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Experiments in Atom Optics*

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Abstract

This article outlines experiments which have highlighted the rapid development of the field of atom optics since the mid 1980s. The distinguishing features of the components used in atom optics are compared with their conceptual analogues in light optics. The potential for atom optic devices, both demonstrated and predicted, are described. Experiments and applications of this new technology are reviewed, and the article concludes with a synopsis of work in this field currently being undertaken in Australasia.

1. INTRODUCTION

1·1 Optics using Atoms

We are all familiar with the important role that light optics plays in modern technological society — from photochromic eyewear to laser surgery, banknote pixelgrams to CD players, and barcode scanners to optical communications superhighways. As physicists we are familiar with the dual concepts of light propagation both as a wave and as a particle.

However, we are perhaps less familiar with the new and rapidly developing field of atom optics, which has the potential to open up a new realm of technology which is the direct analogue of conventional optics for light. Atom optics also exploits the dual wave–particle picture, but this time as applied to atoms, not photons. To this extent, atom optics is a complete realisation of the complementarity principle with direct applications to real life.

Atoms, like photons, possess both a wavelength (the de Broglie wavelength $\lambda_{\rm dB}$) and momentum p. These variables are connected by the relation $l_{\rm dB} = h/p$, where h is Planck's constant. The momentum ($p = mv$) of a typical atom (mass m and velocity v) is large compared to that of a photon of light ($hk = h/\lambda$, where $k = 2\pi/\lambda$), and yields a correspondingly smaller wavelength. For example, a sodium atom travelling at thermal velocities from an oven source (with $v \sim 1000\ {\rm m}^{-1}$) has a de Broglie wavelength of around $2{\times}10^{-11}$ m (0·02 nm), compared to typical light wavelengths of hundreds of nanometres. A diagram illustrating the relationship between the de Broglie wavelength and a number of other parameters is given for sodium atoms in Fig. 1.

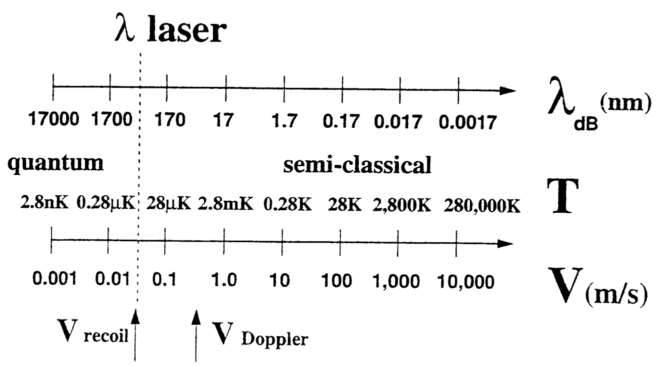


Fig. 1. Comparative parameters for a sodium atom travelling at a range of velocities V (m s^{-1}), temperature T (K) and de Broglie wavelength $\lambda_{\rm dB}$ (nm). The laser wavelength (at the 589 nm sodium D lines) separates the semiclassical treatment of the atom+field from the full quantum regime.

Both the wave and particle nature of atoms have been exploited to duplicate the same optical phenomena as have long been demonstrated for light. However, atoms can be used in new classes of experiments for which there is no photon analogue. This is a result of the fact that atoms possess additional properties which yield particular advantages:

Atoms have a non-zero rest mass. The atomic mass interacts more strongly with gravitational forces than do photons. As a result, atom interferometers can be used to measure local variations in gravitational fields, with potential applications such as mineral exploration. Gravity can also be used as a restoring force, e.g. in gravitational atom traps, or atomic fountains.

Atoms have variable velocities. This is a further consequence of atomic mass, with the result that the dispersion laws for atoms differ from that for photons (which have constant velocity). The result is that the de Broglie wavelength of an atom may be altered, and this leads to changes in the concept of coherence.

Atoms can interact with each other. As a result, the phase shift produced by atomic collisions in, for example, one arm of an atom interferometer, can be used to measure interatomic potentials or refractive indices.

Even so, applications of the wave–particle duality of matter are not new. Electron diffraction and neutron interferometry are just two other examples. What is new is that modern laser and microfabrication technologies enable access to the unique properties that atoms possess, which in turn makes atoms useful for new types of matter–wave applications.

Atoms have internal structure. This is the major advantage that atoms have over other particles such as electrons and neutrons. The well defined internal energy structure of atoms enables both their internal state and momentum (i.e. wavelength) to be precisely controlled through strong, near-resonant, dipole interactions with light — particularly laser light. The control of the internal states also allows these interactions to be rapidly switched on and off, and furthermore provides extremely sensitive detection.

Of particular importance is the existence of dissipative forces arising from spontaneous emission, which enables atoms to be cooled or heated. There is no equivalent to this process in conventional optics, and the result is that the phase-space density of atoms can be increased beyond that of the original source — something that is not possible for light. It is this advantage that underlies atom cooling and trapping.

Atoms have no net charge. Unlike electrons, atoms have no net charge and thus are not subject to strong deflection by external electric or magnetic fields. They may therefore be used to detect the effects of weaker forces, such as gravity.

Atoms are easy to produce. Atomic ovens or jets produce high fluxes of particles, and are more accessible for small-scale (laboratory-scale) experiments than are reactor or accelerator sources for neutrons.

Atoms have variety. The differences in atomic structure, mass, polarisability and magnetic moment allow a variety of manipulation techniques and applications.

1·2 Classes of Atom Optics and Their Applications

The ability to control the motion of atoms using near-resonant laser light forces and new microfabrication techniques has led to the rapid development of the field of atom optics, which has experienced an explosion of activity since the mid-80s. In particular, the advent of high-resolution, tunable lasers has enabled precise access to the internal states of the atom. Intense beams of laser light have in recent years been used to manipulate, cool, trap and coherently 'split' the wavepacket of neutral atoms. The result is an evolving new technology which replicates and extends the analogue of optics for light. This new technology has many potential applications — both to fundamental research and to commercial development.

Many components for this new technology have already been realised: mirrors, gratings, beamsplitters and lenses have been created (Adams *et al.* 1994). These 'optical' elements interact with atomic de Broglie waves in an analogous fashion to light waves interacting with conventional optics. The first generation of devices utilising these components have also now been built.

Experiments in atom optics can be described by a classification that is introduced here and which comprises three main orders. These categories are distinguished by the fundamental nature of the atomic properties being exploited.

Zeroth-order atom optics simply uses elements to manipulate the atom as a particle, and does not involve the wave nature of the atom. Here the force exerted by light interacting with the atom's internal structure (the dipole force) is used to manipulate the position and momentum of the atom (Ashkin 1980; Minogin and Letokhov 1987; Balykin and Letokhov 1989*a*; Kazantsev *et al.* 1991; Letokhov 1992; Balykin and Letokhov 1995). A discussion of light forces is contained in the article by Savage (1996, present issue p. 745).

One application of light forces for controlling the atomic momentum is the laser cooling of atoms (see Savage 1996 and the special issues on 'Laser Cooling and Trapping': Meystre and Stenholm 1985; Chu and Wieman 1989; Bagnato *et al.* 1994). Laser cooling may be achieved in many ways, but a simple means is by the redistribution of the photon momentum of an intense laser beam. Light travelling in the direction of the laser beam is absorbed by the atom near resonance, and the photon momentum transferred to the atom. The atom then re-radiates the light isotropically by spontaneous emission, thereby resulting in a net decrease of the atomic momentum in the direction of the laser (for a laser tuned to the sodium D-lines, this results in a decrease in velocity of $\sim 3\ \mathrm{cm\,s^{-1}}$ for each absorption/emission cycle — the recoil velocity).

