# Atom interferometry

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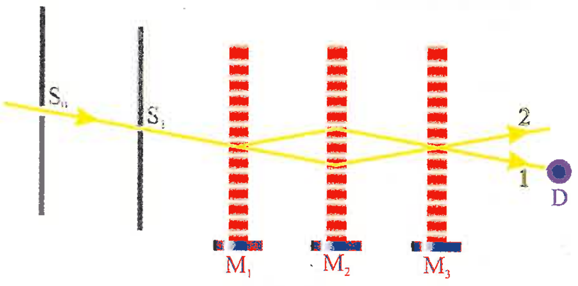
## Historical overview [1]

In 1924, Louis de Broglie generalized to material particles the wave-particle duality, introduced by Einstein for the photon, and gave the formula relating the wavelength $\lambda$ to the particle momentum $p$ ($p = mv$ in the non-relativistic approximation): $\lambda = h/p$. This discovery, derived from theoretical considerations, was rapidly confirmed by matter-wave diffraction experiments:

- in 1927, Davisson and Germer observed the diffraction of electrons on the surface lattice of a metallic crystal;
- in 1930, Estermann and Stern made a beam of helium atoms diffract on the surface of a NaCl crystal.

These experiments were then extended to inelastic diffraction and to neutron diffraction. Such techniques allow the measurement of the local order and give access to the dispersion relation of the surface or volume elementary excitations. These probes (electrons, neutrons, helium atoms) are complementary to X-rays, their interactions with matter being different. Besides, the early diffraction experiments have opened the way towards the realization of matter-wave interferometers, but it took a long time before two majors difficulties were overcome:

- for most matter waves, the accessible values of wavelengths are far shorter than a nanometer. For instance, in our interferometer, lithium atoms $^7$Li, with a velocity of 1060 m/s, have a de Broglie wavelength $\lambda = 54$ pm, ten thousand times smaller than that of visible light;
- there is no natural mirror or beam-splitter for matter waves. Reflection on most solid surfaces is inelastic with a large probability and the small elastic component is not coherent because the surface roughness, large with respect to the wavelength.



▲ **Fig. 1:** Scheme of a three grating Mach-Zehnder interferometer. After collimation by the slits $S_0$ and $S_1$, the matter wave travels through the diffraction gratings which are either material gratings or laser standing waves created by reflection of traveling waves on the mirrors $M_1$, $M_2$ and $M_3$. A detector $D$ is placed on one of the two outputs of the interferometer, labeled 1 and 2 in the figure. The interference signals on both outputs have opposite phases.

A simple generalization of optics was not possible. In 1952, Marton and coworkers built a Mach-Zehnder electron interferometer using electron diffraction from three very thin metallic crystals. However, electron interferometry did not develop much, probably because of the extreme sensitivity to stray electric fields.

Concerning neutrons, apart from an interferometer similar to a Fresnel bi-prism built in 1962 by Maier-Leibnitz and Springer, all neutron interferometers are based on successive Bragg reflection on three gratings (see Fig. 1): the so-called "perfect crystal neutron interferometer", using three gratings cut in the same silicon crystal, was first realized by H. Rauch and coworkers in 1974. This apparatus shows excellent performance and its use is mostly limited by the need of a thermal neutron source. Moreover, neutrons are essentially insensitive to electric fields and interact only weakly with matter, which also reduces the range of possible experiments. In this context, the development of atom interferometry considerably broadens the field of matter-wave interferometry.

