Atom Optics in a Nutshell

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14.1 Introduction

One of the most counter-intuitive aspects of quantum mechanics, the fundamental theory of nature that was developed starting in the early twentieth century, is the concept of wave-particle duality.

We are all familiar with the notions of waves and particles. We have observed water waves when throwing pebbles in ponds as children, and we have learned in high-school that sound and light consist of waves as well. What we may not have learned, though, is that light sometimes behaves as particles instead. Even more unsettling is the fact that atoms, and all massive particles for that matter, sometimes behave as waves.

Wave-particle duality is the central tenet of atom optics: since atoms, very much like light, behave sometimes as waves, sometimes as particles, it is possible in principle to do with them pretty much everything that can be done with light. One can build a broad variety of atom optical instruments such as mirrors, beam splitters, and lenses. One can develop techniques for imaging, microscopy, diffraction, interferometry, and more. One can even realize atom analogs of lasers.

This chapter sketches selected aspects of atom optics, a few of its recent developments, and some of its promise. We start with a brief historical overview of some of the milestones that have lead to our current understanding of atoms, from the Greek philosophers of antiquity to the development of quantum mechanics and the key experiments of the early twentieth century that confirmed the wave-particle duality of atoms and other massive particles. We then discuss how the wave nature of atoms becomes increasingly more evident as their temperature is decreased. For that reason it is oftentimes advantageous to work at extremely low temperatures, close to absolute zero, in applications such as atom microscopes and atom interferometers, or to build atom optics "analogs" of the laser, Bose–Einstein condensates. After outlining the basic ideas behind these devices we conclude with a brief overview of some current and future applications, with an emphasis on the role of atom optics in helping answer fundamental physics questions.

The bibliography is limited to a few milestone papers and is certainly not meant to be comprehensive. It also does not attempt to give proper credit to all research groups who have contributed significant advances to atom optics, sometimes within weeks of the work by research groups mentioned here. Due to their advanced technical content these papers will likely be of limited use to the casual reader beyond their historical interest. The excellent review [6] gives a comprehensive list of references through 2009. The elegant set of lecture notes of [18] also discusses some of the extraordinary promise of atom optics for tests of fundamental physics at a level appropriate for advanced graduate students and experts in the field.

14.2 Particles or Waves?

This short chapter is not the place to give a comprehensive review of our historical understanding of the nature of light. For our purpose it is sufficient to review a few of the key steps that resulted in that understanding. We then draw a similar sketch of the historical development of our understanding of atoms. This will set the stage for a discussion of the close parallels that have guided the development of atom optics.

The central idea that we will need to become somewhat comfortable with is the concept of "wave-particle duality," the co-existence of particle and wave properties in objects that we are used to think of as one or the other, but not both. From

everyday experience we are quite familiar with particles and waves, for instance, from watching the surf rolling on a beach, or tiny grains of sand on that same beach. What we need to grasp, though, is the rather counter-intuitive concept of both light and atoms behaving sometimes as particles, and sometimes as waves. *Why* this is the case is not a question that physics answers—it is a question perhaps best left to philosophers—but *how* this is the case is something that we now understand well. This is described beautifully and with extraordinary predictive power by modern quantum physics.

14.2.1 Light

Perhaps a good place to start is with the great Greek philosophers and mathematicians Pythagoras (c. 570–c. 495 BC), Plato (c. 428–c. 348 BC), and Euclid (c. 325–c. 265 BC). They thought that light consists of rays that travel in straight lines from the eye to the object, and that the sensation of sight is obtained when these rays touch the object, much like the sense of touch. Plato's student Aristotle (384–322 BC), though, had a different theory, considering instead that light travels in something like waves rather than rays. The understanding that light travels from the eye to the object remained largely unchallenged until it was finally disproved more than a thousand years later by Alhazen (965–1039), one of the earliest to write and describe optical theory. He studied in particular light and the nature of vision with the combined use of controlled experiments and mathematics.

Meanwhile the debate between the corpuscular and the wave nature of light already apparent in the conflicting views of the Pythagorean School and Aristotle continued unabated for centuries. Isaac Newton (1642–1726), who performed numerous experiments on light toward the end of the seventeenth century and whose extraordinary contributions include the understanding of the color spectrum and of the laws of refraction and reflection, argued that those effects could only be understood if light consisted of particles, because waves do not travel in a straight line. However, the corpuscular theory failed to explain the double-slit interference experiments carried out by Thomas Young (1773–1829)—we will return to these experiments at some length later on. It was replaced in the nineteenth century by Christiaan Huygens' (1629–1695) wave theory of light. Finally, James Clerk Maxwell (1831–1879) developed the equations that unify electricity and magnetism in a theory that describes light as waves of oscillating electric and magnetic fields. This is the culmination of the classical theory of light, and one of the greatest, if not the greatest achievement of nineteenth century physics. At that point, it appeared that light was indeed formed of waves, and the corpuscular theory seemed ruled out once and for all.

However things changed again at the beginning of the twentieth century in a way that revolutionized physics and profoundly transformed our understanding of nature. In 1900, Lord Kelvin gave a celebrated talk entitled "Nineteenth Century Clouds over the Dynamical Theory of Heat and Light" in which he stated with remarkable insight that [16]

» The beauty and clearness of the dynamical theory, which asserts heat and light to be modes of motion, is at present obscured by two clouds.

He went on to explain that the first of these two clouds was the inability to experimentally detect the "luminous ether"—the medium that was thought to be vibrating to create light waves; and the second was the so-called ultraviolet catastrophe of blackbody radiation—the fact that Maxwell's theory utterly failed to predict the amount of ultraviolet radiation emitted by objects as a function of

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their temperature. As it turns out, these two clouds led to two earthshaking revolutions in physics: relativity theory and quantum mechanics.

Quantum mechanics reopened the centuries-old wave-particle debate, but it resolved it with a very unexpected and dramatic new answer: light behaves sometimes as waves, and sometimes as particles. In trying to understand how the radiation emitted by an object depends on its temperature, Max Planck (1858–1947) advanced the revolutionary idea that energy comes up in tiny discrete lumps, or quanta. With this ad hoc assumption, he was able to explain the experimental data that Maxwell's theory failed to explain. Following on that work, Albert Einstein (1879–1955) proposed that light also comes in small lumps of energy, now called photons. This allowed him to correctly characterize how electrons are emitted from surfaces of metal irradiated by light. (The other cloud mentioned by Lord Kelvin, the absence of a luminous ether, leads to Einstein's theory of relativity.)

What modern quantum theory teaches us is that light sometimes behaves as waves, as in the Young double-slit interference experiment, and sometimes as particles, as in the photoelectric effect. Although photons are massless they carry both energy and momentum that can be used to alter the motion of massive objects. We will talk about all this quite a bit more in this chapter, but first let's turn for a moment to what quantum theory has to say about atoms.

