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LIGHT AND MATTER

CLAUDE COHEN-TANNOUDJI

1. INTRODUCTION

Light has always been a fascinating subject for physicists as well as for scientists in general. What is the nature of light? How is it produced? How does it interact with matter? Is it possible to control these interactions? These are a few examples of problems which have always attracted a great deal of attention and which have been at the origin of important advances in our scientific understanding of natural phenomena.

The purpose of this lecture is to briefly review the evolution of our ideas on light and matter and to describe recent developments where light is used as a tool for acting on atoms and for cooling them at very low temperatures, in the microkelvin and even in the nanokelvin range. We will also mention a few possible applications of such ultracold atoms.

We begin (§2) with a brief review of the modern description of light and atoms and of the basic interaction processes between these two systems. We then show in §3 how it is possible to use the recoil of an atom absorbing or emitting light for controlling its velocity and for reducing the temperature of an ensemble of atoms, a method which is now called "laser cooling". We finally describe in §4 a few applications of ultracold atoms to various research fields, like atomic clocks, atom interferometry and Bose-Einstein condensation.

It is impossible here to give an exhaustive bibliography on this research field. For further information, however, three references are given at the end of this paper, which may interest the reader. These are in fact the three 1997 Nobel lectures in Physics.

2. EVOLUTION OF OUR IDEAS ON LIGHT AND ATOMS

2.1 *Light*

Light was for centuries successively considered as a stream of tiny particles or as a wave. Now, we know that light is both an ensemble of particles and a wave.

First of all, light is an electromagnetic wave, consisting of an electric field and a magnetic field oscillating at a frequency ν and propagating in vacuum at a considerable speed $c = 3 \times 10^8$ m/s. Like any other wave, light gives rise to interference phenomena. If one superposes two separate waves with equal amplitudes, in some points, they vibrate in phase meaning constructive interference whereas, in some other points, they vibrate in opposite phase meaning destructive interference. This gives rise on a screen to a succession of bright and dark areas also called “interference fringes”.

The colour of the light depends on its frequency ν. The frequency spectrum of electromagnetic waves extends from radio-frequency waves to X and gamma rays. Visible light only covers a very small part of this spectral field. It is possible to analyse the spectral content of a light beam by using so called dispersive instruments subjecting light rays to a frequency dependent deviation. For example, if one directs a ray of sunlight through a prism, its frequency components are deviated in different ways. They spread out into different colours displaying what is called “a spectrum”.

At the beginning of this century, after Planck and Einstein’s work, it was agreed that light was not only a wave but also an assembly of particles called “photons”. More precisely, a light-wave with frequency ν is associated with particles, photons, with energy $E = h\nu$ proportional to ν and with momentum $p = h\nu/c$ also proportional to ν. In these equations, c is the speed of light, ν is the frequency of light and h a constant introduced in physics by Planck just a hundred years ago.

The main idea that emerged during the last century is the“ wave-particle duality”. The physical phenomena being observed cannot be understood by considering only the wave nature or the particle nature of light. These two aspects of light are essential and inseparable.

2.2 *Atoms*

Atoms are planetary systems identical to the solar system. They consist of positively charged particles, “electrons”, with a small mass, orbit-

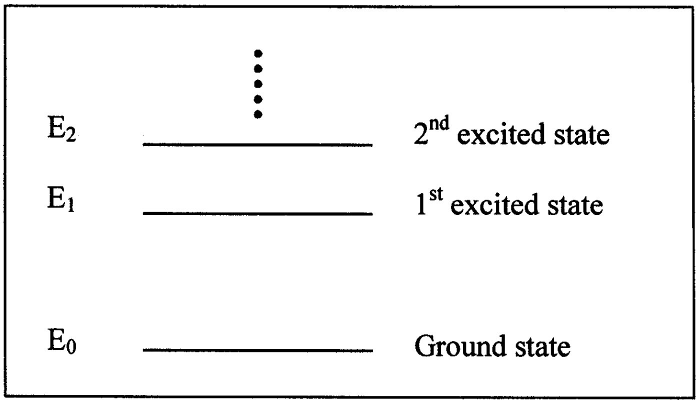

Figure 1: Energy levels of an atom. Each horizontal line has an altitude proportional to the energy of the corresponding level.

ing round a positively charged particle with a higher mass, called the "nucleus".

