Information sheet 3

Atomic optics, Bose-Einstein condensates and atom lasers

In 1992, with the backing of CNRS, Alain Aspect founded the atomic optics group at the Institut d'Optique at Orsay, with Nathalie Westbrook and Robin Kaiser, and later Christoph Westbrook. Atomic optics is a new field of research which aims to use the forces exerted by lasers on atoms to control their paths, in the same way as traditional optics controls light rays with mirrors and lenses. From 1992 to 1996, the atomic optics group carried out a series of experiments which showed the possibilities—and also the limits—of so-called evanescent-wave atomic mirrors, in which atoms bounce off a sheet of light, obtained by the total reflection of light waves produced by a laser inside a glass prism.

According to quantum theory, atoms, which we feel intuitively are particles, also have wave properties (every particle has an associated wave, as Louis de Broglie predicted). So, similarly to light, we can observe the phenomenon of atomic diffraction[5], studied by Alain Aspect and his co-workers using atomic mirrors with an undulating cross-section. This phenomenon makes it possible to analyze the roughness of the prism's surface with an accuracy of under a nanometer (one billionth of a meter).

The wave nature of atoms also makes it possible to develop atomic interferometers, such as the one outlined by Christian Bordé (Laboratoire de physique des lasers[6] and Laboratoire Systèmes de référence Temps-Espace SYRTE[7]). The interference fringes[8] obtained in this way are remarkably sensitive to the effects of gravity (the attraction exerted by all masses, including of course the Earth) or inertia (absolute acceleration or rotation, relative to "fixed stars"). Atomic interferometers thus offer the promise of applications not only in fundamental physics (tests for the effects of general relativity) and in the field of subsurface exploration (by measuring irregularities in gravity), but also in inertial navigation. An inertial navigation platform enables a vehicle, such as a plane or a ship, to determine its path without the need for any external observation, so that it is not at the mercy of a possible failure of satellite or marker radio beacon positioning systems. The cold atom inertial sensor being built at the SYRTE laboratory (in cooperation with the atomic optics group at the Laboratoire Charles Fabry at the Institut d'Optique) will be more accurate than the laser gyros currently used on commercial airplanes.

Following on from the discovery of gaseous Bose-Einstein condensates in 1995 (see information sheet 2), the atomic optics group, joined by Philippe Bouyer, embarked on the study of these new systems. In a Bose-Einstein condensate, a system predicted theoretically by Einstein in 1924 as a result of Bose's work on photons, the atoms are all described by the same quantum wave function. This is the phenomenon that lies at the heart of the superfluidity of helium or the superconductivity of metals observed at low temperatures. However, the phenomenon is also reminiscent of the laser effect, where all the photons are described by the same electromagnetic wave. This is why it has become possible to create *atom lasers*, beams of highly directional and coherent atoms (their wave functions all vibrate

[5] Diffraction is the bending of rays away from the line of propagation. It occurs when a wave encounters an obstacle whose dimension is similar to the length of the wave (for visible light, the wavelength is between 0.4 and 0.8 micrometers; for the matter waves used in these experiments, the wavelength is a few nanometers). Although it was first observed in light, the phenomenon of diffraction affects all waves, including the matter waves (or de Broglie waves) which are associated in quantum physics with electrons, neutrons, atoms, molecules, etc.

[6] Observatoire de Paris/CNRS/Université Paris VI

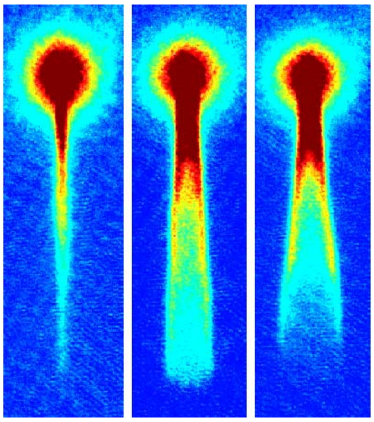
[7] Observatoire de Paris/CNRS/Université Paris VI

[8] Interference is a phenomenon resulting from the superposition of waves of the same nature and equal frequency. For light waves, interference is characterized by narrow alternating light and dark bands. In fact, the phenomenon affects all waves, including matter waves (de Broglie waves).

"in unison"). Thanks to these properties, atom lasers could revolutionize atomic optics and its applications, just as photon lasers revolutionized traditional optics after their discovery in 1960.