14.2.2 Atoms

As with light, a good place to start is again in ancient Greece. This is where Democritus (c. 460–370 BC) and Leucippus (fifth century BC) developed the theory of atomism, the idea of an ultimate particle and that everything was made out of indivisible "atoms." The first experiments that showed that matter does indeed consist of atoms are due to John Dalton (1776–1844). He recognized the existence of atoms of elements and that compounds were formed from the union of these atoms, and put forward a system of symbols to represent atoms of different elements. [The symbols currently used were developed by Jöns Jacob Berzelius (1779–1848).] In a major breakthrough, in 1897 J.J. Thompson (1856–1940) discovered the electron and advanced the so-called plum pudding model of the atom. In that description the volume of the atom was composed primarily of the more massive (thus larger) positive portion (the plum pudding), with the smaller electrons dispersed throughout the positive mass like raisins in a plum pudding to maintain charge neutrality.

Early in the twentieth century Ernest Rutherford (1871–1937) carried out a number of experiments that suggested that atoms consist instead of a tiny, positively charged nucleus, with electrons orbiting around it at relatively large distance, and discovered the existence of positively charged protons. In 1920 he further proposed the existence of the third atomic particle, the neutron, whose existence was experimentally confirmed quite a bit later, in 1932, by James Chadwick (1891–1974). Rutherford's experiments led to the development of the so-called Bohr–Sommerfeld model of the atom.

In a groundbreaking development and with extraordinary insight, Prince Louis-Victor de Broglie (1892–1987) then postulated that if light exists both as particle and wave then atoms, and all massive particles, should be the same (◘ Fig. 14.1). This was the key missing piece of the puzzle [9]. This property, now known as the *wave-particle duality*, guided Erwin Schrödinger (1887–1961), Werner Heisenberg (1901–1976), and others in developing quantum mechanics, the theory that has led to a wealth of extraordinary inventions from the internet to cell phones, from GPS to medical imaging, and to a myriad other developments that impact just about every aspect of modern life.

⬛ **Fig. 14.1** Prince Louis-Victor de Broglie, who came up with the idea that massive particles have a wave character

The first experiments confirming the wave nature of massive particles were carried out by Clinton J. Davisson (1881–1958) and Lester H. Germer (1896–1971), who in 1928 observed the diffraction of electrons by a crystal of Nickel [8]. The first experiments demonstrating the wave nature of atoms and molecules followed soon thereafter, in 1930, in Helium experiments performed by Immanuel Estermann (1900–1973) and Otto Stern (1888–1969) [10], thereby fully confirming the de Broglie hypothesis.

To briefly complete the story as we currently understand it, we now know that protons and neutrons are actually not elementary particles. They belong to a family of particles called baryons, made up of three elementary constituents called quarks (two "up" quarks and one "down" quark for the proton, and one "up" quark and two "down" quarks for the neutron) bound together by the nuclear force. Together with another family of particles called mesons, made up of two quarks, they form the hadrons family.[1] The electrons, by contrast, are believed to be true elementary particles and belong to a family called leptons. They interact with the atomic nuclei via the electromagnetic force, whose "force particle" is the photon. The Standard Model of elementary particle physics comprises two additional types of interactions: the weak interaction, responsible for radioactive decay and nuclear fission, and gravitation, which allows massive particles to attract one another in accordance with Einstein's theory of general relativity (⬛ Fig. 14.2).

However, to break atoms into their subatomic constituents requires very large energies, much larger than normally considered in atom optics experiments. For the purposes of this chapter it is therefore sufficient to consider atoms as essentially "elementary particles" that interact with each other via relatively weak electric and magnetic fields, most importantly for us with light fields.

14.2.3 Particles and Waves

By optical waves one usually means those electromagnetic waves that are visible to the human eye. They have very short wavelengths, of the order of a millionth of a meter or less, and very high frequencies, of the order of 100,000 billion of oscillations

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1 In an exciting new development announced in summer 2015, experiments carried out at the CERN Large Hadron Collider near Geneva, Switzerland provided evidence for the existence on pentaquarks, a new type of hadrons consisting of five quarks.

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🔲 **Fig. 14.2** Clinton J. Davisson and Lester H. Germer (Lucent Technologies Inc./Bell Labs, courtesy AIP Emilio Segrè Visual Archives)

per second.[2] Blue light consists of waves of higher frequency and shorter wavelength than green light, and green light consists of waves of higher frequency and shorter wavelength than red light. Past blue light and toward shorter wavelengths blue is followed by ultraviolet light, X-rays, and gamma rays. These waves are invisible to the human eye. On the other side of the spectrum and moving toward longer wavelengths, red is followed by infrared, microwaves, and radio waves, all also invisible to us. The wavelength of light is usually denoted by the Greek letter lambda, with symbol λ, and its frequency by the Greek letter "nu," written ν.

The particles of light are called photons. They are massless, and their energy E is proportional to their frequency. The proportionality constant is called Planck's constant, This is a fundamental constant that appears in the description of all quantum phenomena.[3] It traditionally denoted by the letter h, so that

$$E = h\nu. \tag{14.1}$$

Photons also carry a momentum, denoted by the letter p, which is inversely proportional to their wavelength,

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2   We recall that waves are characterized by an amplitude, a wavelength, and a frequency: The wave amplitude is defined as half the vertical distance from a trough to a crest of the wave, the wavelength is the distance between two crests of the wave, and the frequency is the number of crests that an observer at rest sees passing in front of her eyes every second.

3   The value of the Planck constant is extremely small, $h = 6.62606957 \times 10^{-34} \, m^2 \, kg/s$, hinting at the fact that quantum mechanics is especially important in the atomic and subatomic worlds.

$$p = h/\lambda. \tag{14.2}$$

In vacuum the product of the wavelength of light and its frequency is equal to the speed of light $c = 299, 792, 458$ m/s, $\lambda\nu = c$.

It might come as a surprise that a massless particle such as the photon carries momentum. We recall that the momentum of an object of mass M is the product of its mass times its velocity v, $p = Mv$.[4] Momentum is a very important quantity in physics: Newton's second law of motion $F = Ma$, where a is the acceleration—the change in velocity v—tells us that the force F required to change the velocity of the object is proportional to its mass (more precisely, that the change in momentum of the object is equal to the force acting on it). This is why it is harder to stop a freight train than a bicycle!

How, then, can a massless object carry momentum? To properly understand why this is the case requires invoking Einstein's special relativity theory. The basic idea is twofold: First, one needs to know that nothing can move faster than the speed of light c, and that the only particles that can move at that speed must be massless. This is because it would take an infinite amount of energy to bring any massive particle to that velocity. Second, the description of classical mechanics embodied in Newton's laws does not apply to particles moving at extremely high velocities, near the speed of light. Their motion must be described instead in the framework of the theory of relativity.[5] Unfortunately in that extreme regime of velocities our intuition tends to fail us, so we will simply take Einstein at his word and accept that photons do carry momentum, a property that has been confirmed in numerous experiments. Remarkably, the fact that light can modify the trajectory of a massive particle was already conjectured during the Renaissance, but without a sound theoretical basis, by none other than the great mathematician and astronomer Johannes Kepler (1571–1630) who observed that the tail of comets always points away from the sun and concluded [17] that

» The direct rays of the Sun strike upon it [the comet], penetrate its substance, draw away with them a portion of this matter, and issue thence to form the track of light we call the tail.