Physicists soon realized that classical mechanics was not appropriate for understanding the motion of the electrons and that it led to nonsense. So, they invented "quantum mechanics" which gives the appropriate description of the dynamics of the microscopic world. This was a true conceptual revolution as important as the revolution of special and general relativity. One of the main predictions of quantum mechanics is the quantization of physical quantities, and in particular the quantization of energy.

In the rest frame of the atom (frame where the center of mass of the atom, which practically coincides with the nucleus because the nucleus is much heavier than the electrons, is at rest), it appears that the energies of the electrons can only take discrete values, labelled by "quantum numbers". Figure 1 pictures, for example, three different atomic energy levels: the lowest energy level called ground state, the first excited level, the second excited level.

2.3 *Atom-Photon interactions*

How do atoms interact with light?

Emission and absorption of light by atoms.

An atom initially in a state E_b can jump from this level to a lower level

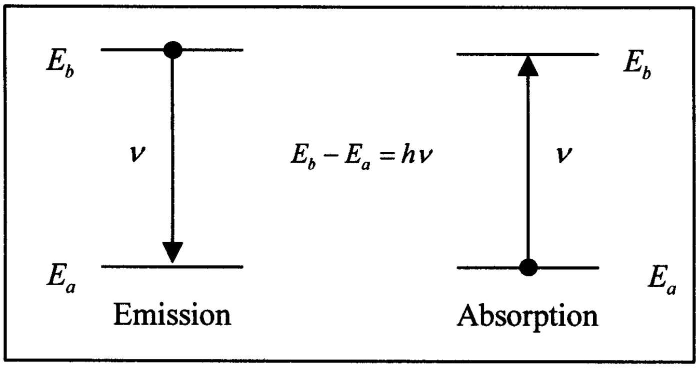

Figure 2: Elementary processes of emission (left part of the figure) and absorption (right part) of a photon by an atom.

E_a emitting light or more exactly emitting a single photon of energy $h\nu$ (Fig. 2). In other words, the energy lost by the atom passing from level E_b to level E_a is taken away by the photon of energy $h\nu$.

The relation between the energy lost by the atom and the frequency of the light being emitted is nothing but the expression of the conservation of energy.

The reverse process exists too, of course: the absorption of light by an atom. An atom initially in a lower state E_a can jump to an upper state E_b while gaining the energy of the absorbed photon. In other words, the atom absorbs a photon and the energy of the absorbed photon allows the atom to go from E_a to E_b. It thus clearly appears that the quantization of atomic energy implies the discrete character of the spectrum of frequencies emitted or absorbed by an atom.

Light: a main source of information on the structure of atoms

The only possible frequencies emitted by an atom are those corresponding to the energy differences between pairs of energy levels of this atom. This result is very important. It means that light is an essential source of information on the atomic world. Indeed, by measuring the frequencies emitted or absorbed by an atom, it is possible to determine the differences $E_a - E_b$ and thus to obtain the energy diagram of this atom. This is what is called “spectroscopy”. Each atom has its own spectrum. The frequencies emitted by a hydrogen atom are different from those emitted by a sodium or a rubidium or a potassium atom. The spectrum of frequencies emitted by an atom is in some way the finger print of this atom, or using more recent terms, its "genetic fingerprint". It is possible to identify an atom by observing the frequencies being emitted by this atom. In other words, it is possible to collect information on the constituents of different types of media by observing the light originating from these media. In astrophysics, for example, spectroscopy allows scientists to attain a deeper level of understanding of the structure of stellar and planetary atmospheres and to identify molecules within interstellar space. The observation of the frequency shifts of the radiation emitted by astrophysical objects allows a better knowledge of the velocity of these objects and makes it possible to measure with higher precision the expansion velocity of the universe. The observation of the emission or absorption spectra is also important for studying media such as plasmas or flames and for analysing their constituents *in situ*.

