Atom optics: matter and waves in harmony

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Atom optics: matter and waves in harmony

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Our ability to manipulate the coherence properties of light has been at the heart of many of the most important scientific and technological innovations of this century. There can hardly be a home in this country that does not possess a laser in the form of a compact disc player or a CDROM. When we talk on the phone, or send messages on the Internet, there is a high probability that our message will be encoded by a laser into pulses of light to be passed through optical fibres. In the last few years physicists have been discovering that it is possible to control the coherence properties of atoms, and are now developing tools analogous to those which have been developed to take advantage of the coherence properties of light. In the next decade we can look forward to seeing the application of lasers, fibres, mirrors and waveguides for atoms. Already we have been able to construct interferometry experiments using beams of atoms and these have proved to be extremely sensitive measurement devices, allowing us to test physical theories and measure fundamental constants to a level of precision not previously possible.

Will these developing technologies ever be as ubiquitous as their optical forebears? In this paper we discuss the anticipated uses of this technology for both fundamental science and industrial applications. Starting from an explanation of the meaning of coherence and a comparison of the properties of photons and atoms, we describe the development of the science of atom optics. The tortuous route towards the great achievement of producing a Bose–Einstein condensate is described, and we explain why this is the most important step towards a laser-like source of atoms. Numerous other optical elements for atoms have been built or are on the drawing board, and we describe how these may be used to manipulate atoms with a precision that has never before been achieved, and look ahead to what we can learn about physics using these tools and at how they can be put to practical use.

Keywords: atom optics; matter waves; Bose–Einstein condensation; atom laser

1. Introduction

The science of optics has a long and distinguished history. It has led to many of the technologies that are important in our lives, such as the telescope and microscope, the laser, and optical lithography as used mainly in the process of microchip fabrication. Atom optics, which is the application of optical techniques to manipulate the wave properties of atoms, has the potential to be of great benefit to humankind too.

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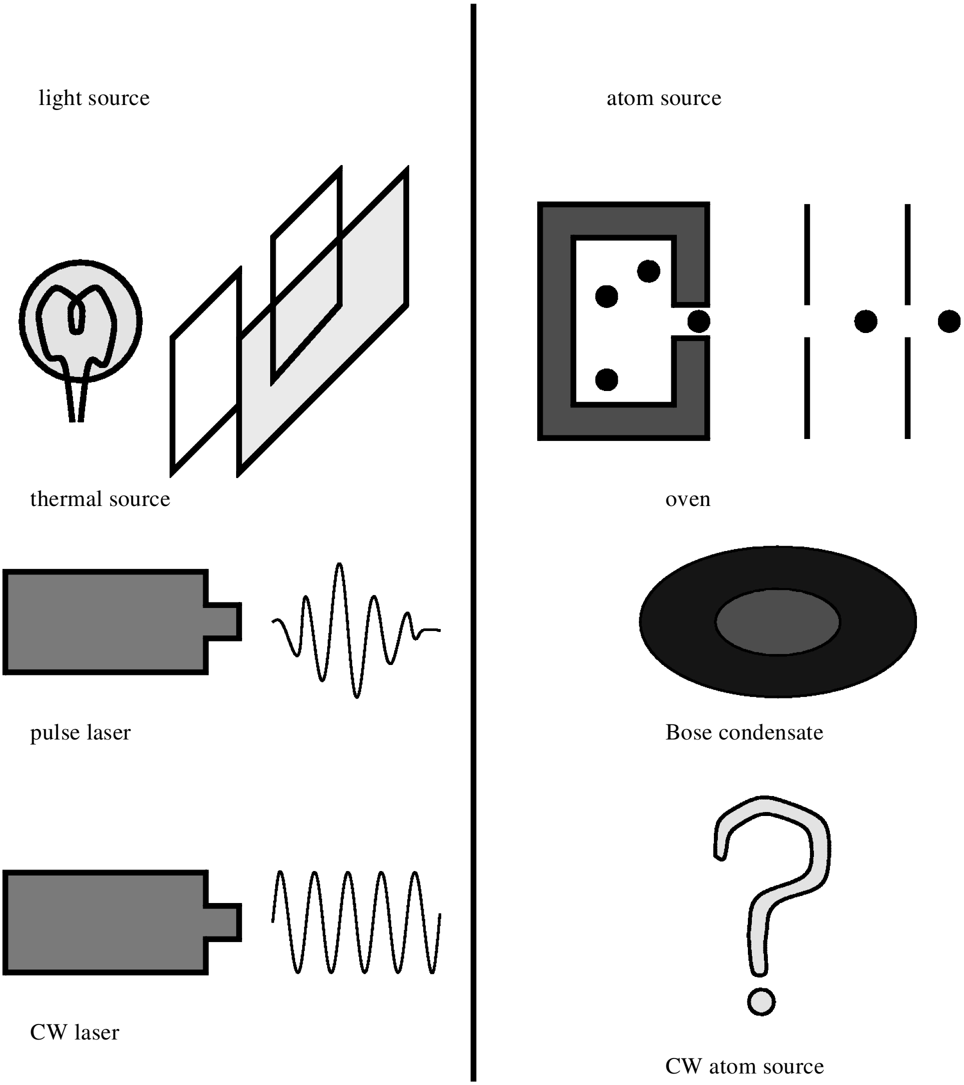