Through many successive interactions, the atom may be slowed significantly, and by extending this process to six laser beams in three dimensions, atoms may be cooled to very low temperatures. Currently there are a number of atomic traps operating on different schemes. Some of these traps have produced the coldest temperatures ever recorded — in the range of tens of nano-Kelvin — and in principle atoms can be trapped in states of zero velocity (Cohen-Tannoudji *et al.* 1990; Gilbert and Wieman 1993; Metcalf and van der Straten 1994; Savage 1996).

Such traps may lead to the development of atomic clocks with very high precision. Cooled and trapped atoms can also provide a dense source of systems in well defined states. These ultracold atoms can then be probed using high-resolution spectroscopic techniques for novel atomic physics applications, or for the investigation of fundamental collective effects such as controlled molecular formation or Bose–Einstein condensation (Anderson *et al.* 1995; Bradley *et al.* 1995; Collins 1995; Davis *et al.* 1995; Griffin *et al.* 1995; Hecht 1995*a*, 1995*b*).

The use of light fields to control atomic trajectories also has important applications, such as the development of nano-technologies. Because the atomic de Broglie wavelength can be made very small ($\ll 0 \cdot 1$ nm), the opportunity arises for the creation of very high resolution structures. The ability to precisely direct atomic beam deposition onto prepared surfaces holds great promise for direct-write lithography (Kiernan 1993; McClelland *et al.* 1993).

First-order atom optics utilises the wavelike nature of the atom in its description, and generally exploits the ability of the atomic wavepacket to be split coherently into two or more states. For example, an atomic beam crossing perpendicular to a single laser beam may experience a deflection due to zeroth-order effects. However, if a second laser beam is propagated counter to the first, a standing light field is set up with a periodicity equal to half the laser wavelength. An atomic de Broglie wave interacting with this spatially periodic field will experience diffraction, and the wavepacket corresponding to the atom can be coherently 'split' between the various diffraction orders.

Perhaps the best example of an application of first-order atom optics is the atom interferometer (Levi 1991; and special issues on 'Optics and Interferometry with Atoms': Mlynek *et al.* 1992; Pillet 1994; Rempe and Schleich 1995; Arimondo and Bachor 1996). As with light interferometry, the atom interferometer coherently splits the de Broglie wave into two paths, and then recombines the partial waves to enable sensitive measurement of the phase difference induced by passage along the two arms. Such an interferometer could be used to sensitively measure phase changes due to collisions, acceleration, or external field gradients such as gravity.

Second-order atom optics relies on the quantum nature of the centre-of-mass motion of the atom, i.e. it requires quantisation of the atomic kinetic energy state. One example is the trapping of cold atoms in the potential wells formed by strong, three-dimensional standing-wave laser light fields (Stein 1994; Collins 1993). Atoms whose kinetic energy is less than the potential well depth exist in eigenstates of the potential and can be made to jump between such states through the application of probe laser fields.

It is also conceivable that atoms may be trapped between two mirrors or in a stepped waveguide to form an atomic cavity. The atomic wavefunctions would then form discrete modes in the cavity. By switching atoms which are present in other states into cavity modes, a coherent gain of atoms could be achieved, resulting in a 'laser' for atoms.

These latter examples may sound far-fetched, but many atom optic devices are with us now (Adams *et al.* 1994). Atom interferometers have already been used to measure external field gradients, accelerations and fundamental constants. Clocks based on trapped atoms and ions are currently being developed. Bose–Einstein condensation has now been achieved in atomic traps. And atomic beams are being manipulated for many purposes, including direct-write lithography on prepared surfaces.

This article will outline the development of the elements used in this new technology.

1·3 Components of Atom Optics Experiments

Atom optics experiments generally consist of three major components: the source of atoms, the 'atom optical' device, and a detector to measure the effect of the device.

Sources. Atomic sources are usually of two types (Ramsey 1986; Scoles 1988). The first is the **effusive source**, where atoms in gaseous form are emitted at subsonic velocities through an aperture from a high-pressure reservoir into a lower-pressure evacuated region. The resulting source has an approximately cosine intensity distribution with respect to the propagation direction, and a Maxwellian velocity distribution. Effusive sources are generally easier to operate, and are used when the atomic flux is plentiful and there are few constraints on directionality.

When the reservoir pressure is increased, a supersonic source can be created, in which three-dimensional motion is converted into (almost) one-dimensional kinetic energy with a narrow longitudinal velocity distribution. Supersonic sources may also be cryogenically cooled to reduce the longitudinal velocity (and hence increase the atomic de Broglie wavelength).

Gas jets consisting of a reservoir with a nozzle are typically used for gas-phase sources. For atoms that do not exist in gaseous form at room temperature, **ovens** are used to create a vapour, with a small aperture in the oven chamber allowing the vapour to be emitted from the source.

A listing of the properties of candidate species for atom optics experiments is given in Table 1, together with the atomic transitions used for the dipole force interaction with laser light fields. Most of the species are metal vapours, for which the strong resonance transitions from the (well populated) atomic ground states are prime candidates for laser manipulation.

Some species — notably the noble gases listed in Table 1 — do not have accessible (visible/infrared) transitions from the ground state since the resonance lines are in the deep ultraviolet. Hence metastable excited states (with dipole forbidden transitions to the ground state) are used which possess sufficiently long lifetimes ($>10^{-4}$ s) and have visible/infrared transitions to higher states. The long lower-level lifetimes are required so that at least several absorption/stimulated emission cycles (typically tens of ns) in the laser-induced transition can be completed in order to alter the atomic momentum significantly during the typical interaction times used (of the order of μs for a 1000 m s^{-1} atom travelling through a 1 mm diameter laser beam).

For some experiments, a better-controlled atomic source may be required. It is often useful to confine the atoms to a particular region of phase space, or to alter the atomic de Broglie wavelength. For example, even atoms from a supersonic nozzle experience some beam divergence due to the small but non-negligible transverse velocities in the beam. In experiments requiring more precise control over the atomic velocity, it is often desirable to load atoms from thermal sources (ovens or jets) into an **atomic trap**, and then release the trapped atoms in a controlled fashion (either by turning the trap off and dropping them, or by imparting a velocity in a particular direction using light forces).

Since atoms cooled following release from the trap can be made extremely cold (velocities of some cm s^{-1}), they can provide a well defined source in momentum space. In the same way, atoms of very large de Broglie wavelength can also be created, even approaching the wavelength of the confining light (the transition from the semiclassical to the quantum regime in Fig. 1). The slower velocities achieved by laser cooling techniques also enable longer interaction times and consequently larger net effects on the atomic momentum.

Table 1. Parameters for commonly used atoms in atom optics experiments

Hydrogen has yet to be successfully manipulated by light forces because of its short resonance transition wavelength, for which cw laser sources do not yet exist