Radiative lifetime

Let us consider an isolated atom in an excited state E_b. Experiment shows that, very shortly, the atom spontaneously falls down to a lower state E_a. This period of time, at the end of which the emission process occurs, is called "radiative lifetime" t_R of the excited state E_b. It thus appears that an atom cannot remain in the excited state forever. Radiative lifetimes, which vary from one atom to another, are typically on the order of 10^{-8} s , that is 10 billionth of a second.

3. Principles of laser cooling

To cool an atom, one must reduce its velocity (more precisely, the dispersion of this velocity around its mean value). In laser cooling methods, this is achieved by radiative forces exerted by the laser beams on the atoms. We first analyse the origin of these radiative forces.

3.1 *Recoil of an atom emitting or absorbing a photon.*

Conservation of linear momentum is a basic law in physics. Consider an excited atom, initially at rest, in an upper state E_b, and suppose that at a certain time, this atom emits a photon with momentum $h\nu/c$. In the initial state, the total momentum of the system is equal to zero. In the final state,

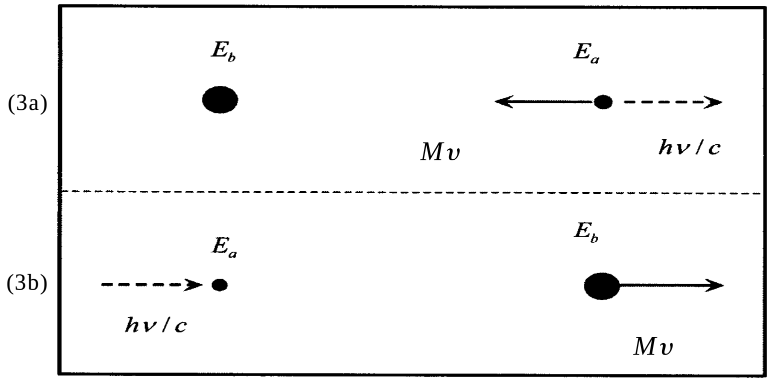

Figure 3: Recoil of an atom emitting (Fig. 3a) or absorbing (Fig. 3b) a photon.

when the photon moves away with momentum $h\nu/c$, the atom which has emitted this photon must recoil with the opposite momentum $Mv=-h\nu/c$ because of the conservation of momentum (Fig. 3a). The same phenomenon is observed, for example, when a gun fires a shell. The gun recoils and this recoil is due to the momentum transferred by the shell. The recoil velocity of the atom is given by $v_{\text{rec}}=h\nu/Mc$.

This recoil phenomenon also occurs when an atom absorbs a photon. Consider an atom initially at rest in the ground state E_a and suppose that a photon is being sent on this atom. What happens then? The atom absorbs the photon, jumps to the excited state and then recoils with the same recoil velocity $h\nu/Mc$ (Fig. 3b). Likewise, when a bullet is being shot on a target, the target recoils because of the momentum transferred by the projectile.

We also know that the absorption of a photon which brings the atom, initially at rest, to the excited state, is necessarily followed by an emission since the atom cannot remain excited forever. Therefore, after a very short time corresponding to its radiative lifetime, the atom falls down while emitting spontaneously a photon. In such an absorption-emission cycle, the atom absorbs a photon, it recoils and then emits a photon, the probabilities of the photon being emitted in one direction or in the opposite one being equal so that the momentum lost during emission averages out to zero. It follows that, in an absorption-emission cycle, the average variation of the atomic velocity is only related to the absorption process. Its value is $v_{\text{rec}}=h\nu/Mc$. This result is essential for the discussion of the next section.