Figure 1. Comparison of the development of light sources and atom sources. Until the laser was developed in the 1960s, optical experiments were performed using thermal light sources and filters. Lasers were able to greatly improve on the coherence properties of thermal light sources. The first lasers produced pulses of light, but now most lasers produce a continuous beam of coherent light (CW laser). In contrast, most atom optics experiments still use thermal sources of atoms produced in an oven. Bose–Einstein condensation experiments put atoms into a single quantum state, and an individual condensate can be considered as equivalent to a single laser pulse. Much current research is dedicated to producing a continuous coherent beam of atoms equivalent to a CW laser.

It is only since the development of quantum mechanics earlier this century that we have become aware that atoms, and other massive particles such as electrons and neutrons, have wave-like properties. The duality between the wave and particle properties of both light and atoms has an interesting history.

In the late 17th century two different models were proposed to describe the properties of light. Newton took the view that light was composed of a stream of 'corpuscles', while Huygens advocated a picture in which light is described by waves. For most of the 18th century Newton's corpuscular picture was the most widely accepted viewpoint, partly because of Newton's high esteem among his peers, and partly because of doubts regarding the nature of the medium through which light waves would propagate. However, by the early years of the 19th century a number of interference and diffraction experiments had been performed by Young, Fresnel, Poisson and others, which could only be described in terms of waves. The wave description of light was then the clearly favoured theory until Einstein's model of the photoelectric effect in 1905 reintroduced a particle-like interpretation and provided a major step towards the development of quantum theory, which eventually led to the current description of light in terms of photons possessing both wave and particle properties.

Now let us compare this with the development of atom optics. The picture of matter as being composed of indivisible massive particles, called atoms, took hold in the late 19th century. Later, de Broglie proposed that massive particles had an associated wave and this idea was developed by Schrödinger, leading to the famous equation that bears his name. Experimentally, the wave properties of massive particles were first demonstrated by Davisson and Germer in 1927 in their electron diffraction experiments. Subsequently, Estermann & Stern (1930) demonstrated diffraction of helium atoms and hydrogen molecules from lithium fluoride crystals in 1930. Their experiments effectively started the field of atom optics as they were the first to demonstrate the wave-like properties of atoms.

In the last 15 years there has been a renewal of activity in atom optics, culminating in the recent production of gaseous Bose–Einstein condensates in which a macroscopic number of atoms occupy the same quantum state. In such a condensate the waves associated with each of the atoms are in phase with one another in a way that is directly analogous to the behaviour of photons in a laser (see figure 1).

As the development of a laser-like source of atoms proceeds physicists have built, and continue to develop, the equivalents of optical elements such as mirrors and waveguides with which to manipulate the resulting atom beams. With these new tools many exciting new experiments become possible. For example, the fact that atoms have mass has enabled the use of atom interferometry to probe the nature of gravity with greater sensitivity than ever before; indeed atom interferometry experiments are often amongst the most precise in science. The complex internal structure of atoms has been used to gain new insight into the quantum measurement process, and the interactions of atoms with one another have revitalized areas of statistical physics that have found new uses in describing the features of Bose–Einstein condensates. On a practical level atom optics has the potential to allow us to manipulate and assemble atoms on a microscopic scale in ways that were previously impossible.