14.2.4 Atoms as Waves

We will soon come back to the photon momentum and its importance in atom optics. But before doing so we turn to the other actor in our story, the atoms, and sketch how they are described when they behave as matter waves, or de Broglie waves.

Very much like any other type of waves, they are characterized by a frequency and a wavelength, as first postulated by Louis de Broglie and then formalized in the framework of quantum theory. The de Broglie wavelength λ_{dB} of a non-relativistic massive particle of mass M is related to its momentum p by the equation

$$p = h/\lambda_{dB}, \tag{14.3}$$

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4   Unfortunately the Greek letter ν used for frequencies and the roman letter v used for velocities look quite similar.

5   In the theory of special relativity the energy E of a particle is related to its momentum p by the equation $E^2 = p^2c^2 + M^2c^4$. For a massless particle, $M = 0$, this reduces simply to $E = pc$. For photons the energy is $E = h\nu$, and we have seen that in vacuum $\lambda\nu = c$, from which it follows that $p = h/\lambda$. As it turns out, the familiar definition of the momentum $p = Mv$ is only approximate. It holds for non-relativistic massive particles, that is, for particles moving much more slowly than the speed of light.

in complete analogy to the situation with photons. However, its kinetic energy takes the familiar form $E = Mv^2/2$ or, remembering that for atoms $p = Mv$ and with the relationship between p and λ_{dB},

$$E = h^2/(2M\lambda_{dB}^2). \tag{14.4}$$

So, while there are important similarities between light waves and matter waves, as evidenced by the relationships between momentum and wavelength of Eqs. (14.2) and (14.3), there are also important differences due to the fact that photons are massless objects while atoms have a mass. For optical waves, the energy is proportional to the momentum, $E = pc$, while for (non-relativistic) matter waves the energy is proportional to the square of the momentum, $E = p^2/2M$. This has important implications for atom optics.

Under everyday circumstances we experience atoms just as particles, not as waves. To understand why this is so let us estimate the size of the de Broglie wavelength. To do so, we need to figure out the momentum of an atom. Since the masses of the various atoms are known and can easily be found in a number of reference books or the internet all we need to do is determine their typical velocity. Let's imagine for a moment a box filled with some atomic gas, maybe Lithium or Sodium, at a temperature T. If it were possible to observe the individual atoms under a microscope, we would see that they move in random directions, going left or right or up or down or forward or backward, some faster, some more slowly, like little kids on a playground. Denoting the average velocity of all these atoms by the symbol $\langle v \rangle$, we would find that it is equal to 0, $\langle v \rangle = 0$: there are lots of atoms in the container, billions of billions of them, and just about as many of them are moving at a given velocity in one direction as in the opposite direction.

But if we took the square of all the individual velocities and averaged the result, call it $\langle v^2 \rangle$, we would find that it is different from zero. This is because the square of any number, be it positive or negative, is a positive number, and the average of a bunch of positive numbers is also positive. Importantly we would also discover that the higher the temperature T of the sample, the larger $\langle v^2 \rangle$, and that T is proportional to $\langle v^2 \rangle$. This is in fact precisely how temperature is defined: it is (in some units) the kinetic energy, or average energy of motion $M\langle v^2 \rangle/2$ of the atoms. The temperature at which all atoms cease to move is absolute zero, $T = 0$. It is impossible to cool anything below that temperature since the atoms cannot move more slowly than not moving at all![6]

Equation (14.3) teaches us that the de Broglie wavelength is inversely proportional to p—the smaller p, the larger λ_{dB}. Near absolute zero the atoms move extremely slowly. They have a very small momentum p, and hence a large de Broglie wavelength. At higher temperatures the atoms move faster, their momentum is larger, and their de Broglie wavelength is therefore smaller. This decrease is proportional to the square root of the temperature, or, in mathematical terms, λ_{dB} is proportional to $1/\sqrt{T}$. At room temperature, one finds that it is of the order of a tenth of a billionth of a meter, or a tenth of a nanometer, 10^{-10} m (this is 0.0000000001 m), a size comparable to the radius of an atom. This is why it is so difficult to observe the atoms as waves: their de Broglie wavelength is simply too small to be observable under normal circumstances.

A good strategy to investigate and exploit the wave nature of atoms is therefore to work at very low temperatures, where their de Broglie wavelength is more easily observable. For a typical atom cooled to a millionth of a degree above absolute zero

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6 This is the classical physics view of things. The situation is somewhat more subtle in quantum mechanics, which teaches us that atoms still move a tiny bit at $T = 0$, but there is no need for us to worry about this here.

the de Broglie wavelength is of the order of a micron, a millionth of a meter. A millionth of a meter is still very small, so even at extremely low temperatures the wave nature of atoms is quite elusive—except that one micron also happens to be close to the wavelength of visible light. This is an important coincidence because as we know, to measure the size of any object we need to have an appropriate "measuring stick," not too big and not too small, just right. Because the wavelength of visible light turns out to be perfectly matched to the de Broglie wavelength of ultracold atoms, it can serve as that perfectly matched measuring stick. For this and several other reasons to which we will return the combination of visible light and ultracold atoms is a marriage made in heaven.

14.2.5 Cold Atoms and Molecules

Over the years optical and atomic scientists have developed exceedingly sophisticated methods to control the way light interacts with atoms. It is possible to exploit this know-how to prepare and manipulate atoms with extraordinary sophistication, and in particular to cool atoms to temperatures only a minute fraction of a degree above absolute zero.

At first sight, using light to cool atoms doesn't seem to make much sense: our intuition tells us that when we shine light on an object it becomes warmer, not colder. Therefore to use laser light to cool atoms requires one to be rather clever and to understand in detail the way they interact. For a simple qualitative discussion of the basic idea, though, it is sufficient to recall that atoms can both absorb photons (as happens, for instance, in your eyes) or emit them (for instance, in a light bulb.) We also need to keep in mind that all physical processes must satisfy two fundamental laws of nature: conservation of energy—one cannot create energy out of nothing; and conservation of momentum—a moving object will keep moving in a straight line at constant velocity unless one applies a force to it. This is Newton's first law. So, when a photon is absorbed by an atom both its energy and its momentum are transferred to the atom. In the reverse process, when an atom emits light, it loses the momentum h/λ that the photon carries away by changing its velocity.[7]

Remembering that the temperature of a gas is a measure of the energy of random motion of the atoms, this suggests a way by which light can be used to cool atoms: If we can somehow arrange for the moving atoms to predominantly absorb photons propagating *toward* them, then the momentum transferred to them by the photons will be opposite to their direction of motion. They will be pushed back and slowed down. The trick is of course that this needs to be done to all atoms, whether they move up or down, left to right or right to left, and backwards or forward. This is important: one needs to avoid as much as possible having atoms absorbing photons propagating in the same direction as they move, since this would accelerate them rather than slow them down. It turns out that this can actually be achieved by using six different light beams with just the right wavelengths. This mechanism, called Doppler cooling [14, 24], allows to cool atomic gases very significantly, down to roughly a thousandth of a degree above absolute zero. One can do even better by using more complex arrangements of light beams and by cleverly exploiting the internal structure of the atoms. Combining a variety of techniques it is now possible to cool atomic samples to within a