Atom	Mass	Transition	λ(nm)	λ_{dB} (nm)	τ(ns)	$\Gamma/2\pi$(MHz)	T_d (μK)	V_d (cm/s)	ν_r (kHz)	T_r (μK)	V_r (cm/s)	I_s (mW/cm^2)
				for V=1 m/s								
He*	4	$2^3S_1 \rightarrow 2^3P_2$	1083	100	98	1.62	38.9	28.4	42.3	4.08	9.21	0.167
		$2^3S_1 \rightarrow 3^3P_2$	389		99	1.6	38.4	28.3	330	31.6	25.6	3.57
Ne*	20	$3s[3/2]_2 \rightarrow 3p[5/2]_3$	640.2	20	19.4	8.19	197	28.6	24.2	2.34	3.1	4.09
Ar*	40	$4_s[3/2]_2 \rightarrow 4p[5/2]_3$	811.5	10	31	5.14	123	16.0	7.53	0.73	1.23	1.26
Kr*	84	$5_s[3/2]_2 \rightarrow 5p[5/2]_3$	811.3	4.8	30	5.30	127	11.4	3.59	0.35	0.59	1.30
Xe*	131	$6_s[3/2]_2 \rightarrow 6p[5/2]_3$	881.9	3.0	34	4.67	112	8.4	1.95	0.188	0.34	0.892
Li	7	$2S_{1/2} \rightarrow 2P_{3/2}$	670.7	57	27.3	5.82	140	40.7	63.0	6.08	8.50	2.53
Na	23	$3S_{1/2} \rightarrow 3P_{3/2}$	589.0	17.4	16.4	9.70	233	29.0	24.9	2.40	2.95	6.19
Rb	85	$5S_{1/2} \rightarrow 5P_{3/2}$	780.0	4.7	26.5	6.00	144	11.9	3.84	0.37	0.60	1.65
Cs	133	$6S_{1/2} \rightarrow 6P_{3/2}$	852.1	3.0	30	5.30	127	8.9	2.05	0.20	0.35	1.12
Mg	24	$2^1S_0 \rightarrow 2^1P_1$	285.2	16.6	2.0	80	1920	81	101.6	9.8	5.8	474
		$2^1S_0 \rightarrow 2^3P_1$	457.1		4.6 ms	34.5 Hz	8.3×10^{-4}	0.054	39.7	3.8	3.6	5×10^{-5}
Ca	40	$3^1S_0 \rightarrow 3^1P_1$	422.8	10.0	4.5	35.3	847	42	27.8	2.68	2.36	61.2
		$3^1S_0 \rightarrow 3^1P_1$	657.5		0.40 ms	0.39 kHz	9.4×10^{-3}	0.14	11.5	1.11	1.52	13.5
Cr	52	$^7S_3 \rightarrow {}^7P^0_4$	425.6	7.7	31	5.14	123	14	21.1	2.03	1.80	8.71
Sr	88	$5^1S \rightarrow 5^3P_0$	689	4.5	21μs	7.58 kHz	0.182	0.41	4.8	0.46	0.66	3.0×10^{-3}
H	1	$1^2S \rightarrow 2^2P$	121.6	399	1.60	99.5	2,390	446	1.34×10^4	1300	328	7230

λ (nm) = transition wavelength

λ_{dB} (nm) = h/mV = de Broglie wavelength = 399/M nm (for 1m/s atoms)

τ (ns) = upper state transition lifetime

$\Gamma/2\pi$ (MHz) = transition linewidth **in MHz** = $1/\tau(\mu s)$ MHz

T_d (μK) = h $\Gamma/2\pi$ (MHz)/2k = Doppler limit T = 24.0 $\Gamma/2\pi$ (MHz) μK

V_d (cm/s) = $[h\Gamma(\text{MHz})/2m]^{1/2}$ = Doppler limit velocity

= 44.7 $[\Gamma/2\pi\ (\text{MHz})/M]^{1/2}$ cm/s

* = metastable atom

ν_r (kHz) = $h/2m\lambda^2$ = recoil frequency = $199/[M\lambda^2(\mu m)]$ kHz

T_r (μK) = $(h/\lambda)^2/mk$ = recoil temperature = $19.15/[M\lambda^2(\mu m)]$ μK

V_r (cm/s) = $h/m\lambda$ = recoil velocity = $39.9/[M\lambda(\mu m)]$ cm/s

(Note: in the recoil limit $\lambda_{dB} = \lambda_{laser}$)

I_s (mW/cm^2) = $\pi hc/3\lambda^3\tau$ = saturation intensity = $20.8/[\lambda^3(\mu m)\tau(ns)]$ mW/cm^2

k = Boltzmann's constant = 1.381×10^{-23} J/K

h = Planck's constant = 6.626×10^{-34} JHz^{-1}

1M (amu) = 1.661×10^{-27} kg

Atom optical devices. These are generally of three types: matter elements (crystals or microfabricated structures), static fields (electric or magnetic), and oscillating electromagnetic fields (laser light).

The earliest experiments in atom optics in the 1920s used **optical elements made from matter** to reflect and diffract atoms from smooth metallic and crystalline surfaces (Stern 1929; Knauer and Stern 1929; Estermann and Stern 1930). Clearly the inability of atoms to penetrate matter limits the application of such experiments to reflective devices. Indeed, a field of surface studies has originated using diffractive atom scattering as a diagnostic technique.

However, such reflective surface devices were generally regarded as unpromising for atom optical elements since they are relatively inefficient, and require exceptional smoothness and cleanliness to avoid random changes in momentum due to scattering from irregular features. With modern vacuum techniques, thermal caesium atoms have been reflected through up to 40 millirad from a polished glass surface in a regime intermediate between specular and diffuse scattering but with an efficiency of >50% (Anderson *et al.* 1986), while hydrogen atoms have been reflected and focused from a liquid helium film on a curved quartz substrate with >80% efficiency (Berkhout *et al.* 1989).

Furthermore, prior to the development of laser cooling, the small ($\ll$1 nm) de Broglie wavelength of the available thermal atoms resulted in relatively small first-order atom optic effects. For example, thermal potassium atoms with a de Broglie wavelength of $0\cdot0175$ nm were first diffracted from a single 23 μm slit in 1969, yielding diffraction effects resolved by less than 10 microrad (Leavitt and Bills 1969).

However, advances in microelectronics have in recent years improved fabrication techniques to the extent that the scales of the structures produced are smaller than an optical wavelength, and are approaching realisable atomic de Broglie wavelengths (tens of nm). Such structures can be used in transmission, thereby obligating the need for extremely uniform surface finish. Furthermore, atom optic elements made from matter work for any atomic or molecular species, since their operation (for **diffractive elements**) depends only upon the de Broglie wavelength of the species and not on its internal structure.

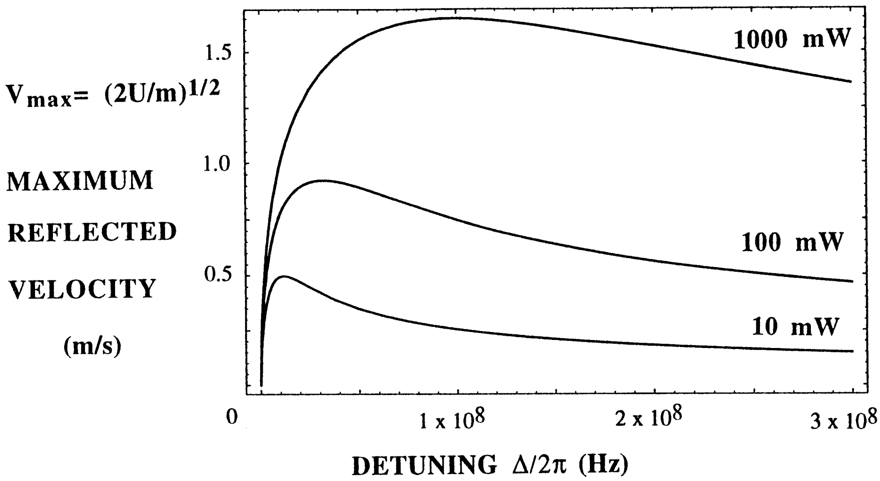
Static electric or magnetic fields can also interact with the atom to alter the atomic momentum. Early experiments in 1951 used hexapole magnetic fields to focus thermal atoms in a specific magnetic sublevel (Friedburg and Paul 1951). In 1995, a static magnetic field from a current-carrying wire has been used to perform a Stern–Gerlach experiment on a beam of laser-cooled atoms released from a trap, with the atoms being spatially separated according to their magnetic sublevel (Rowlands *et al.* 1995).