2. Physics background

Some of the most important characteristics of a light source are its coherence properties. It is the high degree of coherence in laser light that differentiates it from most other sources of light. Before the development of the laser virtually all experimental light sources were thermal, but now lasers are the preferred light source for many, and probably most, optical experiments. In the same way, until very recently, exper-

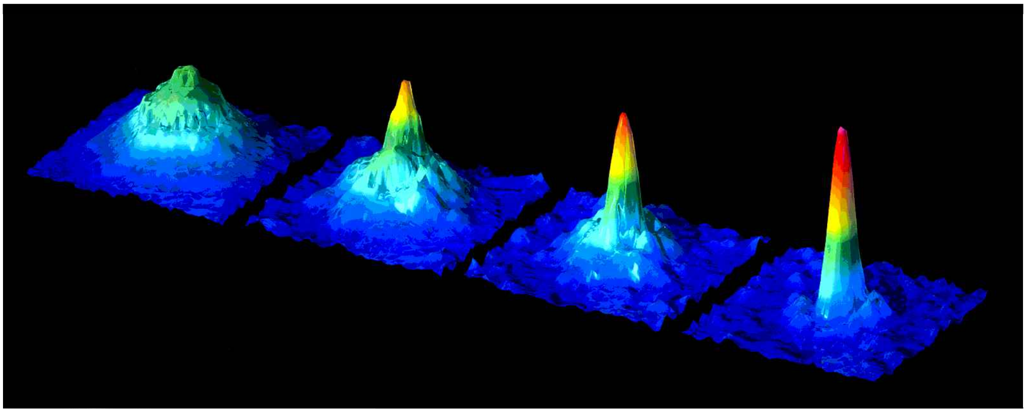

Figure 2. Experimental demonstration of Bose–Einstein condensation (BEC) by the Rempe group at the University of Konstanz (Ernst *et al.* 1998). These are false-colour cross-section images of cold atoms 18 ms after being released from a magnetic trap. Each plot represents an area of *ca.* 1 mm × 1 mm. The wider the spread of atoms the higher the temperature of the initial cloud of atoms. From left to right the temperatures are 780 nK, 420 nK and 280 nK: the rightmost picture shows BEC, and the atoms have spread very little as they were all in the trap ground state. As the atoms do not have a thermal velocity distribution it is not possible to fit a temperature to this image. Image copyright University of Konstanz.

iments in atom optics have had to rely on thermal sources, such as beams produced by ovens, but now with the development of laser-like sources of atoms it is expected that these will in future prove to be of considerable benefit to experimenters. But what do we mean by coherence? And why is it so important?

Roughly speaking coherence is the property that describes how the phase of a source of waves fluctuates in time. In the case of a thermal light source, light is emitted at random times and the phase associated with the light waves varies randomly (except over very short time-scales). By contrast, in laser light the phase of the light remains correlated over much larger intervals of time. Having been produced in a uniform manner the photons, or wave packets of light, 'march in step' rather than being 'out-of-sync' with one another.

The coherence properties of a light source are often described in terms of a coherence length. This is the distance that light can travel in the time it takes for the phase of the light to become randomized. For a good, well-filtered, thermal source of light this may typically be a few centimetres, whereas for laser light this can be as large as hundreds of kilometres.

Photons of light have no rest-mass, and travel at the speed of light. The situation is different for massive particles. For a particle of mass m moving at velocity v the particle can be described by a matter wave with de Broglie wavelength $\lambda = h/mv$, where h is Planck's constant. In a filtered thermal beam of massive particles each individual particle may have a wavelength λ close to that of the other atoms in the beam, but the waves associated with the particles are out of phase with one another. However, in an atom laser the aim is to put all of the atoms into the same motional state so that the associated waves are in phase. In a gas of identical bosons, with particles of integer spin such as certain kinds of atoms, this occurs when the de Broglie wavelength exceeds the average spacing between the atoms.