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7   It turns out that the bulk of energy conservation is achieved via transitions of an atomic electron between different orbits around the nucleus, while the bulk of momentum conservation is normally achieved by changing the velocity of the atom.
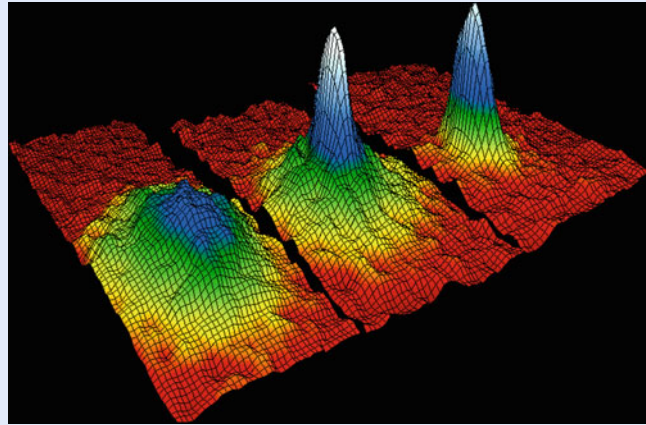
Fig. 14.3 The first atomic BEC ever created by the JILA group of E. Cornell and C. Wiemann in 1995 (Image credit Michael Matthews, JILA)

billionth of a degree above absolute zero or even colder, to a point where their de Broglie wavelength is of the order of a fraction of a millimeter !

A major experimental milestone resulting from the use of such cooling techniques was reached in 1995 (Fig. 14.3) by the groups of Carl Wieman and Eric Cornell at JILA [2], and soon thereafter by Wolfgang Ketterle and coworkers at MIT [7]. They succeeded in realizing atomic Bose–Einstein condensates, a tour-de-force for which they were awarded the 2001 Physics Nobel Prize. A Bose–Einstein condensate is a state of matter where all atoms "condense" into a single quantum object where they are all in the same state, some sort of a "super atom." Ideally the atoms form then a single macroscopic quantum wave, much like photons in a laser behave collectively as a single entity. This exotic object was predicted as early as 1924 by Albert Einstein, expanding on work by the Indian physicist Satyendra Nath Bose, but it is not until atomic samples could be cooled to the extraordinarily low temperatures now possible that it could be produced and observed in its almost pure form.

14.3   Atomic Microscope

We mentioned earlier that if we had at our disposal a microscope that could track individual atoms, we would be able to observe their random thermal motion. While this is not possible at room temperature at this time, the availability of ultracold atomic systems has now made such devices a reality at temperatures approaching absolute zero.

The key idea is that because ultracold atoms carry very little energy of motion it is possible to trap them in extremely shallow potentials, in particular in the periodic potentials that can be produced by standing optical waves—these are the waves produced by two light beams of the same wavelength propagating in opposite directions. Atoms can be trapped in the troughs of these waves in such a way that if they try to escape, then radiation pressure pushes them back down, somewhat like a ball always rolls down to the bottom of a slope. Using standing waves along two or three directions the landscape in which the atoms are trapped resembles an egg crate. It is called an optical lattice potential, or simply optical lattice, and atoms can be trapped at its local minima, as sketched in Fig. 14.4. In 2009 Marcus Greiner and his collaborators at Harvard University devised a microscope that successfully imaged individual atoms localized in such a tightly
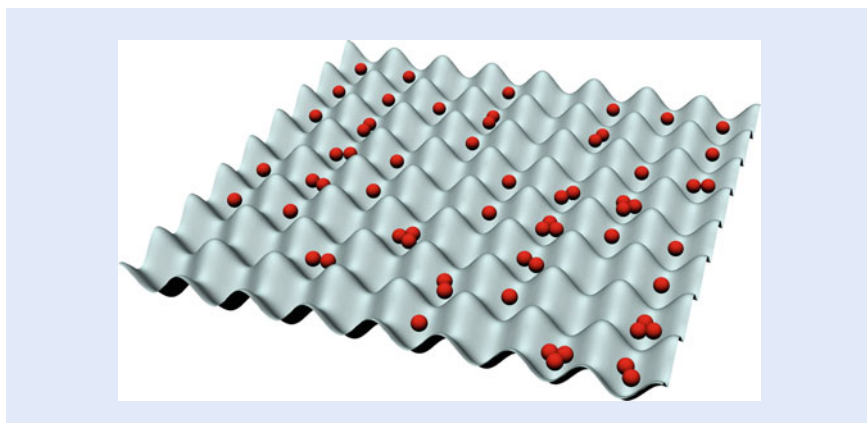
■ **Fig. 14.4** Artist rendition of the way ultracold atoms can be trapped in an optical lattice (Image credit Andrew Daley, University of Strathclyde)
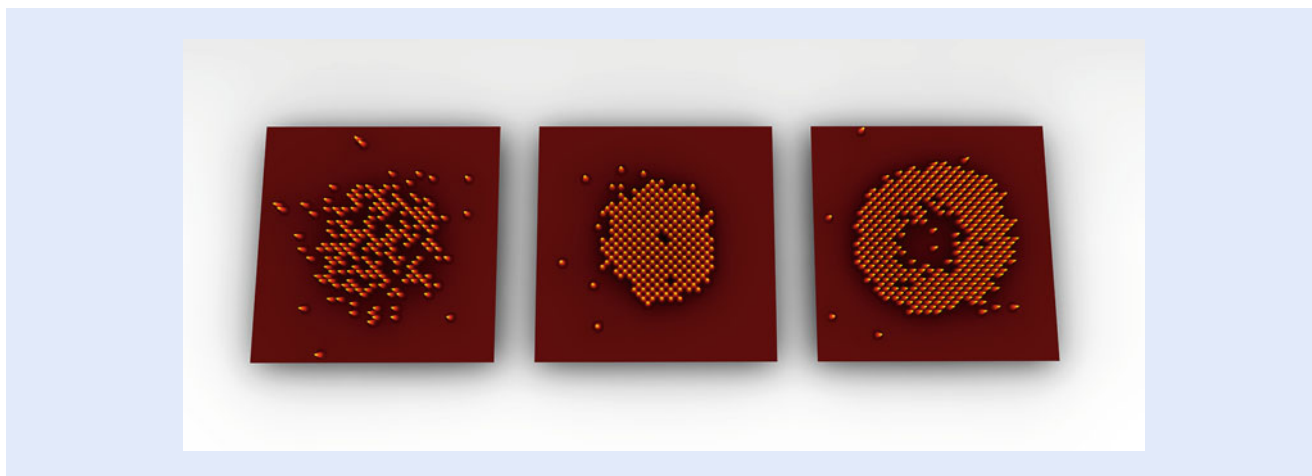
■ **Fig. 14.5** Illustration of the way atoms can be manipulated and probed individually in an atom microscope. In this case, the system is modified to observe the transition from a Bose–Einstein condensate (*left*) to the so-called Mott insulator (© Immanuel Bloch, Max-Planck Institute for Quantum Optics)

spaced optical lattice [3]. This was soon followed by a second microscope (■ Fig. 14.5) developed by Immanuel Bloch's group at the Max Planck Institute for Quantum Optics [23]. In these groundbreaking experiments the atoms trapped and individually imaged were bosons[8] but more recently that same technique has also been extended to fermions [5, 19].