In some very recent experiments, the Stern–Gerlach effect has been used to reflect cold atoms dropped onto a magnetic mirror consisting of spatially varying periodic fields prepared on a flat surface. Multiple bounces (up to four) following impact velocities of up to $0\cdot7$ m s^{-1} have been demonstrated for Rb (Roach *et al.* 1995) and a similar experiment has been performed for Cs where three bounces were observed (Sidorov *et al.* 1996). Single-bounce reflection efficiencies of up to 94% were achieved in the Rb experiment, and approached 100% in the Cs experiment.

Table 2. Typical laser parameters used in the creation of optical potentials for the manipulation of sodium atoms

Shown is the maximum velocity for which atoms can be reflected from a conservative ($\Delta > \Gamma$) potential U

$U = (h\Delta/2)\ \ln[1 + 2\Omega_R^2/(4\Delta^2 + \Gamma^2)]$	for large Δ (conservative potential)
$\sim h\Omega_R^2/4\Delta$	for very large $\Delta \gg \Gamma, \Omega_R$



LASER BEAM AREA:		0.1 cm^2	(r = 1.78 mm)		
LASER POWER:		10	100	1000	mW
LASER INTENSITY:		10^2	10^3	10^4	mW/cm^2
MAX. VELOCITY	($\alpha\ I^{1/4}$)	0.49	0.92	1.65	m/s
TEMPERATURE	($\alpha\ I^{1/2}$)	0.67	2.3	7.5	mK
DETUNING Δ AT V_{max}		13	30	100	MHz

ATOM:	Sodium
SATURATION INTENSITY:	6.2 mW/cm^2
MASS:	23 x 1.66 x 10^{-27} kg
LINEWIDTH (FWHM) $\Gamma/2\pi$:	9.7 MHz
RECOIL VELOCITY:	2.95 cm/s (2.4 μK)

Like elements made from matter, static field devices do not suffer from the decoherence effects caused by spontaneous emission. Generally speaking, however, the static field interactions are somewhat weaker, and are less flexible than are light forces. Furthermore, atoms in the ground state and negative magnetic sublevels move towards regions of high static field strength and therefore cannot be focused or trapped. Low-frequency fields have, on the other hand, been used to demonstrate the focusing of ground-state atoms (Shimizu 1993).

By contrast, rapidly oscillating electromagnetic fields have one primary advantage, namely the exploitation of tunable, **near-resonant dipole force interactions** with the internal states of the atom, which can yield forces much greater than are obtainable for static fields. Since the turn of the century, radiation pressure has been known to produce small but measurable forces on matter due to non-resonant reflection of light (Lebedev 1901). In 1933 resonant light forces from a sodium lamp were used for the first time to demonstrate the deflection of a sodium atomic beam (Frisch 1933). Because the light flux from the lamp was very low, the deflection observed was a mere 10 μm.

However, it was not until the 1980s, with the advent of narrowband laser sources of much higher intensities which can precisely tune to atomic resonances, that the creation of practical optical devices for atoms was realised. Table 2 indicates typical laser parameters used for the creation of light potentials to control atomic motion. The ability to control the interaction by resonant tuning is a major advantage of **laser-based atom optics elements.**

The effect of spontaneous emission resulting from these resonant processes can in some instances be a disadvantage, such as the stochastic spread of the atomic momentum due to diffusion, whereas in other cases it may be advantageous, e.g. in the application of dissipative light forces. These days, the near-resonant dipole force is the primary mechanism for controlling the atomic momentum in modern atom optics.

Detectors. A range of techniques exist for detection in atom optics, some of which are sufficiently sensitive to detect a single atom.

Neutral atoms can be collected using a **hot wire detector** (Hughes and Schultz 1967) which adsorbs the atom briefly before boiling it off. In the process, the atom is ionised if the work function of the surface is greater than or equal to the ionisation potential of the atom. The ions are then detected as a current proportional (under certain conditions) to the incident atomic flux. The technique is useful for atoms of low ionisation potential such as the alkali metals. However, it is relatively inefficient for atoms with ionisation potentials approaching the work function of the surface (e.g. 6 eV for tungsten), and not useful at all for atoms with strongly bound electrons. A further disadvantage is that the spatial resolution is limited by the thickness of the wire (tens of μm), and the temporal resolution is limited by the adsorption time and the inductance of the entire system (hundreds of μs). Finally, hot wire detectors provide no information on the atomic velocity, except when used in conjunction with a time-of-flight apparatus (which then suffers from the limitations of the hot wire's temporal resolution).

Atoms with significant excitation energy, such as the **metastable rare gases**, can be detected readily using detectors developed for charged-particle or short wavelength photons (Hotop 1995). Metastable atoms yield particular advantages for atom optics applications, since they are generally detected with nearly unit efficiency. Furthermore, any metastable atoms which do not interact with the atom optic device are invariably scattered from surfaces in the experimental apparatus, causing de-excitation and thereby yielding a zero background level. Hence, experiments can be arranged so that only those atoms which interact with the atom optic device are detected, thereby improving the experimental sensitivity enormously.

Metastable detectors include **electron emitting devices** such as channeltrons, microchannel plates etc. which release electrons either through an Auger process or by direct emission from the surface. These detectors are nearly 100% efficient, are faster than hot wire detectors, and can provide two-dimensional information with high spatial resolution ($<10\ \mu$m in the case of microchannel plates). Other techniques, such as monitoring the fluorescent decay of the metastable state, or the use of detectors which fluoresce upon impact by metastables, are also employed, but are less efficient and do not possess the advantages of charged-particle detectors. Like hot wire detectors, none of these methods provide velocity resolution.

The most versatile detection method employed for atom optics experiments is **laser-induced fluorescence (LIF)**. Despite the fact that the collection efficiency of the emitted radiation is very rarely unity, the detected atoms can, however, be made to undergo multiple absorption/emission cycles during transit through the detection laser. Furthermore, LIF is state-selective, and may either employ the same transition as is used to manipulate the atom in the atom optical device, or use a different transition in order to remove the background contribution of scattered light from the device. In this way LIF has similar advantages to metastable detection, and in some circumstances, by selecting the appropriate lower level, can be used to detect only those atoms which have interacted with the device.

Another great advantage of LIF is the ability to measure the atomic Doppler shift with reference to a stationary reference source, such as a saturated absorption cell. As a result, this technique can be made velocity (and hence de Broglie wavelength) selective. Typical laser bandwidths of 1 MHz yield a velocity resolution of $\sim 1\ \mathrm{m\,s^{-1}}$, although in practice the resolution is often limited by the natural linewidth.

2. ZEROTH-ORDER ATOM OPTIC ELEMENTS

We distinguish here between zeroth-order atom optic elements, which alter the atomic momentum but in which the atom can be treated as a particle, and other elements which utilise a wavefunction treatment for the atomic centre-of-mass motion. Atomic traps, while usually employing zeroth-order processes, are not discussed here as they are treated elsewhere in this issue (Savage 1996, p. 745).

2·1 Mirrors

Specular reflection is perhaps the simplest optical phenomenon, and was one of the first demonstrated for atom optics (Stern 1929; Knauer and Stein 1929) using reflection from a surface. However, the **surface reflectivity** involves a complex interaction between the electronic wavefunction of the incoming atom, and the extended structure of the solid with its many relaxation processes. Specular reflection is only one of many possible interaction channels, with the result that even on perfectly clean crystalline surfaces, reflection is not very efficient. Only atoms with very small kinetic energies (or thermal atoms near grazing incidence) can be reflected due to the dominance of inelastic processes at higher energies.

For atoms which are very cold (as released from a trap, for example), the interaction with a comparatively hot surface that also possesses significant internal energy will result in heating of the atoms. Furthermore, the equivalent of spontaneous emission — the excitation of phonons — may occur, which destroys the atomic coherence.

The dipole potential produced by a high-intensity laser can in principle be used to reflect atoms whose kinetic energy along the reflection axis is sufficiently small. However, the spatial extent of even a tightly focused laser beam is such that atoms may typically undergo many spontaneous emission events before reflection occurs, thereby destroying the atomic coherence or greatly diffusing the specularly reflected beam.