The behaviour of such a gas was first described by Bose and Einstein in the 1920s. They described how a gas, when cooled to a such a low temperature that the de Broglie wavelength of the atoms was greater than their mean separation, would 'condense' into a single quantum state. At the time this phase-transition was regarded as being of purely academic interest as the temperatures required were far below those available to experimenters. According to their theory, in a gas of bosons, particles of integer spin such as certain kinds of atoms, at temperature T (kelvins) the mean number of atoms occupying the ith excited vibrational state of the atoms motion is

$$\bar{n}_i = \frac{1}{\mathrm{e}^{(\varepsilon_i - \mu)/kT} - 1}, \tag{2.1}$$

where ε_i is the energy of the ith excited state, and μ is the chemical potential, which is the energy required to add an additional atom to the condensate.

When the temperature is very low we see that almost all of the bosons are in the ground state ($i = 0$), and we have Bose–Einstein condensation (BEC) (see figure 2).

3. Atom optics

Although the first experiments to demonstrate the wave properties of atoms were carried out in the 1930s, the field of atom optics remained relatively unexplored until the late 1980s and early 1990s when a number of groups started to develop experiments to demonstrate interference using atoms. Some of the first results to appear were the atom interferometry experiments of Carnal & Mlynek (1991) at the University of Konstanz and Keith *et al*. (1991) at the Massachusetts Institute of Technology (MIT). The Konstanz experiment was an atomic version of the Young's double slit experiment in which helium atoms passed through a pair of microfabricated slits 8 µm apart in a thin gold foil and produced an interference pattern in a detector. The MIT experiment used sodium atoms in a more complex set-up, which used three microfabricated gratings. Within a few months Riehle *et al*. (1991) and Kasevich & Chu (1991) had also demonstrated different configurations of atom interferometers.

Another important element in optical systems for atoms is the equivalent of a mirror for atoms. The most common approach for constructing an atomic mirror is to use evanescent waves. This works on the principle that the interaction of an intense quasi-resonant light field with the internal electronic structure of an atom creates a force on the atom. The result of this 'dipole force' is that atoms are attracted to regions of space where there is intense 'red-detuned' light that has a frequency less than that of the internal atomic transition, and repelled from regions of intense 'blue-detuned' light, which has a higher frequency than the electronic transition of the atom.

So, a sharply defined region of intense blue-detuned light is what is required to reflect an atom, and this can be produced using the evanescent wave that is produced when light undergoes total internal reflection within a prism. The evanescent wave is a light field above the surface of the prism that decays exponentially with the height above the prism on a scale which is approximately that of the wavelength of the light. An atom falling towards such a prism will 'bounce'. The concept of an evanescent wave mirror was first proposed by Cook & Hill (1982) and first demonstrated experimentally by Balykin *et al*. (1988); the group at the École Normale Supérieur in

Paris (Aminoff *et al*. 1993) was able to observe several bounces by atoms on such a mirror, in effect creating an 'atomic trampoline'. It is also possible to use evanescent waves to line the interior of hollow optical fibres, and in this way create a hose down which atoms can travel (Renn *et al*. 1995). In addition to those described here an ever increasing range of coherent optical elements for atoms has now been made, or is being developed (Arimondo & Bachor 1996).

Perhaps the most important optical equivalent for atoms that is currently being developed is a laser-like source for atoms. Such a source would produce a highly coherent beam of atoms as found in a Bose–Einstein condensate. Although the idea of BEC has been around for a long time the experimental realization of a condensed gas has been the culmination of many years of hard work. During the 1980s much work was done to try to laser-cool atoms into a condensed state. In its basic form, laser cooling (Wineland & Itano 1987) uses light scattering at a frequency below that of an atomic resonance to selectively slow fast moving atoms via the Doppler shift. More advanced laser-cooling techniques such as sub-Doppler laser cooling and laser 'sideband cooling' techniques have subsequently been developed (see Chu & Wieman (1989) for a selection of articles on different aspects of laser cooling). Laser cooling brought the temperatures of trapped atoms down to the microkelvin range, but still the approach was not quite successful in producing the high densities and extremely low temperatures required to achieve BEC. It was only later when an additional process of evaporative cooling was used that these conditions were met. Evaporative cooling works by the same principle that a hot cup of coffee cools; the hottest atoms are allowed to leave a trapped cloud of atoms and those that remain are allowed to rethermalize, which has the effect of reducing the temperature of those that remain. Using this technique a group led by Cornell and Wieman (Anderson *et al*. 1995) were the first to produce a condensate. They produced a condensate consisting of approximately 2000 rubidium atoms cooled to 100 billionths of a degree above absolute zero, the lowest temperature ever produced, making the atom cloud the coldest place in the Solar System—a feat soon followed by Ketterle's group at MIT (Davis *et al*. 1995) using sodium atoms.