Among the outstanding results of the Orsay atomic optics group, we can mention:

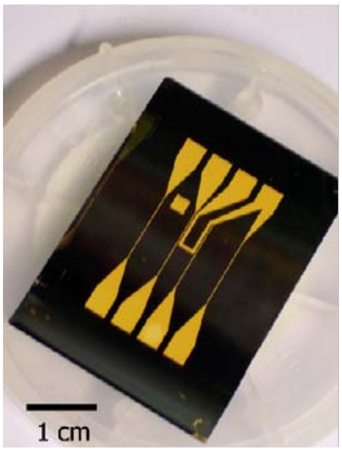
- The study of atom lasers, i.e. of atoms that are propagated while all remaining in the same quantum wave function.



Atom lasers. The illustration shows several atom laser beams a few millimeters long, which are more or less collimated. They are obtained by letting atoms escape from a Bose-Einstein condensate trapped in a device similar to that used for Bose-Einstein condensation of metastable helium (see below). © Groupe d'optique atomique /LCFIO

- The measurement of highly elongated phase fluctuations of Bose-Einstein condensates, or "quasi-condensates". Understanding these fluctuations is crucial to using condensates in guided atomic optics. By making simpler devices possible, guided atomic optics, especially on atomic chips, opens up new horizons for application outside research laboratories.

- The production and study of micro-Bose-Einstein condensates on an "atomic chip", a tiny device produced using nanoproduction methods used in microelectronics and optoelectronics (in cooperation with the Laboratoire de photonique et nanostructures (photonics and nanostructure laboratory) at Marcoussis.



Atomic chip (cooperation LCFIO-LPN). The gold wires in the center, mere micrometers in size, are deposited on a silicon substrate. They make it possible to trap and guide the ultra-cold atoms, and condense them. Miniaturizing laboratory experiments in this way encourages the development of applications for ultra-cold atoms. © Groupe d'optique atomique /LCFIO

- The creation in 2001 of the first Bose-Einstein condensate of metastable helium, which is at first sight paradoxical, since these atoms are likely to de-excite and release energy, a tiny fraction of which would be sufficient to heat up the condensate enough to make it lose its coherence and turn into an ordinary thermal gas.

For their research into Bose-Einstein condensation of metastable helium, the researchers in the atomic optics group have developed instruments which make it possible to detect these atoms one at a time, by accurately determining the position and moment of detection.

This possibility paves the way for fascinating developments in *atomic quantum optics*, just as the development in the 1950s of techniques for counting photons paved the way for modern (photon) quantum optics. For instance, the atomic optics group has revealed the atom group effect, similar to the "photon group" discovered at the end of the 1950s and known as the "Hanbury-Brown and Twiss" effect[9]. The atomic optics group's projects in the field of atomic quantum optics especially concern entangled pairs of atoms, similar to the entangled pairs of photons studied in the early 1980s.

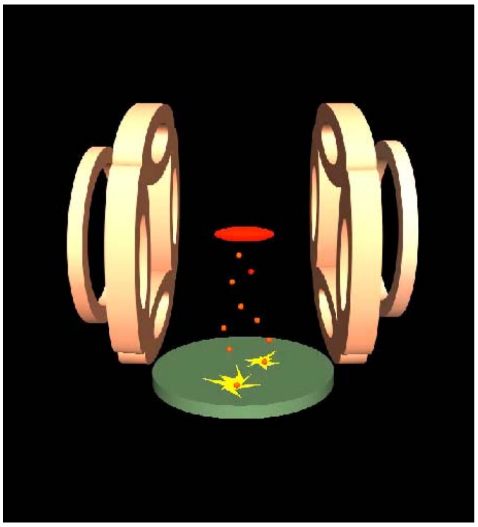


Diagram of the device for Bose-Einstein condensation of metastable helium. The coils, through which current flows, make it possible to trap a cloud of ultra-cold atoms (red ellipsoid). If these atoms are cooled to below 1 microkelvin (less than a millionth of a degree above absolute zero), a Bose-Einstein condensate is obtained, i.e. a collection of atoms which are all described by the same wave function. The detector (shown in green) makes it possible to detect, one at a time, the atoms released from the trap and which fall under the influence of gravity. © Groupe d'optique atomique /LCFIO

[9] Photons emitted by an incoherent source tend to be detected together, even though they are *a priori* independent (for example, photons emitted from both sides of a distant star. It was in particular by analyzing this effect that Roy Glauber (2005 Nobel prize for physics) developed his formalism which underpins modern quantum optics.