Ultracold atoms trapped in optical lattices provide a powerful proving ground to study a number of effects in manybody physics, the situations dominated by the collective behavior of large ensembles of constituents. This is a broad and challenging area of research that is central to the understanding of many phenomena in fields ranging from condensed matter physics to nuclear physics. For example, the collective behavior of electrons in crystal structures is key in understanding their electrical and optical properties.

However experiments in solids can be challenging, in part because it is difficult to control the strength of inter-particle interactions. In contrast, a number of

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8   Atoms come in two classes, bosons and fermions. Bosons are characterized by the fact that identical bosons can, and like to, occupy the same quantum state in unlimited number. In stark contrast, two identical fermions cannot be in the same quantum state.

powerful tools are available to control these interactions in ultracold atoms. And atom microscopes even permit to address and manipulate individual atoms in the system. For these reasons they provide a remarkable tool to simulate and investigate manybody effects in exquisitely controlled situations. They offer considerable promise to help understand a number of complex manybody phenomena. As noted by Martin Zwierlein [25], whose MIT group developed the first fermionic atom microscope [5],

> » High-resolution imaging of more than 1,000 fermionic atoms simultaneously would enhance our understanding of the behavior of other fermions in nature, particularly the behavior of electrons. This knowledge may one day advance our understanding of high-temperature superconductors, which enable lossless energy transport, as well as quantum systems such as solid-state systems or nuclear matter.

14.4 Interferences

We can easily observe the interference of waves when we drop a pair of pebbles in a quiet pond. Each pebble is the source of a small wavelet that propagates away in regular circles, and when the two meet they interfere to produce a complex pattern of crests and troughs.

Similar interferences are also familiar in optics, most famously perhaps in the Young double-slit experiment mentioned earlier. In that case, an optical wave propagates from one side to the other of an absorbing screen through either one or two parallel slit openings (or even more simply one or two pinholes). In the case of a single slit, after it passes through the hole the light wave begins to spread much like the wave generated by a single pebble—the narrower the slit, the larger the angle of spread. With two slits the situation is then akin to what happens with the two pebbles: As they spread spatially the light beams originating at the two slits begin to overlap and interfere, much like the wavelets in the pond. This results in a pattern of alternating dark and bright regions, the analog of the crests and troughs. The more pure the color of the light, the higher the contrast between the bright and dark fringes. This interference phenomenon, perhaps the most direct demonstration of the wave nature of light, is what led Huygens to develop his wave theory of light.

Remarkably, interferences still occur if the light beam is so feeble that only one photon at a time flies past the screen, perhaps one every second, or one every minute, or even one per month! If one waits long enough for the successive photons to slowly build an image, say, on a photographic plate or a CCD camera, that image will still exhibit the same precise interference pattern as if the beam were intense and produced an image in the blink of an eye. The interference pattern builds up one photon at a time!

This should seriously bother you, because one would expect that each individual photon goes through either one slit or the other, but not both, and the situation should then be completely analogous of the one pebble case. *Obviously*, we should not observe interferences in that case. But this is not so: "Obvious" is obviously not a good characterization of what can happen in the quantum world.

14.4.1 Atom Interferences

The situation may seem even more bizarre with atoms, which we are used to think of as particles. But since they obey the same wave-particle duality as photons it is
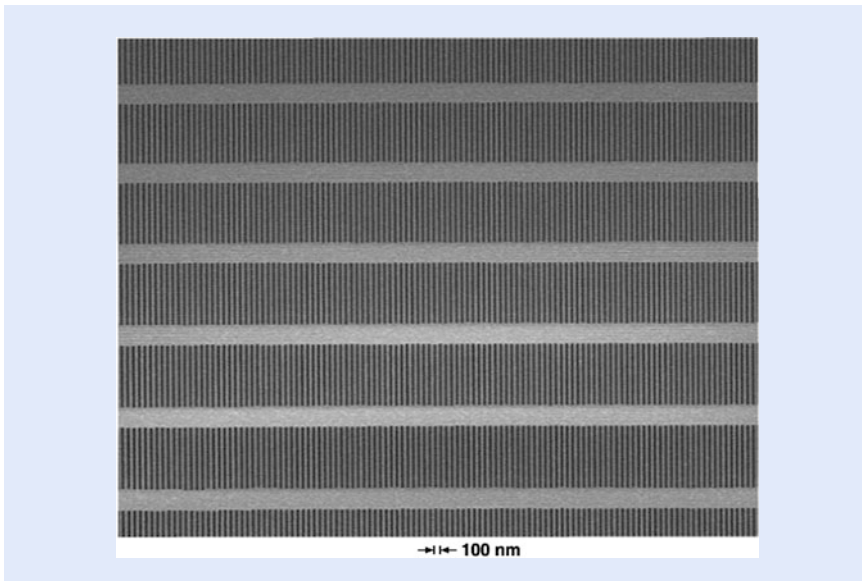
■ **Fig. 14.6** Scanning electron micrograph of a free-standing 100 nm-period diffraction grating for atomic matter waves in a silicon nitride membrane of area 500 μm by 5 mm (courtesy David E. Pritchard, MIT)

possible to produce and observe the interference of matter waves as well. A simple way to do so is to mimic Young's optical double-slit experiment. Practical challenges are that for interferences to be easily observable the width of the slits must be much narrower than de Broglie wavelength, and also that the slit separation should typically be of the order of that wavelength. Modern nanotechnology has solved this problem and makes it possible to fabricate a variety of combinations of holes and slits through which matter waves can propagate. For example, one can pass a beam of atoms through a large array of parallel slits. This is an atom optics analog of the diffraction gratings widely used in optics. An important and useful property of such gratings is that the interferences of the individual wavelets result in different wavelengths (colors) exiting the grating at different angles. Likewise, a nanofabricated mechanical grating can redirect an atomic beam, or even a single atom, in a direction that depends on its energy and momentum. As a result, properly designed gratings can act as mirrors or as beam splitters for atoms (■ Fig. 14.6).

One can also use light instead of nanofabricated elements to achieve that goal. In the discussion of laser cooling we mentioned that if a photon is absorbed by an atom, then its momentum must be transferred to that atom because of momentum conservation. So, if a photon propagating from left to right is absorbed, then that atom must experience a small velocity kick in that same left to right direction. If, however, the photon propagates from right to left, the velocity kick to the atom will be from right to left as well. And if the atom interacts simultaneously with *two* light fields, one propagating to the left and the other to the right, then it suffers both a velocity kick to the left *and* a velocity kick to the right. As a result the atom "goes in both directions," or more precisely the atomic matter wave is split into two partial waves, one propagating to the left and the other to the right. Acting together, the two light beams act as an atomic beam splitter.