Producing BEC is not the end of the story for atom lasers. A single bose condensate when released from its confining potential behaves much like a single pulse of laser light, and Ketterle and co-workers (Mewes *et al*. 1997) have been able to couple out a large series of pulses from a single condensate. Attempts are being made to use such pulses to perform atom-optics experiments such as interferometry, but ultimately it would be nice to produce a continuous source of coherent atoms analogous to a continuous-wave laser. At the time of writing coherent streams of atoms lasting for as long as 100 ms have just been announced in experiments which effectively punch a 'hole' in the magnetic trap used to confine a Bose–Einstein condensate through which atoms are able to leak continuously (Bloch *et al*. 1999). It would still be desirable to make the whole process of trapping, cooling and condensing of atoms a continuous one. Schemes for the continuous loading of atoms into a degenerate gas have been considered by a large number of groups and experimental steps towards this end are under way. Some schemes, such as that of the Mlynek group at the University of Konstanz, have atoms continuously pumped into a standing wave optical potential using evanescent waves. Similar techniques, which use magnetic fields instead of evanescent waves, are being developed by Hind's group at the University of Sussex.

4. Applications

At present two main applications are being implemented using atom optics. One is high-precision atom interferometry, and the other is fabrication of structures on the atomic scale.

Atom interferometry can offer a number of benefits over other forms of matter interferometry. Atoms are less susceptible to stray fields than electrons, and atom beams are easier to produce than neutron sources. In addition they have a considerably higher mass, which is of significant benefit for the detection of gravitational phenomena. The experiments of Kasevich & Chu (1991) in particular have been able to detect changes in the Earth's gravitational field at an extremely sensitive level, detecting changes in the acceleration due to the Earth's gravitational field down to about one billionth of g. With such a high accuracy it has even been suggested that atom interferometry could be sensitive to quantum mechanical fluctuations in the gravitational field, offering a way to test for quantum theories of gravity (Percival & Strunz 1995; Power 1999). Rotations can also be very sensitively measured using atom interferometers, as demonstrated in a recent experiment by Gustavson *et al.* (1997) in which an atomic gyroscope was created in an interferometer using caesium atoms. Maybe in future, if the technology can be miniaturized, atom interferometers could form the basis for very accurate navigational instruments.

A second important application for atom optics is in the fabrication of microstructures. With high-precision optics it may be possible to position atoms onto a substrate with great accuracy, which may enable structures to be built on a much smaller scale than current optical lithographic techniques allow, mainly due to the short de Broglie wavelengths of the atoms. Furthermore, many of the techniques for depositing atoms operate in parallel, with many identical microstructures created simultaneously adjacent to one another. This has clear benefits in terms of efficiency and reliability. Periodic microstructures, in particular, can be efficiently implemented in this way. This technology has the potential for application in fabricating new generations of microchips on virtually an atom-by-atom scale, and it could also form the basis for very high density data-storage devices.

The suggestions above represent only a couple of the possible applications for atom optics. If the development of the technology proceeds at a similar pace to that of laser optics, we can expect that far more uses will be found than those so far envisaged.

5. Conclusions

Although the wave-like properties of atoms were first demonstrated in the 1930s it is only in the last decade that atom optics has developed into a widely useful tool. The development of BEC has led to the possibility of laser-like sources of atoms, which will further increase the scope of what can be done with this branch of physics.

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William Power was born in Barnet, Hertfordshire, in 1969. He studied physics at Imperial College, graduating with first class honours in 1990. He studied for a Masters degree at the University of Rochester, USA, between 1990 and 1992, and then did research into Laser–Atom Interactions to obtain his PhD from Imperial College in 1995. After that, he was awarded a European Science Exchange Fellowship from The Royal Society, which allowed him to work for a year on atom and quantum optics at the University of Konstanz in Germany. William has recently been investigating the possibility of using atom interferometry to look for quantum effects in gravity at Queen Mary and Westfield College in London. He is currently working as an analytic consultant for Analyticon Limited.