3.2 *Atom in a laser beam*

We try now to understand what happens when the atom interacts, not with a single incident photon, but with a resonant laser beam. The atom absorbs a photon, jumps to the excited state, falls back to the ground state while emitting a photon, then absorbs a second photon, jumps to the excited state, falls back again while emitting another photon, then absorbs a third photon and so on. The atom thus performs a sequence of absorption-emission cycles. During each absorption-emission cycle, the velocity of the atom changes on the average by an amount $v_{rec} = h\nu / Mc$. As the average radiative lifetime of an atom in the excited state is on the order of 10^{-8} *s*, about 10^8 (one hundred million!) absorption-emission cycles can take place per second. After each of these cycles, the velocity of the atom changes by an amount $h\nu/Mc$. For a sodium atom, one finds that $v_{rec} \simeq 3$cm/s, whereas for a cesium atom $v_{rec} \simeq 3$mm/s. These are very low velocities compared to those of the molecules within the air surrounding us, which are on the order of 1 km/s. This explains why the velocity changes due to recoil effects have been most of the time neglected. In fact, the situation proves to be radically different for an atom in a laser beam. Absorption-emission cycles are then repeated 100 millions times per second, causing a velocity change per second which amounts to 100 millions times the recoil velocity, corresponding to an acceleration or a deceleration γ on the order of 10^6 m/s^2. Let us compare, for example, with what happens in our daily life: an object, when falling, is subjected to an acceleration g of 10 m/s^2 because of gravity. A sodium atom, when irradiated by a laser beam undergoes an acceleration or a deceleration γ which is 10^5 times higher!

3.3 *Stopping an atomic beam*

This considerable force exerted on atoms by light and resulting from the cumulative effect of a great number of slight recoils, makes it possible to stop an atomic beam. Consider an atomic beam coming out of an oven at a temperature of 300 K or 400 K. It propagates at a speed of the order of 1 km/s. Let us assume that this atomic beam is irradiated by a counter-propagating resonant laser beam. The atoms are then subjected to the radiation pressure force exerted by the laser beam, they slow down, they stop and they can even return in the opposite direction. An atom, with an initial velocity $v_0 = 10^3$ m/s, submitted to a deceleration $\gamma = 10^6$ m/s^2 will be stopped in 10^{-3}s, that is to say in one millisecond. The distance L travelled by this atom before stopping is given by a well-known formula $L=v_0^2/2\gamma$ and is equal to 0.5 m. It is thus possible, in a lab, to stop an atomic beam within a distance of the order of 1m with appropriate laser beams.

One must not forget however that, as atoms decelerate, they get out of resonance because of the Doppler effect. It is thus necessary to modify either the frequency of the laser beam or the frequency of the atoms to maintain the resonance condition and to keep the radiation pressure force at its highest level throughout the whole deceleration process.

Slowing down atoms consists in lowering the average velocity of these atoms. A clear distinction must be made between the global movement of an ensemble of atoms characterized by the mean velocity and the dispersion of velocities around this mean value. In physics, temperature is associated with this velocity spread, *i.e.* with the disordered motion of the atoms. The warmer the temperature of the medium, the higher the velocity dispersion of its constituents. For cooling a system, this velocity spread has to be reduced. How is it possible to cool atoms with laser light?

3.4 *Doppler cooling*

The simplest cooling scheme uses the Doppler effect and was first suggested in the mid seventies by Hansch, Shawlow, Wineland and Dehmelt. The concept is basically simple: the atom is then no longer irradiated by one laser wave but by two counter-propagating laser waves (Fig. 4). These two laser waves have the same intensity and the same frequency ν_L, ν_L being tuned slightly below the atomic frequency ν_A. What happens then? For an atom at rest with zero velocity, there is no Doppler effect (Fig. 4a). The two laser waves have then the same apparent frequency. The forces being exerted have the same value with opposite signs. The two radiation pressure forces coming from each side exactly balance each other and the net force exerted on the atom is equal to zero. For an atom moving to the right with a velocity v, the frequency of the counter-propagating beam seems higher because of the Doppler effect. This apparent frequency, which is thus increased, gets closer to resonance. More photons are absorbed and the force increases. On the other hand, the apparent frequency of the co-propagating wave is reduced because of Doppler effect and gets farther from resonance. Less photons are absorbed and the force decreases. In that case, the two radiation pressure forces no longer balance each other. The force opposite to the atomic velocity finally prevails and the atom is thus submitted to a non-zero net force opposing its velocity. This net force F can