Much like the observation that optical interferences build up "one photon at a time," this is his very strange. Loosely speaking, the atom can move in two directions at the same time, and be in two places at the same time. In the classical world such a behavior would be impossible: The atom would go either to the left *or* to the right, but not to the left *and* to the right.

This counter-intuitive behavior is at the core of the double-slit experiment: The observed interferences can only be understood if the atom is described as a wave that propagates simultaneously through both slits, so as to produce the interfering partial waves, just like with the two pebbles. Yet, if the atom is a particle, then surely it must go through either one or the other slit, but not both, right? So, what is going on? Can we not place small detectors near the slits, and measure which of them the atom went through? The answer is that one can certainly do that, but if one makes this "which way" determination, then the interferences disappear! In other words, if we don't ask "which way" the atom went then it behaves as a wave and produces interferences, but if we measure which slit it went through then it behaves as a particle, with no interferences.[9] How can that be? The great physicist Richard Feynman put it beautifully when he wrote [11]

» Because atomic behavior is so unlike ordinary experience, it is very difficult to get used to, and it appears peculiar and mysterious to everyone – both to the novice and to the experienced physicist. Even the experts do not understand it the way they would like to, and it is perfectly reasonable that they should not, because all of direct, human experience and of human intuition applies to large objects. [. . .] We choose to examine a phenomenon which is impossible, absolutely impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality, it contains the only mystery.'

14.4.2 Atom Interferometry

Optical interferometry is a remarkably powerful technique that uses the wave nature of light to measure small distances or displacements with extraordinary accuracy and sensitivity. As an example, the LIGO interferometers[10] built in Louisiana and the state of Washington to detect gravitational waves are able to measure length changes of one part in 10^{21} (this is one followed by 21 zeros!). Obviously, not all optical interferometers are that sensitive (or that expensive) but because of their remarkable properties, they are ubiquitous in R&D laboratories and industrial settings.

Optical interferometers come in many variations, but the basic idea is always pretty much the same. They rely on some combination of beam splitters and mirrors to divide a light beam into two or more partial beams that propagate in different environments where they are subjected to different forces and fields before being recombined to produce an interference pattern. For instance, one of the beams could go through an atomic vapor while the other propagates through vacuum, or one beam could have travelled a longer distance than the other; or perhaps one beam bounces off a moving mirror while the other is reflected by a mirror at rest. The key point is that the spatial and temporal features of the resulting interference pattern contain a great deal of information about the different environments that the partial beams propagated through (◘ Fig. 14.7).

Especially since the invention of the laser, optical interferometers have found countless uses in fields as diverse as physics, astronomy, engineering, applied science, remote sensing, seismology, telecommunications, biology, medicine, and manufacturing, to list just a few examples. Applications range from the measurement of extraordinarily small distances to the precise determination of specific

9   The same is also true for the photons of the previous section, and for any quantum particle.
10   The LIGO acronym stands for Large Interferometer Gravitational Wave Observatory.
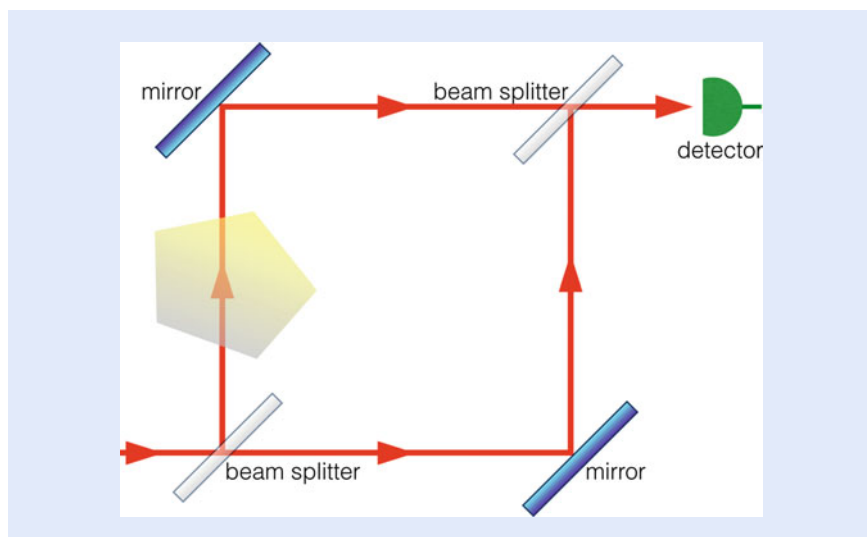
◘ **Fig. 14.7** Schematics of an interferometer, with two beam splitters to first separate and then recombine the partial beams. One of the beams propagates through some kind of an environment that modifies that interference fringes observed at the detector

atomic or molecular properties, from navigation and guidance to tests of the fundamental laws of physics, from medical imaging to electronic chip fabrication, and much more.

Despite all these successes there are situations where there is considerable benefit in using matter-wave interferometry instead. This is because not surprisingly, massive particles are orders of magnitude more sensitive than photons when it comes to measuring accelerations. For example, one finds that everything else being equal, interferometric gyroscopes (called Sagnac interferometers) using atoms rather than photons have a sensitivity that is larger by the ratio of their rest energy Mc^2 to the energy $h\nu$ of a photon,[11] that is, by $Mc^2/h\nu$. For visible red light and a typical atom such a Cesium this is a factor of about 10^{10}, or 10 billions! This is why atom interferometers are so well adapted to the precise measurement of rotations and accelerations, and can also serve as sensors for other forces and fields [6].

Gravimeters are one example of a practical device that can benefit significantly from atom interferometry. They are important in oil and mineral exploration, where they rely on the fact that different types of rocks or liquids have different densities. They determine the local value of gravity by measuring the acceleration of a free falling mass. Atom interferometers permit in principle to significantly increase the precision of these measurements over other methods. Using small atomic samples as free masses, they operate by splitting their atomic matter waves into two partial waves of different velocities. After some time during which the atoms are free falling the velocities of the two partial waves are then interchanged by a matter wave "mirror." Finally they are recombined to produce an interference pattern from which one can infer the acceleration with high precision and accuracy. To take advantage of the fact that the precision increases with the free fall duration one sometimes uses "atomic fountains" to increase that time. In that case

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11   The rest energy of a massive particle is its energy when it is not moving. For a particle at rest, $p = 0$, the relativistic energy equation $E^2 = p^2c^2 + M^2c^4$ of footnote 5 reduces to $E = Mc^2$, the equation for the rest energy of a massive particle famously associated with Einstein.

the atoms are launched upward before eventually turning around and falling back down toward the earth (for a brief history of atomic fountains see [15]).