To overcome this, a mirror based on an **evanescent light** field produced by total internal reflection of a laser within a dielectric substrate was proposed (Cook and Hill 1982). The advantage of this device is that the spatial extent of the light field in the direction perpendicular to the dielectric surface is of the order of the light wavelength. Such a mirror was first demonstrated in 1987 (Balykin *et al.* 1987) using a sodium atomic beam with incidence angles of several milliradians. (A similar device which uses a standing evanescent wave is shown in Fig. 10 of Section 3·2·3.) Because of the ability of the laser field to tune precisely to the internal state of the atom, the same mirror was used for state-selective reflection (Balykin *et al.* 1988*c*), with potential applications to isotope separation.

However, the evanescent field strengths generated by typical cw lasers ($\sim$1000 mW into areas of $\sim$10 mm^2) are insufficient to reflect atoms with velocities much greater than 1 m s^{-1} (Table 2). Considerable work has therefore been undertaken to enhance the evanescent wave intensity using surface waveguides. The surface waveguides are of two types: a metallic layer coated on the dielectric surface, in which surface plasmons are excited (Esslinger *et al.* 1993; Feron *et al.* 1993; Seifert *et al.* 1994*a*), or a dielectric coated multilayer structure which effectively acts as a light storage cavity (Kaiser *et al.* 1994; Seifert *et al.* 1994*b*). Enhancements of the intensity I at the surface by factors exceeding 100 have been reported, with the result that reflected velocities of >3 m s^{-1} were obtained (but note that $v_{\rm max} \propto I^{1/4}$ is a very weak function of the laser intensity).

2·2 Beam Deflectors, Collimators and Compressors

We have already noted the effect of radiation pressure from a sodium lamp in deflecting an atomic beam (Frisch 1933). Laser light forces may also be used to more efficiently deflect atoms in free space during passage through a travelling-wave light field at near-normal incidence to the atomic propagation direction.

However, more interesting effects arise from passage through a **standing wave** formed by counterpropagating high-intensity laser fields, particularly at small detunings where dissipative forces become important. Atoms near to normal incidence with a transverse velocity component along the standing wave can thereby experience cooling or heating forces which cause the atoms to be deflected from the original beam direction (Early 1988; Hemmer *et al.* 1992; Li 1994). Such a deflection could be used to steer atomic beams in two dimensions, thereby creating the equivalent of an electron gun for atoms (Li 1994).

Alternatively, the cooling forces in a standing wave may be used to collimate a diverging atomic beam (Aspect *et al.* 1986; Dalibard *et al.* 1987; Tanner *et al.* 1988; Chen *et al.* 1992; Milic *et al.* 1996; Scholten *et al.* 1996), in principle reducing the transverse velocity to near the recoil limit. For a thermal atomic beam travelling at 1000 $\mathrm{m\,s^{-1}}$, cooling to within several recoil velocities (typically $\sim$0·01 $\mathrm{m\,s^{-1}}$) is equivalent to a beam divergence angle of 0·01 mrad—better than most lasers. This enables the atomic beam to propagate over long distances without losing intensity, which is important for experiments which require an atomic beam to be delivered to a location well removed from the source, e.g. for atomic physics collision measurements, or for atom lithography.

The cooling forces may be applied in two dimensions by using either crossed pairs of counterpropagating waves (Balykin *et al.* 1984), or an axicon arrangement where the atomic beam is illuminated from all radial directions (Balykin and Sidorov 1987). Alternatively, by employing a combination of two-dimensional collimation and two-dimensional magneto-optic trapping techniques, a **high-brightness source** of atoms can be created (Scholz *et al.* 1994; Hoogerland *et al.* 1996*a*, 1996*b*) as shown in Fig. 2.

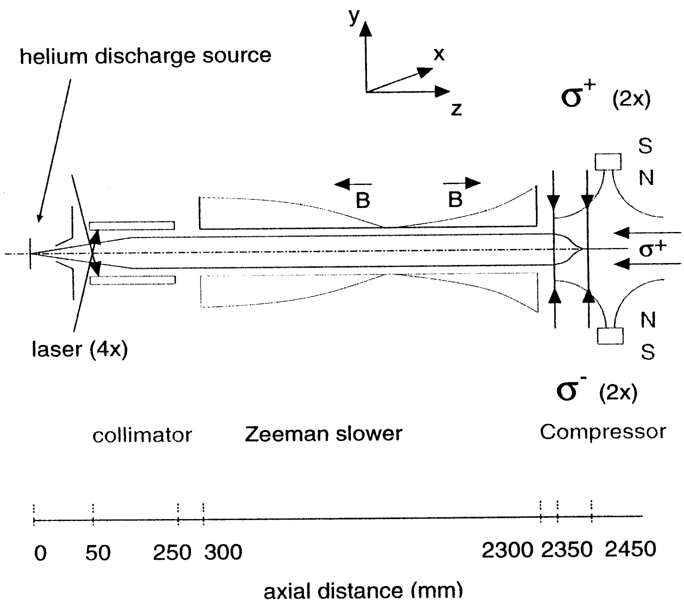


Fig. 2. A high-brightness metastable helium source, showing the collimation, slowing and compression stages. After Hoogerland *et al.* (1996*a*).

Here, an expanding atomic source is first collimated by dissipative (spontaneous) light fields directed at a range of near-perpendicular angles to the atomic axis in order to cool a range of Doppler-shifted transverse velocities. The collimated beam is then cooled by a counterpropagating laser field to increase the interaction time with the latter (compression) stage of the device. The Doppler shift of the cooled atoms is compensated by a Zeeman shift which is induced by a varying longitudinal magnetic field. The cooled atoms then enter another set of two-dimensional, dissipative transverse laser beams, but this time their transverse Doppler shift is compensated for by a magnetic field which increases radially from the atomic beam axis. The atoms are pushed towards the atomic beam axis to compress their transverse dimension, and then their transverse velocity is reduced in what is essentially a two-dimensional magneto-optic trap (MOT). The result is a high-brightness source of cooled atoms.

A similar principle is employed in the **atomic funnel** (Riis *et al.* 1990) which utilises a quadrupole magnetic field to provide a radially varying restoring force for atoms with longitudinal velocities of up to 20 $\mathrm{m\,s^{-1}}$ that are then transversely damped by optical molasses. Note that none of these devices have an optical analogue because they use dissipative forces, and they therefore 'violate' a fundamental law of conventional optics by producing a beam of higher brightness than the original source. This is an important distinction, and a considerable advantage, of atom optics.

As noted before, counterpropagating laser beams of high intensity produce standing-wave fields in which stimulated processes dominate spontaneous processes. Although dissipative forces are still present and can (for sufficiently small detunings) produce important cooling or heating effects along the standing wave, the atomic momentum can also be altered by interaction with the periodic structure of the potential. The standing-wave spatial period is $\lambda/2$ in the propagation direction, with a Gaussian profile in the transverse direction as shown in Fig. 3.

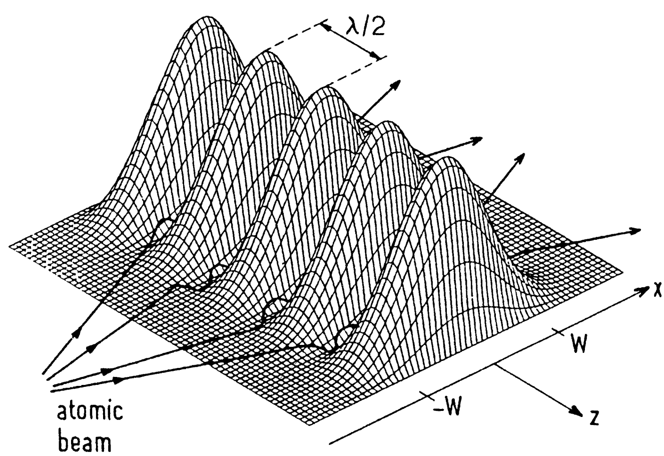


Fig. 3. Periodic potential formed by a standing laser wave (propagation in the $\pm z$ direction). For red (blue) detuning, the peaks correspond to nodes (antinodes). After Salomon *et al.* (1987).