## Birth of atom interferometry

The experiments of I. Rabi, later modified by N. F. Ramsey, represent atomic analogs of polarization interferometry in optics, the internal states of the atom (or the molecule) playing the role of the polarization states of the photon. With light, such an experiment simply consists of putting a birefringent plate between two polarizers. We will not discuss here this type of experiment, which allowed in particular the outstanding development of atomic clocks. In the following, we will focus on experiments which are the atomic analogs of optical interferometers where the two paths followed by the wave are spatially separated. The first experiments, dating back to 1991, were already very precise:

- a Young double slit experiment was realized by O. Carnal and J. Mlynek using an atomic beam of metastable helium [2];
- D. Pritchard and coworkers built a Mach-Zehnder interferometer using a sodium atomic beam and diffraction from material gratings [3];
- an interferometer based on Ramsey fringes in saturated absorption was built by J. Helmcke and coworkers for a calcium beam [5], following an idea by Ch. Bordé [4]. This apparatus allowed a demonstration of the Sagnac effect for atomic waves;
- a Mach-Zehnder interferometer using cold sodium atoms and laser diffraction was built by M. Kasevich and S. Chu [6]. This interferometer served to measure the local acceleration of gravity $g$ with a relative uncertainty on the order of $10^{-6}$ [6].

This research field has developed very rapidly since 1991 (see [7] and the book "Atom interferometry" [8]): various atom interferometers have been built, most of them of the three-grating Mach-Zehnder type, as in Fig. 1.

## Atom diffraction

The coherent manipulation of matter waves made of atoms (or molecules) is based almost only on diffraction. Two main techniques can be used: diffraction from material gratings and diffraction by laser standing waves.

### Diffraction from material gratings

Many interferometers are based on micro or nanostructures. Apart from the Young slits used by the group of J. Mlynek, the main tool is the grating cut through very thin films using nano-

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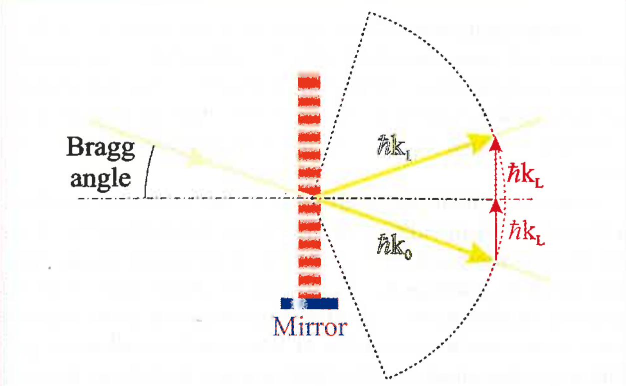


▲ **Fig. 2:** Diffraction of a matter wave in the Bragg regime: one photon is absorbed in one of the two traveling waves forming the standing wave and is emitted by a stimulated process in the other traveling wave. During this process, the kinetic energy of the particle (hence the modulus of the atomic wavevector) and the total momentum are both conserved.

lithographic techniques. The grating period ranges between 100 and 300 nm. They allow the diffraction of atoms (Na, He, etc.), small molecules ($Na_2$, $H_2$), small helium clusters (J. P. Toennies and his group developed a very original mass spectrometry technique based on diffraction from a grating to study these fragile clusters) as well as large molecules (the group of A. Zeilinger and M. Arndt has observed diffraction and interference effects with $C_{60}$, $C_{70}$, $C_{60}F_{48}$ and even a biomolecule, a porphyrin). The fact that diffraction from material gratings is universal is very interesting, but this versatility is counterbalanced by two drawbacks. The gratings are difficult to produce and very fragile. Moreover, the diffraction efficiency is rather low and the only adjustable parameters, the period and the open fraction of the grating, do not allow a full optimization of the diffraction efficiency. Finally, the attractive van der Waals interactions between the grating and the atomic wave makes this diffraction process not well adapted to ultra-cold gases.

## Diffraction by light

In 1933, P. Kapitza and P. A.M. Dirac proposed to diffract electrons from a standing light wave. The process can be explained by momentum conservation between the scattered photon and the diffracted particle: one photon is absorbed in one of the two traveling waves creating the standing wave and is emitted by a stimulated process in the other traveling wave. During this process, the particle receives the momentum of two photons; in the Bragg geometry, where the light wavefronts are the analogs of the crystal planes in X-ray diffraction, this momentum transfer does not modify the kinetic energy of the particle (see Fig. 2).

