way to confine a neutral atom was in a cell. However, during these last three years, several atomic traps have been demonstrated, based either on the action of an inhomogeneous static magnetic field (magnetic trap) or of a laser field (light trap). Here, we briefly review these two kinds of trap, with the aim of giving an overview of the potentialities offered by these new devices.

Neutral atom traps should have applications in various branches of physics. Spectroscopists and atomic clock physicists may find in the very slow atoms emerging from a trap a way to improve the precision of their measurements. Moreover these traps could lead to the observation of collective quantum effects such as Bose Einstein condensation for spin polarized hydrogen. One avoids in these traps the problem of molecular recombination of atomic hydrogen on the walls of the cell.

A general characteristic of neutral atom traps is their very shallow depth, which is inherent in the physical principle involved in the confinement: to confine atoms near a given point, the atomic energy levels are curved so that the energy of the atomic level occupied by the atom is minimal at the centre of the trap. The inhomogeneous shift of the energy level is produced either by a magnetic field (Zeeman shift) or by a laser field (light shift). In the first case, the energy depth of the trap $U_M$ is given by $U_M = \mu_B \Delta B$ where $\mu_B$ is the Bohr magneton, and $\Delta B$ the difference between the maximal and minimal values of the magnetic field. For a typical $\Delta B$ of 1 T, one gets a depth $U_M \approx 0.7$ K. For a laser field, the light shift of the energy levels involved in a transition, quasi-resonant with the laser, can be estimated to be $U_L \approx \Delta E I$, where $\Delta$ is the electric dipole moment of the transition, and $I$ the laser electric field. A CW laser of 1 W power, focussed on 10 µm, produces in sodium atoms a depth $U_L \approx 2$ K.

Because of these very small depths, the filling and the stabilization of the traps are quite difficult. One needs very slow atoms, whose temperature is smaller than the depth of the trap. Such slow atoms can either be produced by the usual cryogenic techniques, or by the recently-developed laser deceleration and cooling techniques [1–3]. Once trapped, the atoms can be kept in the trap only if the various heating mechanisms — collisions with the background gas, heating inherent to laser trapping techniques — can be overcome. One thus needs a very good vacuum (pressure $< 10^{-9}$ Torr) and possibly an additional cooling mechanism.

Magnetic Traps

The magnetic trap was the first device to be used for confining neutral atomic size particles. In 1977, K. Kügler, W. Paul and U. Tränk kept neutrons in a toroidal superconducting magnet ring for 20 minutes [4]. In this experiment, realized at the LL Grenoble, the azimuthal velocity of the neutrons in the storage ring was in the range 7 – 20 m/s, and the transverse velocity was lower than 4 m/s. Neutrons were injected along a radius of the ring, and were deflected in the ring by a totally reflecting mirror system. This mirror system was then promptly taken out of the ring before the neutrons had completed their first turn.

A naïve observer would have thought that a magnetic trap for neutral atoms would have been realized immediately after this. The magnetic moment of an atom is indeed two to three orders of magnitude larger than the magnetic moment of a neutron, at least if the atom has a non zero electronic angular momentum in its ground state. The magnetic force in a given magnetic field is then increased by the same factor. However, eight more years were to pass before the first successful magnetic trapping of neutral atoms.

The problems are indeed very different for atoms and neutrons. First, one needs to find a source of slow atoms. Up to recent times, this was not easy as in a normal thermal atomic beam, there is a deficiency of slow atoms with respect to the Maxwell-Boltzmann distribution. Laser deceleration of atomic beams (see Fig. 1) has thus been a crucial step to the production of trappable slow atoms. Second, one has to find a way of introducing the atoms into the magnetic trap, equivalent to the removal of the mirror system used for neutrons. Here also, laser cooling constitutes an elegant way of extracting a sufficient amount of kinetic atomic energy.

The first magnetic trap for neutral atoms (sodium) was achieved by W. Phillips, H. Metcalf and co-workers at NBS Washington [5]. The quadrupole trap (initially proposed by W. Paul) is made of two parallel coils with current in opposite directions. Atoms with a positive magnetic quantum number along the axis, defined by the local magnetic field ("low field seekers"), are then attracted towards the centre of the trap, where the field is zero. The maximum field in the trap is 250 Gauss leading to a maximum trappable velocity of 3.5 m/s. The authors have checked that for such slow atoms, the magnetic moment follows the magnetic field adiabatically: the probability for non adiabatic or Majorana transitions, which would reverse the magnetic moment, is very small.

To fill the trap, the current in the coils is first set to zero and atoms are deceler-
Optical Traps

Like magnetic traps, optical confinement of neutral atoms usually relies on the curving of the atomic energy levels. For stable trapping, a potential with a local minimum at the centre of the trap is necessary. Intense laser beams provide such a potential, which can be written near a resonant transition [2]:

$$U_0 (r) = \frac{h}{2 \Delta} \log \left( 1 + \frac{s(r)}{b} \right)$$

where $$\Delta = \omega - \omega_0$$ is the detuning between the laser ($$\omega_0$$) and atomic ($$\omega$$) frequencies, and $$s$$ is the saturation parameter:

$$s(r) = \frac{\omega_0^2}{\Delta^2} \left( \frac{r}{\Delta^2 + r^2} \right)$$

In eq. 2, $$\omega_0 (r)$$ is the local Rabi frequency at point $$r$$, proportional to the atomic dipole $$d$$ and to the laser electric field $$E(r)$$:

$$\omega_0 (r) = d E(r)/\hbar$$

$$\tau$$ is the spontaneous lifetime of the excited state of the atomic transition.