Those atoms traversing the potential for which the instantaneous transverse kinetic energy is less than the local potential peak height, can exhibit an oscillatory motion generally known as **channelling** (Prentiss and Ezekiel 1986; Salomon *et al.* 1987; Balykin *et al.* 1988*a*; Wang *et al.* 1990; Ovchinnikov and Letokhov 1992; Li *et al.* 1994). Such atoms are confined to move along the potential valleys until the Gaussian decrease in the laser intensity allows the atoms to escape in the transverse direction. The result is that atoms can either continue in the original transverse direction or be reflected from the periodic potential, depending upon the phase of the oscillation at the time of escape.

A clear demonstration of channelling was obtained using a curved standing wave formed by spherical laser wavefronts (Balykin *et al.* 1989, Fig. 4). Channelled atoms were separated from atoms with higher transverse velocity that traversed the peaks of the periodic potential and remained unchannelled. The effects of channelling in a linear standing wave are not so clear, and require a detailed analysis of the resulting transverse spatial atomic beam profile in terms of trajectories in the standing wave (Li *et al.* 1994).

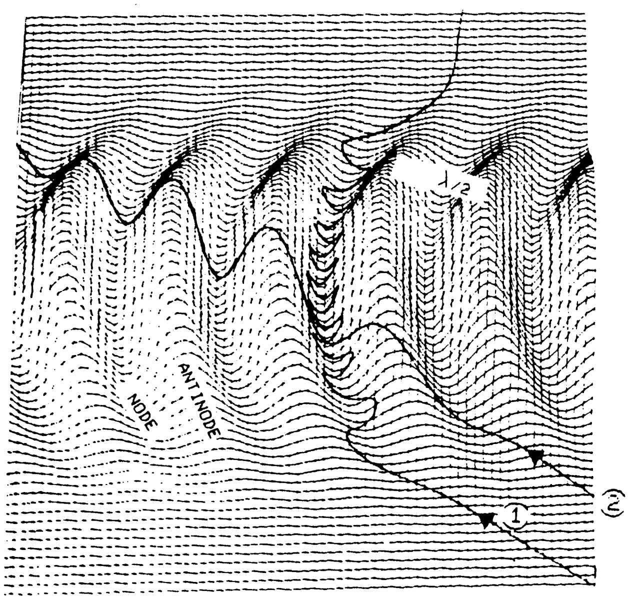


Fig. 4. Use of a curved standing wave to deflect an atomic beam, where slower atoms (1) are channeled in the curved periodic potentials. After Balykin *et al.* (1989).

2·3 Lenses

The focusing of atoms acting as particles is achieved primarily by devices based on light forces, since optical fields are particularly well suited to producing the potential gradients required for lens formation. The first use of the dipole (gradient) light force to manipulate atoms occurred in 1978 with the focusing of a sodium beam using a red-detuned, **copropagating laser** (Bjorkholm *et al.* 1978, 1980*a*, 1980*b*). The dipole force attracted the atoms to the high-intensity region at the centre of the laser beam, producing a spot size of less than 30 μm. However, the fact that the atoms were confined to the regions of highest intensity meant that strong diffusion effects resulted in significant aberrations. By using a blue-detuned laser with a TEM_{01}-mode toroidal beam profile, it may be possible to produce a lens without such diffusive effects (Balykin and Letokhov 1987; Gallatin and Gould 1991; McClelland and Scheinfein 1991), since the atoms will be focused to the region of low intensity at the centre of the laser profile.

A **cylindrical lens** may also be realised using radiation pressure (spontaneous) forces produced by two diverging, counterpropagating laser fields perpendicular to the atomic beam (Balykin *et al.* 1988*b*). If the on-resonant lasers are of equal intensity and are equidistant from the atomic beam axis, then the imbalance of light forces at any position away from the axis will provide a transverse restoring force for the atoms. This scheme was used to generate an image of an atomic oven source with two apertures, and can be extended to produce a lens in two dimensions using crossed pairs of counterpropagating lasers. However, as with the axial focus lens, diffusive aberrations led to a maximum resolution of 50 μm.

Diffusive effects can be limited by using the gradient (dipole) force at high intensities and large detunings, where stimulated processes dominate, spontaneous events are negligible and the force on the atoms becomes purely conservative. An example of a lens created in this manner is the **standing light wave** created by two intense, counterpropagating lasers (Fig. 5).

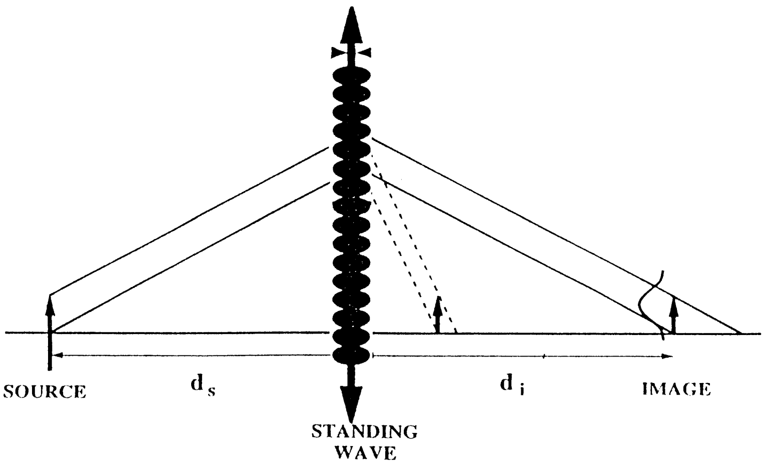


Fig. 5. Standing wave acting as a lens for atoms. The dashed line is the image obtained for small red detuning, the solid line for large detuning. After Li *et al.* (1996).

The potential peaks in the periodic spatial pattern act as a series of mirrors which can be used to reflect atoms in the manner described above. Slower atoms which are reflected propagate back towards the atomic beam axis where they can form an image of the source, while those faster atoms which exit the standing wave in the same direction as they enter form a diffuse background. The first demonstration of such a lens used two orthogonally polarised, crossed standing waves to image (in two dimensions) a diverging beam of rubidium atoms, which was directed normal to the plane of intersection of the standing waves. The two perpendicular focusing elements produced two crossed line foci, with a bright spot at their intersection representing the image of the atomic source (Esslinger *et al.* 1992).

If the standing-wave field is truly conservative, e.g. at large detunings, the image and the source are equidistant from the standing wave (solid lines, Fig. 5). However, at small detunings, dissipative forces can become important. For red (blue) detunings, the atoms can be heated (cooled) in the standing wave, with the result that the atoms are focused closer to (further from) the standing wave than the 1:1 image position produced by the conservative force (dotted lines, Fig. 5). The result is the creation of a **variable focal length lens** for atoms (Li *et al.* 1996).

Standing laser light waves may also act as lenses on a microscopic scale. Each of the potential peaks itself has a field gradient that can produce focusing of atoms in the near field, i.e. within the standing-wave (Fig. 6). The first demonstration of such a **microlens** was performed using a large-period standing wave field generated by reflecting a laser from a glass surface (Sleator *et al.* 1992*a*). In the region near the surface, the incoming and outgoing beams interfere, producing a standing wave parallel to the surface whose period is governed by the incidence angle (in this case ~10 mrad, yielding a lens some 45 μm high). By focusing the laser to a width of 80 μm the transit time of the helium metastable atoms was made less than the transition lifetime, thereby avoiding diffusive effects. Images of microstructures on micron scales illuminated by a helium metastable beam were thereby obtained.