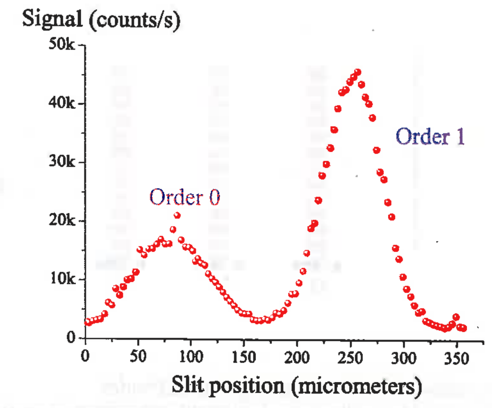
In the 1960's, this theoretical idea was generalized to atoms which is particularly interesting because atom diffraction can be achieved with low light intensities (typically a few tens of mW/cm$^2$) thanks to the atomic resonance phenomenon. However, the first observation of atom diffraction peaks was made only in 1983 by the group of D. Pritchard. Since then, several variants of laser diffraction have been developed, in particular Raman diffraction, a process during which the atom changes its internal state by absorbing and emitting photons with different frequencies. Raman diffraction is widely used, especially with cold atoms, because it allows the direct and diffracted beams to be distinguished through their internal states. In all cases, one has to avoid spontaneous emission so that the diffraction process remains coherent: indeed, spontaneous photons can break the coherence of diffraction by giving some spatial information on the atomic path. The simplest way is to use a laser frequency slightly different from the atomic resonance frequency, but some other tricks can be used.

In the Bragg geometry represented in Fig. 2, diffraction can be described as a Rabi oscillation between two levels of a quantum system, one level representing the incident atomic wave and the other one the diffracted wave. The diffraction probability can thus be varied between 0% and 100% simply by adjusting the intensity of the interaction (which is proportional to the laser power density divided by the laser frequency detuning from atomic resonance) or the interaction time; such a versatility is ideal to build the mirrors and beam-splitters of a Mach-Zehnder interferometer. Figure 3 shows an example of atomic diffraction observed with our apparatus.

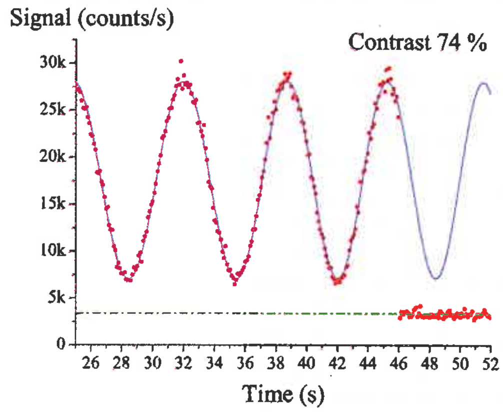
## Our interferometer

Our interferometer [9] is similar to the one of D. Pritchard [3, 8]: in both apparatuses, near the second grating, the two atomic paths are sufficiently separated so that a perturbation can be applied on only one atomic path. For this purpose, the separation of both arms at this point has to be as large as possible: it is 100 µm in our apparatus, whereas for most experiments done by D. Pritchard and coworkers, this separation was only 55 µm. These values may seem small, but, in both cases, they represent millions of de Broglie wavelengths!

We chose to use lithium (its smaller mass leads to a larger wavelength, 54 pm in our present experiment) and laser diffraction: to the resonance wavelength of 671 nm is associated a grating period of 335 nm and a first order diffraction angle of 160 µrad. In our interferometer as in the one of D. Pritchard, the distance between consecutive gratings is about 60 cm. One has to collimate the atomic beam far better than the diffraction angle: this is done by two narrow slits. Our interferometer is thus pretty long: between the source and the detector, the lithium beam travels over 340 cm! The main difficulties of this experiment are the high precision needed for the alignments and the weakness of the output atomic flux (a few tens of thousand atoms per second).