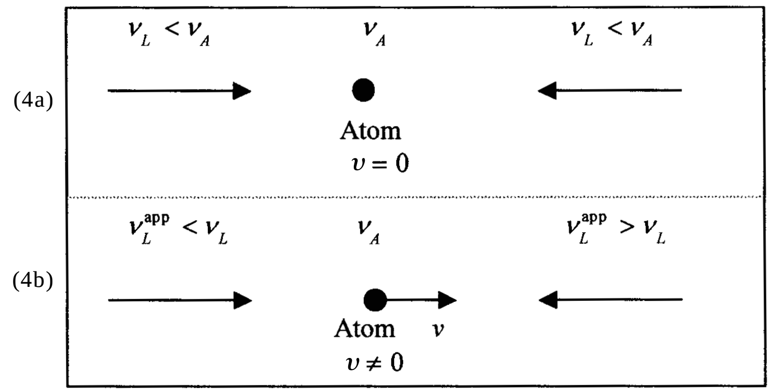

Figure 4: Principle of Doppler laser cooling. For an atom at rest (Fig. 4a), the two radiation pressure forces exactly balance each other. For a moving atom (Fig. 4b), the apparent frequency of the counter-propagating wave increases and gets closer from resonance. It exerts a stronger radiation pressure force on the atom than the co-propagating wave, whose apparent frequency is decreased because of the Doppler effect and gets farther from resonance.

be written for a small velocity v as $F = \alpha v$ where α is a friction coefficient. In other words, an atom moving in such an arrangement of two counter-propagating laser beams encounters a friction force opposing its motion. It finally gets stuck as if it was moving in a sticky medium which has been called "optical molasses" by analogy with honey. The atomic velocity is damped out by this force and tends towards zero.

3.5 *Sisyphus cooling*

By studying theoretically the Doppler laser cooling mechanism, it has been possible to predict the temperatures that may be achieved. These are on the order of a few hundreds of microkelvin, *i.e.* on the order of 10^{-4} K. These are very low temperatures compared to room temperatures which are on the order of 300 K. In fact, when, at the end of the eighties, the measurements became precise enough, it turned out, and that was a real surprise, that the temperatures in optical molasses were 100 times lower than expected, meaning that there were other mechanisms at work. We have, with my colleague Jean Dalibard, identified and studied in detail one of these mechanisms: Sisyphus cooling.

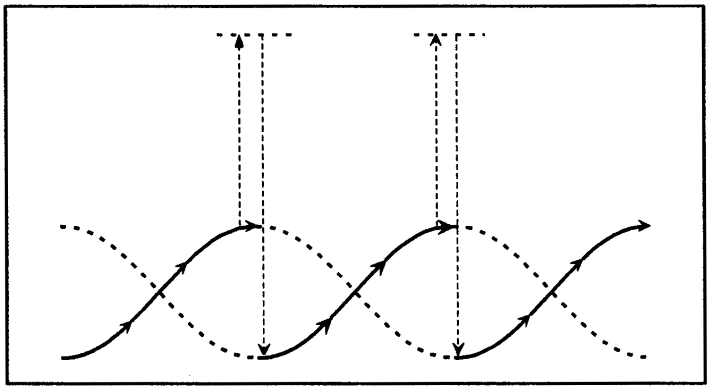

Figure 5: Sisyphus cooling.

Without exploring all the details of such a mechanism, let us try now to describe briefly how it works. Laser cooling experiments use pairs of counter-propagating waves. These waves interfere and produce a standing wave with spatially modulated intensity and polarization. One can also demonstrate that atomic energy sublevels are slightly shifted by light, by an amount proportional to light intensity and related to light polarisation. Moreover, in the ground state, there are in general several energy sublevels, corresponding to different quantized values of the projection of the atomic angular momentum along a given axis. The atom can be considered as a small spinning top. In the simplest case (spin 2), there are two spin states: spin up and spin down. Such energy levels, with spatially modulated light-shifts, are represented in Fig. 5. The moving atom runs up and down potential hills and valleys. This landscape changes according to the different atomic sublevels. Consider an atom moving to the right, initially at the bottom of a potential valley in a specific sublevel, and then climbing up the potential hill. When it reaches the top of the hill, it has a high probability to absorb and emit a photon and thus to move to the other energy sublevel, being then put back at the bottom of the next valley. This scenario can repeat itself, the atom climbs up another potential hill and, before reaching the top, is transferred again to the other sublevel and so on, again and again...Like the hero of the Greek mythology, the atom is doomed to a continual climbing of hills, losing kinetic energy as it climbs. After a while, the atom is so exhausted that he can no more run up hills and finally gets trapped in a well. Theoretical studies combined with experimental results have confirmed the validity of this picture and shown that it is possible in that way to reach the microkelvin range, *i.e.* a temperature of 10^{-6} K. We have also finalized other methods in the lab leading even further, to the nanokelvin range, *i.e.* 10^{-9} K, one billionth of Kelvin...