14.4.3 Fundamental Studies

Because of their remarkable potential sensitivity atom interferometers are now a tool of choice not just in practical applications, but also in tests of the fundamental laws of physics, such as the Equivalence Principle. This is the fundamental principle which states that all objects fall with the same acceleration under the influence of gravity. It forms the foundational basis of Einstein's Theory of General Relativity. The best tests of the Equivalence Principle to date have shown that the accelerations of two falling objects differ by no more than one part in 10^{13}—this is one followed by 13 zeros [21]. A group led by Mark Kasevich at Stanford University aims for an improved test of this principle to one part in 10 ^{15} by dropping atoms of two different isotopes of rubidium[12] in a 10 m high drop tower [22] (◘ Fig. 14.8).
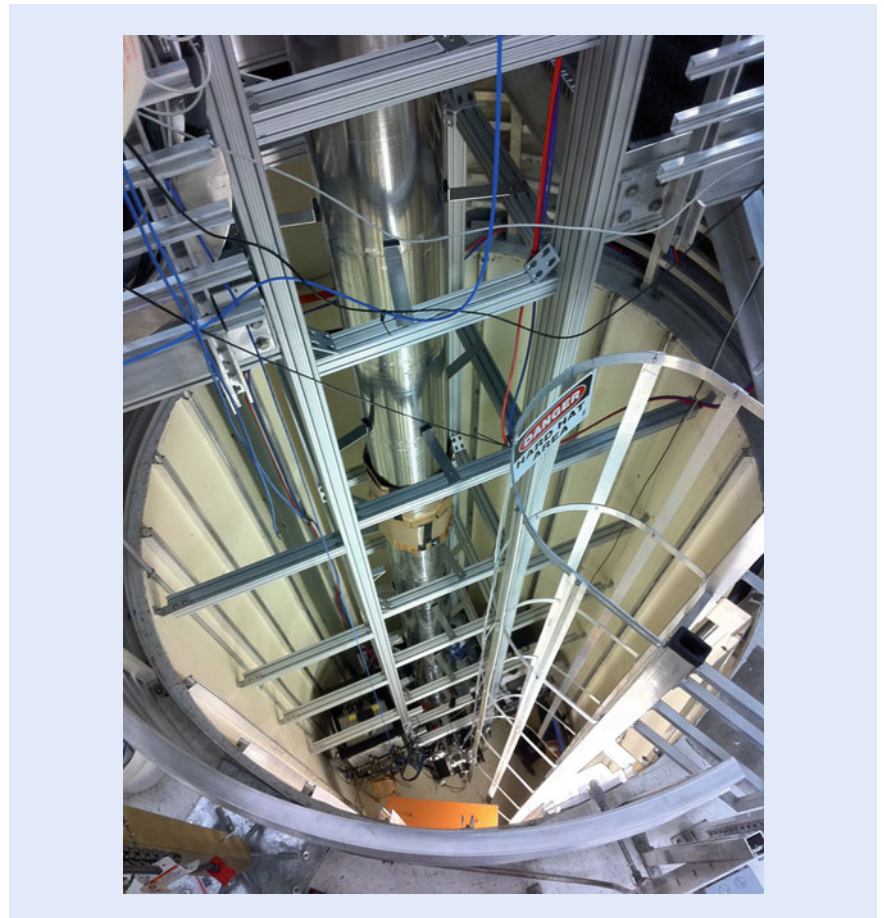
◘ **Fig. 14.8** Stanford 10 m tower used for tests of the equivalence principle (courtesy Mark Kasevich, Stanford University)

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12   Isotopes are variations of a chemical element that all have the same number of protons and electrons, but differ by the number of neutrons in their nucleus, and hence have different masses.

In another example, atom interferometry offers great promise for the development of a new mass standard. Surprisingly perhaps, the kilogram is the last physical unit that is defined by an artifact, the International Prototype Kilogram. It is the mass of a block of platinum–iridium alloy stored in an environmentally controlled vault in the basement of the International Bureau of Weights and Measures in Sèvres, near Paris. In addition to being subject to damage, this standard presents the fundamental issue of not being based on a physical law.

One proposal is to define the unit of mass in terms of a frequency. This would be possible provided that one assigns to the Planck constant h a fundamental value, much like the speed of light c is assigned a fundamental value that allows to connect lengths to times.[13] The basic idea is that the momentum imparted on atoms by light is proportional to the frequency of that light, and inversely proportional to the mass of the atom, the proportionality factor being given by Planck's constant. If it were assigned a fundamental value, then one could connect masses to frequencies extraordinarily accurately. Future space-borne atom interferometers might then allow the measurement of atomic masses anywhere on Earth better than 1000 times more accurately than is presently the case.

A third example of a basic science application of atom interferometry is in gravitational wave detectors. Four centuries after Galileo (1564–1642) used telescopes to study and revolutionize our understanding of the Universe they remain our most powerful tool to learn about it, whether they detect radio waves, sub-millimeter waves, infrared radiation, visible light, ultraviolet radiation or X-rays. However, it is believed that extremely significant additional information would be provided by the detection and characterization of the gravitational waves produced by the motion of massive objects, in particular closely orbiting compact massive objects such as neutron stars or black holes binaries, merging supermassive black holes, collapsing supernovae, or pulsars. Gravitational waves might also provide information on the processes that took place in the early Universe, shortly after the Big Bang. However they interact only extremely weakly with matter, and so far they have remained elusive.[14]

It is expected that in the near future Advanced LIGO, the upgraded version of the LIGO gravitational wave antennas, will be sensitive enough to detect gravitational waves at the rate of maybe a few events per year. To further increase sensitivity and the frequency of observations, future systems will likely need to be space-based, one example being the proposed Laser Interferometer Space Antenna (LISA). Mark Kasevich and his coworkers at Stanford have proposed an alternative space-based hybrid approach (◘ Fig. 14.9) combining optical methods and atom interferometry [13]. Their proposal draws on the use of an optical method to measure the differential acceleration of two spatially separated, free falling atom interferometers whose mirrors and beam splitters are produced by light pulses sent back and forth between them through space. Comparing the matter-wave interference fringes in the two interferometers would provide a record of the effect of gravitational waves on the travel time a laser pulse linking the two atom interferometers. It is argued that using atoms instead of mirrors as test masses would reduce a number of systematic errors.

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13 State-of-the-art atomic clocks can measure times to accuracies in excess of one part in 10^{17}, so that reducing the determination of a physical quantity to a measurement of time or frequency is particularly favorable.