▲ **Fig. 3:** Bragg diffraction of a lithium atomic wave by light. The intensity in the diffraction orders 0 and 1 is recorded by moving the detector. The laser standing wave has been adjusted to give a high diffraction probability into the first order. In a separate experiment, we have verified the absence of other diffraction orders, in agreement with the theory of Bragg diffraction



▲ **Fig. 4:** Atomic interference fringes recorded by moving the position of the third grating of the interferometer. Each point corresponds to a counting time of 0.1 s. Once the background signal (recorded on the right of the figure) has been removed, the measured fringe contrast is 74%.

Figure 4 shows fringes recorded by sweeping the position of the third grating: the fringe contrast of 74% is worth noticing as it is the best ever obtained with a hot atom interferometer. The measured phase noise (about 17 mrad for a measuring time of 1 second) gives an idea of the achieved sensitivity.

## Measurements based on atom interferometry

A wide range of high sensitivity measurements can be achieved with atom interferometers.

### Atomic and molecular physics properties

By applying a perturbation on one of the two atomic paths inside the interferometer, the phase shift and the attenuation of the corresponding wave by this perturbation can be measured on the interference signal. Such experiments have been made by the group of D. Pritchard and more recently by the group of J. P. Toennies. The main interest is either a direct access to quantities which are difficult to measure, for example the electric polarisability of atoms or molecules, or the access to new quantities, such as the index of refraction of gases for atomic waves.

### Inertial effects

Because of the Sagnac effect, a rotation of the interferometer induces a dephasing of the fringes. Compared with laser gyrometers, the sensitivity is considerably larger as it scales like the total energy of the interfering particle. The corresponding gain is equal to the ratio of the total energy of the atom to the energy of the photon, *i.e.* $mc^2/\hbar\omega \approx 10^{10}$! However, this comparison overestimates the gain, because the detected flux and the area of the interferometer are assumed to be the same for both types of gyrometers. After a first demonstration of the Sagnac effect with atomic waves by J. Helmcke and coworkers in 1991 [5], a very high performance apparatus has been built by the group of M. Kasevich [10] achieving a sensitivity of $6 \times 10^{-10}$ rad/s$\sqrt{\text{Hz}}$. Spatial applications are under development (HYPER project of ESA);

Atomic interferometers are also sensitive to accelerations. This sensitivity has been used to develop high precision measurements of the local acceleration of gravity and of its gradient. The experiments, which involve a cold atom interferometer using the geometry of an atomic fountain, were performed by the groups of S. Chu at Stanford University [11] and of M. Kasevich at Yale. Measurements of the gravitation constant $G$ are in progress in the group of M. Kasevich and in the group of G. Tino at Firenze. Finally, the group of M. Kasevich is developing the prototype of a compact accelerometer based on atom interferometry.

### Fundamental constants

The present efforts concerns the measurement of the fine constant structure a. With a set-up similar to the one used as an accelerometer, S. Chu and coworkers have measured very precisely the photon-recoil frequency $\hbar k^2/2M$ of a Cesium atom. Combining this value with independent measurements of the Rydberg constant $R_\infty$, the proton-electron mass ratio $m_p/m_e$ and the Cesium-proton mass ratio $M/m_p$ provides a determination of $\alpha$ with an accuracy of 7.4 ppb [12] through the relation $\alpha^2 = (2R_\infty/c) \times (m_p/m_e) \times (M/m_p) \times (h/M)$.

### Prospects

The progress in cooling and in the manipulation of cold atoms, particularly the availability of Bose-Einstein condensates and the development of atom lasers open extremely rich prospects for atom interferometry. Not only the de Broglie wavelength is greatly enhanced for cold atoms, but also, with respect to the experiments described here, the new feature is the existence of coherent sources of atomic waves and the possibility of non linear and coherent interactions between atomic waves. The revolution induced by these new possibility is somewhat similar to the one opened for ordinary optics by the advent of the laser and it should lead to numerous and fascinating developments in the near future.

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