At such temperatures, atomic velocities are on the order of cm/s or even mm/s whereas, at an usual room temperature, they are on the order of km/s. These cooling methods have made it possible to slow down considerably the disordered motions of atoms and almost to stop them. Let us mention too, without going into details, that atoms can be confined in small spatial regions, called traps, by using laser polarization gradients or magnetic field gradients.

4. A few applications of ultracold atoms

4.1 *Atomic clocks*

Ultracold atoms move very slowly. For example, Cesium atoms cooled by Sisyphus cooling have a velocity on the order of 1 cm/s. This allows them to spend a longer time T in an observation zone where a microwave field induces resonant transitions between two sublevels g_1 and g_2 of the ground state which are used to define the unit of time: the second. By convention, the second corresponds to 9 192 631 770 periods of oscillations $1/\nu_0$, where ν_0 is the frequency of the transition connecting g_1 and g_2. The important point here is that the width $\Delta\nu$ of the microwave resonance line whose frequency is used to define the unit of time is inversely proportional to the observation time T. Long observation times give rise to narrow atomic resonance lines allowing a very precise determination of the atomic frequency ν_0. The stability and accuracy of atomic clocks can thus be considerably improved by using ultracold atoms.

In usual atomic clocks, atoms from a thermal cesium beam. cross two microwave cavities fed by the same oscillator. The average velocity of the atoms is several hundred m/s, the distance between the two cavities is on the order of 1 m. The microwave resonance between g_1 and g_2 is monitored and is used to lock the frequency of the oscillator to the center of the atomic line. The narrower the resonance line, the more stable the atomic clock. In fact, the microwave resonance line exhibits Ramsey interference fringes whose width $\Delta\nu$ is determined by the time of flight T of the atoms from one cavity to another. For the longest devices, T, which can be considered as the observation time, can reach 10 ms, leading to values of $\Delta\nu$ on the order of 100 Hz.

Much narrower Ramsey fringes, with sub-Hertz line-widths can be obtained in the so-called “Zacharias atomic fountains”. Atoms are captured in a magneto-optical trap and laser cooled before being launched upwards by a laser pulse through a microwave cavity. Because of gravity they are decelerated, they return and fall back, passing a second time through the cavity. Atoms therefore experience two coherent microwave pulses, when they pass through the cavity, the first time on their way up, the second time on their way down. The time interval between the two pulses can now be on the order of 1s, i.e. about two order of magnitudes longer than with usual clocks. This explains how the stability and accuracy of atomic clocks have been recently improved by two orders of magnitude by using fountains of cold atoms.

To increase the observation time beyond one second, a possible solution consists of building a clock operating in a reduced gravity environment. Tests have been performed with an experimental set-up embarked in a plane making parabolic free flights. These tests have been successful and it is planned now to put such a cold atom clock in the International Space Station around 2005.

Atomic clocks working with ultracold atoms can of course provide an improvement of the Global Positioning System (GPS). They could also be used for basic studies. A first possibility could be to build two fountains clocks, one with Cesium and one with Rubidium, in order to measure with a high accuracy the ratio between the hyperfine frequencies of these two atoms. Because of relativistic corrections, the hyperfine frequency is a function of $Z\alpha$, where α is the fine structure constant and Z is the atomic number. Since Z is not the same for Cesium and Rubidium, the ratio of the two hyperfine frequencies depends on α. By making several measurements of this ratio over long periods of time, one could check cosmological models predicting a variation of α with time. The present upper limit for $\dot{\alpha}/\alpha$ in laboratory tests could be improved by two orders of magnitude. Another interesting test would be to measure with a higher accuracy the gravitational red shift and the gravitational delay of an electromagnetic wave passing near a large mass (Shapiro effect).