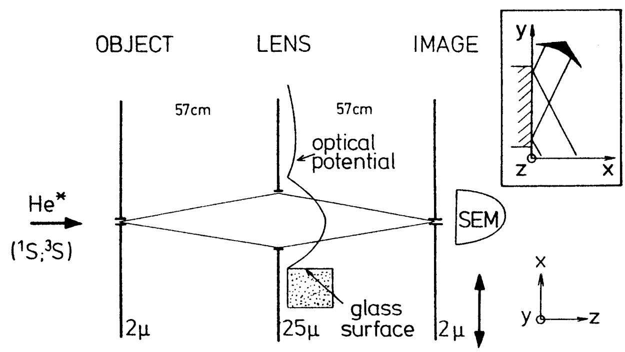


Fig. 6. Large-period lens. The inset shows reflection geometry of laser to form a standing wave parallel to the glass surface. After Sleator *et al.* (1992*a*).

Arrays of microlenses have been demonstrated to produce focusing of sodium (Timp *et al.* 1992; Berggren *et al.* 1994) and chromium atoms (McClelland *et al.* 1993; McClelland 1995) onto prepared surfaces. This was performed by placing the surface parallel to and at the peak of the Gaussian intensity profile of a free-space standing wave, where the microlens flux of a normal incidence atomic beam is focused (Fig. 7). By this method surface features of around 65 nm width have been deposited with a highly reproducible registration equal to the standing-wave period. The effects of diffusion were minimised by using large detunings to create conservative potentials. Similar experiments have recently been performed in two dimensions, yielding a grid-like pattern of chromium islands of similar feature size (McClelland *et al.* 1996).

These deposition techniques are of great importance for the development of microstructures, particularly with application to microelectronics. The demonstration of stable metallic deposition (McClelland *et al.* 1993, 1996; McClelland 1995) has been followed by the etching of semiconductor surfaces using metastable atoms (Berggren *et al.* 1995).

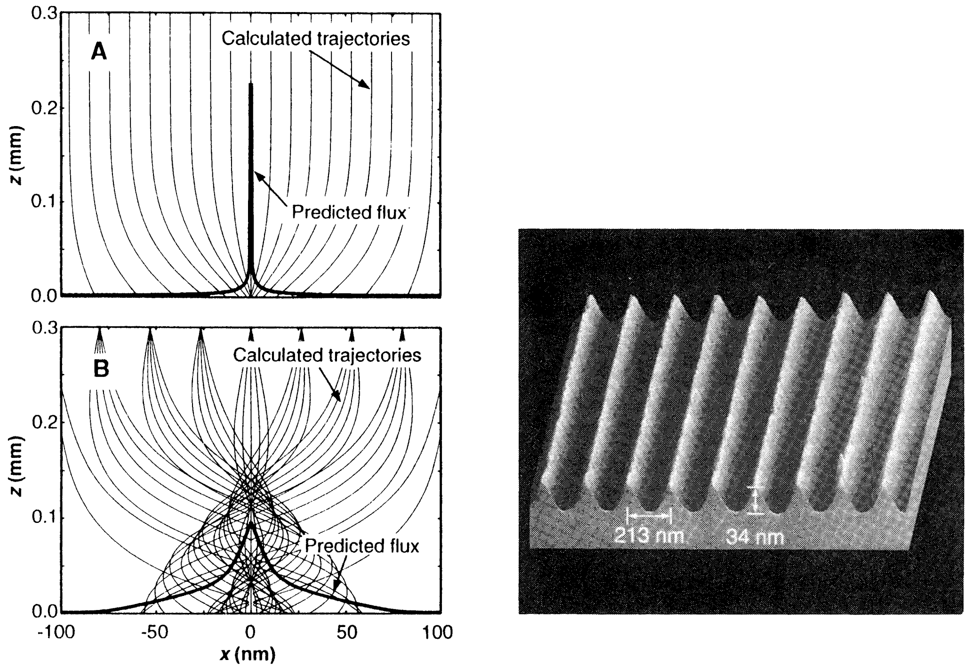


Fig. 7. Computed atomic trajectories and deposited chromium lines produced by a standing-wave array of microlenses. After McClelland *et al.* (1993).

Metastable atoms possess significant internal energy, particularly the rare gases, the most energetic of which is helium with 20 eV in the 2^3S state. These energetic atoms can be used to disrupt the chemical bonds of self-assembling molecular monolayers (SAMS) which are attached to metal coatings on crystalline silicon surfaces. By removing these molecules (which have a small 'footprint' on the surface) in precisely controlled regions of the metal-coated silicon substrate, chemical etchants can be used to dissolve the remaining metal layer to expose the silicon wafer (Berggren *et al.* 1995).

Techniques such as these, which employ highly collimated beams of atoms that can be focused, deflected and channelled, hold great promise for **atom lithography**.

3. FIRST-ORDER ATOM OPTIC ELEMENTS

In this section we consider those elements for which a de Broglie wave treatment is useful to describe the interaction with the atom optic device, but for which quantisation of the atomic motion is not necessary. Principles of atom interferometry are dealt with only briefly as this is covered elsewhere in this volume, but experiments in atom interferometry are included, with particular emphasis on applications.

3·1 Lenses

3·1·1 Zone plates

Atom optic devices made from matter feature more prominently in first-order atom optics, a resurgence that has been primarily due to the development of microfabrication techniques for free-standing structures. Sub-micron feature sizes down to ~100 nm can now be created which approach the de Broglie wavelength of cold atoms, thereby enabling significant diffractive effects to be observed.

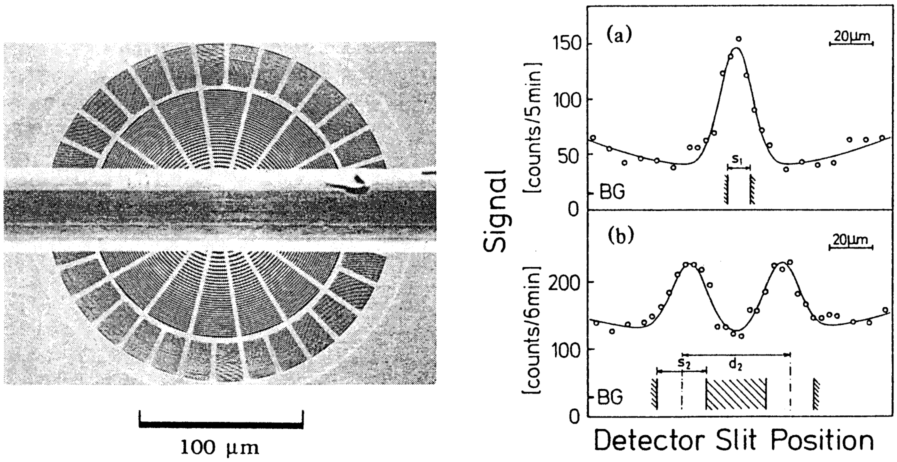


Fig. 8. Left: Scanning electron microscope image of a zone plate, with zeroth-order blocking wire. Images of (*a*) a single slit and (*b*) a double slit. After Carnal *et al.* (1991*b*).

One example is the zone plate which, while originally developed for X-ray imaging at wavelengths below 100 nm, has been used for diffractive imaging of atomic de Broglie waves (Carnal *et al.* 1991*b*). A magnified image of a transmission zone plate is shown in Fig. 8, and consists of a series of annular transmission regions whose width diminishes at larger radius, which are supported by radial bars. However, the transmission of the zones is at best 50%, and the undiffracted zeroth order must be suppressed by a wire covering the centre of the zone plate. This, together with losses due to the supporting bars, and the fact that only ~10 % of atoms are diffracted into the first order, reduce the efficiency of the zone plate to <10%.