14 Note added: This is no longer the case! A few months after this article was completed the LIGO Scientific Collaboration and the Virgo Collaboration reported the first direct observation of a gravitational wave signal, resulting from the collision of two massive black holes [1]. This historic breakthrough, 100 years after Einstein's 1916 prediction, opens the way to a new era in observational astronomy.
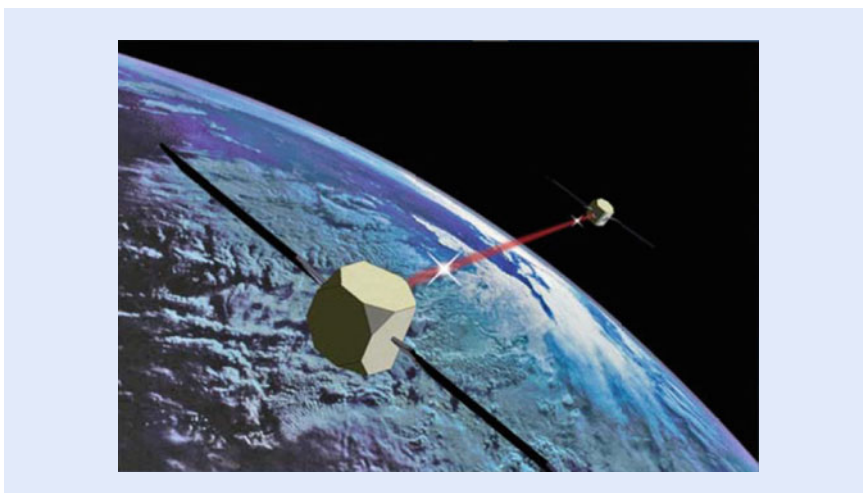
Fig. 14.9 A proposed space-borne atom interferometer gravitational wave detector. Two widely separated atom interferometers are controlled by light pulses sent back and forth between them. Passing gravitational waves will modify the travel time of the light pulses between the interferometers, resulting is a shift on their interference fringes that provide a record of the gravitational wave (courtesy Mark Kasevich, Stanford University)
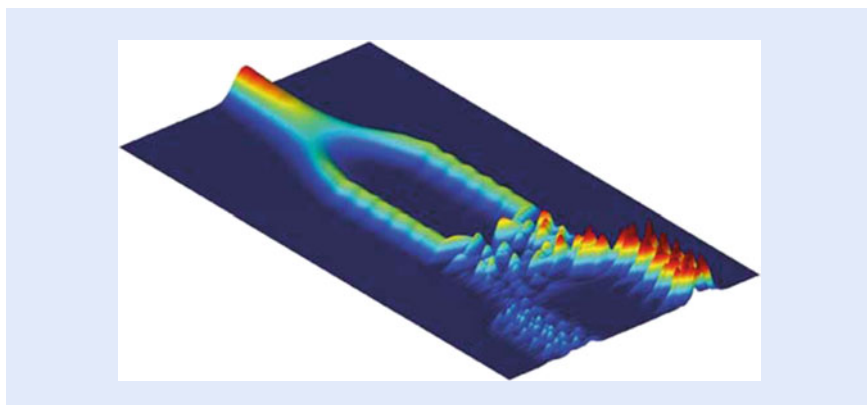
14.4.4 BEC Atom Interferometers

In conventional optics it is often favorable to use lasers rather than conventional light sources, if only because they can have very high photon fluxes within a very narrow range of wavelengths. So one might ask whether the same is true in atom optics, and whether it would be advantageous to use an "atom laser," or Bose–Einstein condensate, rather than a regular beam of non-condensed ultracold atoms.

The simple answer is that this is typically not the case, because of an important difference between photons and atoms: Two light beams propagating in different directions in free space can cross without perturbing each other, because photons don't directly interact. In contrast, atoms do collide. Collisions are random events that result in uncontrolled changes in the interferences between the atom matter waves. This leads to additional detection noise that can significantly limit the sensitivity and accuracy of measurements. As collisions become more frequent when the atomic flux is increased this limits the applicability of Bose–Einstein condensates in atom interferometry.

This problem can, however, be circumvented to some extent by reducing the collisions between atoms. This can sometimes be achieved in ultracold atomic samples by using magnetic fields to control the collision rate. In the best cases it is possible to almost completely suppress collisions, leading to the potential for high precision interferometry with Bose–Einstein condensates. Alternatively, under appropriate conditions other quantum effects can be exploited to increase the sensitivity of the system and the precision of measurements, using, for example, the so-called squeezed states or number states of the matter waves.[15] An atom interferometer based on this principle was recently realized in the group of Jörg

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15 Quantum objects are subject to fundamental random fluctuations called quantum noise—this is why even at $T = 0$ atoms are not completely still, see footnote 6. But it is sometimes possible to prepare atoms or photons in such a way that this noise is "squeezed away," or more precisely transferred to a place where it does not add imprecision to a specific type of measurement.

🔲 **Fig. 14.10** BEC atom interferometer using squeezed states of the matter waves to reduce the noise below the so-called shot noise limit of conventional systems (courtesy Jörg Schmiedmayer, Technical University Vienna)

Schmiedmeyer at the University of Vienna [4], see 🔲 Fig. 14.10. Another possible approach involves the use of fermionic atoms instead of bosons, although the interference contrast tends to be reduced in that case.

14.5 Outlook

It is widely accepted that quantum mechanics is the fundamental theory of nature. It has been and continues to be put to numerous, increasingly elaborate tests that it has so far passed with flying colors. Yet, in everyday life we don't observe the remarkable quantum effects that we can achieve with small ensembles of atoms or with photons under exquisitely controlled conditions. We cannot make a car be "in two places at the same time," or, in the famous example of Schrödinger, we cannot have a cat that is both alive and dead at the same time. Our everyday world seems to be most definitely governed by the laws of classical physics, not by quantum mechanics. This is extremely puzzling, because if the quantum mechanical description of nature is more fundamental than its classical description, then quantum mechanics should govern not just the microscopic world, but the macroscopic world as well.

Why and how macroscopic systems lose their quantum features and become essentially classical are challenging questions that are being addressed by a number of researchers, both theoretically and experimentally. On the theoretical side, proposed explanations range from relatively mundane mechanisms, such as increasingly fast decoherence resulting from the contact of objects of increasing size to their environment, to speculations about the role of gravity in washing out quantum features in massive objects.

On the experimental side, there are exciting efforts to observe quantum interferences in increasingly macroscopic objects, with the goal of improving our understanding of the physical mechanisms that wash out quantum features in objects of increasing complexity. For example, a group around Markus Arndt at the University of Vienna has succeeded in demonstrating the wave nature of large organic molecules, from the "buckeyball" C_{60} to the very large molecule TPPF152 ($C_{168}H_{94}F_{152}O_8N_4S_4$,) which contains 430 atoms and has a thermal de Broglie wavelength of about one picometer, a millionth of a millionth of a meter [12]. It is hoped that eventually such experiments will help determine whether the quantum to classical transition is a practical and relatively mundane issue or a truly

fundamental occurrence. Is there a fundamental limit on the size of objects that can behave as de Broglie waves, or are the challenges only practical?

In an ambitious proposal, Oriol Romero-Isart, Markus Aspelmeyer, Ignacio Cirac, and coworkers have recently proposed a method to prepare and verify spatial quantum superpositions of a nanometer-sized object separated by distances comparable to its size [20]. It is hoped that such experiments will eventually be able to operate in a parameter regime where it will be possible to test various proposed mechanisms beyond quantum mechanics that have been advanced to explain the washing out of quantum properties in macroscopic objects. It will be exciting indeed to see these proposed experiments being realized and start answering questions that have surrounded quantum mechanics and its interpretation since its early days, nearly 100 years ago.

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