4.2 *Atomic interferometry*

Wave-particle duality applies not only to light but also to matter. In 1924, Louis de Broglie introduced the idea that a wave, called since then the de Broglie wave, must be associated with every material particle. For a particle with mass M, the wavelength of this wave, the so-called de Broglie wavelength λ_{dB}, is given by the equation $\lambda_{dB} = h/Mv$, where v is the velocity of the particle. When the velocity decreases, the de Broglie wavelength increases and several effects related to the wave nature of atomic motion become important and easier to observe.

New research fields, like atom optics and atom interferometry, have thus experienced during the last few years a considerable development, extending to atomic de Broglie waves the various experiments which were previously achieved with electromagnetic waves. For example, Young fringes have been observed by releasing a cloud of cold atoms above a screen pierced with two slits. The impact of the atoms on a detection plate is then observed giving a clear evidence of the wave-particle duality. Each atom gives rise to a localized impact on the detection plate. This is the particle aspect. But, at the same time, the spatial distribution of the impacts is not uniform. It exhibits dark and bright fringes which are nothing but the Young fringes of the de Broglie waves associated with the atoms. Each atom is therefore at the same time a particle and a wave, the wave allowing one to get the probability to observe the particle at a given place.

In contrast to light interferometers, atomic wave interferometers are sensitive to gravitational effects which can be measured with a great accuracy. The equivalent of the Sagnac effect for light has been observed with atomic de Broglie waves. The inherent sensitivity of such "atomic gyrometers" can exceed that of photon gyrometers by a very large factor. This is due to the fact that slow atoms spend a much longer time in the interferometer than photons. Other interesting applications have been developed, like atom lithography, which allows atoms to be deposited on a substrate to form controlled structures with a resolution of a few tens of nanometers.

4.3 *Bose-Einstein Condensation*

At very low temperatures and high densities, the average distance between atoms can become comparable to the de Broglie wavelength. Equivalently, the phase space density $n\lambda_{dB}^3$, where n is the number of atoms per unit volume, can become larger than 1. In this regime, where the wave packets of the atoms overlap, spectacular effects can occur as a consequence of the symmetry properties of the wave function describing an ensemble of identical particles. Bosons trapped in an external potential are predicted to condense in the quantum ground state of the trap.

Up to now, the only evidence for such an effect, called Bose-Einstein Condensation (BEC), came from studies on superfluid liquid Helium and excitons in semiconductors. The strong interactions which exist in such systems modify qualitatively the nature of the condensation. A great challenge was therefore to observe BEC in an ultracold dilute atomic gas where interactions are much weaker. Great efforts have been devoted to observing BEC in spin-polarized hydrogen, which is the only quantum gas to remain gaseous at absolute zero. New techniques for cooling and trapping atomic gases have been developed, such as evaporative cooling and magneto-static trapping. Phase space densities very close to 1 have been achieved.

Only within the last few years has it been possible, by combining laser manipulation techniques with evaporative cooling and magneto-static trapping, to observe BEC on alkali atoms, such as rubidium, sodium, lithium. A new exciting research field has been opened by these experiments. All condensed atoms are described by the same wave function, giving rise to macroscopic matter waves with remarkable quantum properties (coherence, superfluidity...) which have been observed and studied in great detail. Coherent sources of atoms, called "atom lasers", are obtained by extracting atoms from a condensate with various types of output couplers. They can be considered as the equivalent, for de Broglie waves, of lasers for electromagnetic waves, and spectacular advances are expected when these sources will become operational and will be used for atomic interferometry.

5. Conclusion

The investigations about the nature of light and its interactions with matter have led to spectacular scientific advances during the last century. A new understanding of the microscopic world has emerged with the development of quantum mechanics. Wave-particle duality has been extended to all physical objects. New light sources, with remarkable properties, the lasers, have been invented.

It has also been realised that light is not only a source of information on the structure of atoms, but also a tool for acting on these atoms. Various methods, like optical pumping, laser cooling and trapping have been developed for controlling the various degrees of freedom of an atom. This increased control of light-matter interactions opens new perspectives for research. New physical objects, like matter waves, atom lasers, degenerate quantum gases, have appeared. Some applications of these scientific advances are still to come. They will, hopefully, open new avenues for Science during the new century.

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