The force $$\nabla U_0$$ deriving from the potential $$U_0 (r)$$, is the so-called dipole force. Depending on the sign of the detuning, this force attracts the atoms towards the high intensity regions (for $$\Delta < 0$$), or repels the atoms from these regions (for $$\Delta > 0$$).

In this experiment, about 500 sodium atoms were trapped in a volume of 1000 μm³ for a few seconds. The 220 mW dye laser is focussed to a 10 μm waist radius, and it is tuned to a frequency of 650 GHz below the sodium D₂ line. This leads to an optical well depth of 5 mK.

**Fig. 2** — The first realized laser trap confines the atoms in the high intensity region located near the focal plane of a strongly focussed laser beam. In this experiment, the detuning of the laser $$\omega_0 - \omega$$ was negative, and sufficiently large so that one could neglect the scattering force (see Fig. 1) compared to the dipole force creating the trapping potential. Additional laser cooling was also applied, to compensate for the heating due to the fluctuations of radiative forces.
fluctuations originate from the random nature of the optical trap: the dipole force fluctuates around its average value. These fluctuations make the atom quickly leak out of the shallow trap. For this reason, the trapping force is rather amusing since it illustrates very well the non-straight-forward evolution of the physical concepts investigated in Paris.

Up to now, we have only been considering light traps based on the potential (1) arising from the dipole force. This force can be shown to result from the in-phase component of the laser-induced atomic dipole moment. Another kind of force, proportional to the quadrature component of the induced dipole and to the local Poynting vector of the laser wave, the scattering force, has been observed using a very sensitive spectroscopic technique based on the atomic level light shifts induced by the intense standing wave. The atomic spatial distribution appears to be strongly peaked around the nodes, with a half width at half maximum that is \( \Delta x = 80 \text{ nm} \) for a detuning \( \Delta / \lambda \approx 1/10 \). The extension to three dimensions of this technique using laser decelerated and laser cooled atoms is now being investigated in Paris.

Fortunately, many schemes were then proposed to circumvent the Optical Earnshaw Theorem. They use for instance time dependent laser intensity, in analogy with radio frequency traps for ions, or optical pumping mechanisms preventing a strict proportionality between the force and the Poynting vector. As an example, Fig. 4 shows a scheme...
interaction potentials which are not well known for the moment.

- Is it possible to cool further?

Laser cooling has proved to be very efficient in most of these trapping experiments and numerous proposals have been made to enter the nanoKelvin — microKelvin regime. An obvious way is to use longer lived excited states since the radiative cooling limiting temperature is proportional to the upper state natural line width. Also much less energetic photons like radio frequency photons may be used. Most of the proposed methods will take advantage of the long storage time now allowed by these traps. Achieving temperatures in the microKelvin range will benefit not only the Bose-Einstein condensation "quest". At such temperatures, the atomic De Broglie wavelength becomes very large, typically of the order of optical wavelengths. One can think of doing interferometry with these atoms in a similar way that cold neutrons have been shown to interfere. With such a large De Broglie wavelength, it is also conceivable that cold atoms might bounce elastically on solid surfaces since microscopic surface defects would then be too small to be "seen" by the colliding atom. If this is true, one could imagine storing these cold atoms in a box!

In a different domain, spectroscopists and atomic clock physicists hope to improve the precision of their experiments with laser cooled neutral atoms or ions. With cold particles, the better control of the second order Doppler effect (relativistic time dilation) and the long interaction time should allow a resolution of $10^{-14} - 10^{-15}$ for atomic lines in the visible range. In addition, neutral atoms can be confined to high densities unlike ions for which the density is limited by space charge effects. Using such narrow atomic transitions, one hopes to lock lasers with a relative stability in the range $\Delta v/v \cong 10^{-15} - 10^{-17}$. These clocks would in turn enable some very fundamental tests in physics.

In conclusion, it appears that the physics involved in the trapping of neutral atoms is now rather well understood. Both magnetic and light traps work in a predictable and reproducible way. On the other hand, these recent techniques open several new fields in domains as different as statistical physics, molecular physics, atomic interferometry and metrology. Judging from the two dozens of laboratories working now in the field of neutral atom cooling and trapping, we

![Diagram](image-url)
expect exciting new developments in the near future.

REFERENCES

Chemical Physics

The Board of the Chemical Physics Section of the Atomic and Molecular Physics Division have decided to coopt the following:
E.A.G. Armour, University, Nottingham
E. Kochanski, University, Strasbourg
A. Varandas, University, Coimbra

A General Assembly of the Chemical Physics Section will be held during the ECAMP III Conference held this year from 6-9 April in Budapest. At the micro­phone A.R. Mackintosh, Chairman of the Selection Committee and to his right: W. Buckel, retiring President of EPS, N. Kroo, Chairman of the Conference, and the two award winners, K. Alex Müller and J. Georg Bednorz.

Presentation of the 1988 Hewlett-Packard Europhysics Prize during the 8th EPS General Condensed Matter Physics Conference held this year from 6-9 April in Budapest. At the micro­phone A.R. Mackintosh, Chairman of the Selection Committee and to his right: W. Buckel, retiring President of EPS, N. Kroo, Chairman of the Conference, and the two award winners, K. Alex Müller and J. Georg Bednorz.

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Quantum Electronics

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A full list of the Board will appear in the Directory that will be published in the June issue of Europhysics News.

The Chairman, H. Walther and the Secretary, F.R. Aussenegg announce that the Division will be holding a Business Session on Tuesday, 13 September 1988 in conjunction with EQEC '88 at Hannover. Members please note.