Fresnel diffraction theory predicts that the resolution is given by the width of the outermost zone, which in the device shown is $0 \cdot 4\ \mu$m. This zone plate was used to image thermal metastable helium atoms (de Broglie wavelengths 0·05–0·25 nm) emitted from both single and double slits of ~10 μm size — Fig. 8). Because of the finite velocity spread of the atomic source, the resolution was limited by chromatic aberration.

3·2 Beamsplitters

An important element of many first-order atom optic devices is the beamsplitter, which is able to coherently split the atomic wavefunction into two or more partial waves. In some cases this is achieved purely by diffraction of the de Broglie wave (representing the centre-of-mass motion of the atom), as is used in diffraction from a matter grating. In other cases, the internal state of the atom is altered by passage through either optical or static fields, and can then be represented by a coherent superposition of states, each of which is associated with a particular momentum state for the centre-of-mass motion. The splitting of the superposition states then results from the differential effect of the field on the momentum of the states as they traverse the field.

The first example of an atomic beamsplitter was the Stern–Gerlach experiment (Gerlach and Stern 1922) which separated atoms according to their spin state in a static magnetic field. However, in order for this process to be coherent, each atom needs to be prepared in a superposition state prior to the separation of the internal states by the field. Only then can the coherently split states be useful for atom optic applications such as interferometry. Furthermore, in order to make a useful interferometer, the beamsplitter should produce a large spatial or angular separation of the partial waves, preferably in only two orders.

The beamsplitters discussed in this section were initially developed as individual elements (not as part of an atom interferometer), although some were later incorporated in the interferometers discussed in Section 3·3. We leave discussion of beamsplitters which were developed as integral components of interferometers until that section.

3·2·1 Matter diffraction gratings

By analogy with zone plates, matter diffraction gratings rely on the diffractive effects of small-scale structures to produce a number of diffraction orders with a coherent relationship. The earliest diffraction of atoms used a **crystalline surface** (LiF and NaCl) as a reflection grating for hydrogen and helium atoms (Estermann and Stern 1930), producing diffraction angles of up to 20°. However, as noted previously for surface mirrors, such processes are relatively inefficient and rely heavily on high surface purity. As a result, such diffractive techniques have been turned around to provide a diagnostic tool for surface analysis.

The fabrication of **micro-gratings** enabled the demonstration of atom diffraction in transmission. The first experiment in 1988 employed a 200 nm grating period and used a highly collimated (10 μrad) thermal beam of sodium atoms with a de Broglie wavelength of 0·017 nm (Keith *et al.* 1988). First-order diffraction peaks were observed with a hot wire detector and were separated by a splitting angle of 240 μrad. In a similar experiment (Carnal *et al.* 1991*a*), a thermal helium metastable beam ($\lambda_{\rm dB} \sim 0\cdot 1$ nm) was diffracted from a 500 nm period grating to produce second-order diffraction at angles slightly less than 400 μrad from the beam axis.

Like the zone plate lens, matter gratings are relatively inefficient (~10% in first order), and can suffer from serious distortions in the grating periodicity. Their advantage is that they are not species-specific, and they can be made with a smaller periodicity than standing light waves (for which $\lambda/2 > 200$ nm).

3·2·2 Transmission light gratings

Standing laser light waves have also been used as diffraction transmission gratings. A number of early experiments reported observation of diffraction effects from **periodic light potentials**, but the first set of experiments to yield a quantitative comparison with theory commenced in 1985 (Pritchard and Gould 1985; Gould, *et al.* 1986; Martin, *et al.* 1987). These experiments used a similar highly collimated sodium beam apparatus to that employed for the matter grating experiment in the same laboratory. A cw dye laser tuned near the sodium D_2 resonance line was focused using a cylindrical lens onto a mirror located just on the opposite side of the atomic beam, thereby forming a standing light wave.

Such a periodic optical potential can be regarded as a diffraction grating in the wave picture by considering the interaction of the atomic de Broglie wave with the periodic structure. Alternatively, the quantum picture may be employed if the atom is viewed as exchanging photons between the co- and counter-propagating waves during each absorption/stimulated emission cycle. Each pair of photon exchanges causes the atom to absorb two units ($2\hbar k$) of recoil momentum ($v = \hbar k/m \sim 3\ \mathrm{cm\,s^{-1}}$ for a sodium atom), while interaction with the same wave yields no momentum change. A diffraction order corresponds to each pair of photon exchanges.

The tightly focused beam waist used (Pritchard and Gould 1985; Gould *et al.* 1986; Martin *et al.* 1987) enabled a range of possible momentum angles to be transferred from the light field to the atom during the photon exchange events (**Kapitza–Dirac scattering**). This is illustrated by the left-hand diagram in Fig. 9. A number of diffraction peaks up to fourth order ($8(2\hbar k)k$) were observed in this experiment, with diffraction angles $< 100\ \mu$rad.

A similar experiment was performed by the same group using a standing wave with a large waist containing almost exclusively plane-wave fronts (Martin *et al.* 1988). As a result, only **Bragg scattering** from a single photon-exchange pair can result, since conservation of energy constrains the momentum exchange to lie on a circle of constant energy (right-hand diagram in Fig. 9). The result is the production of a single diffraction peak separated by two photon momenta ($2(2\hbar k)k$) from the unperturbed beam (first order Bragg scattering). If the incidence angle of the atomic beam is increased relative to the standing wave, first-order scattering is prevented by momentum conservation, and second-order scattering (involving two photon exchange pairs of $4(2\hbar k)k$) takes over.

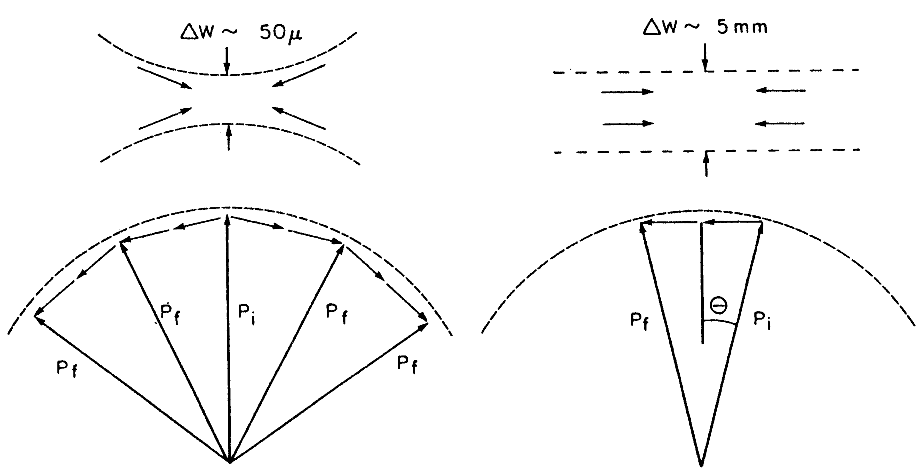


Fig. 9. Comparison of Kapitza–Dirac (*left*) and Bragg (*right*) scattering (p_i is the initial momentum and p_f the final momentum). After Martin *et al.* (1988).

Both orders were observed in the Bragg scattering experiments, as well as Pendellosung oscillations in the first-order intensity, which arise when the depth of the scattering region is altered. However, the separation of the diffracted orders was the same as for Kapitza–Dirac scattering, being limited once again by the standing-wave periodicity.

3·2·3 Reflection light gratings

An alternative scheme was proposed to increase the diffraction angles using a **standing evanescent wave** (Hajnal *et al.* 1989*a*). By totally internally reflecting a laser beam inside a dielectric substrate, and then retroreflecting the laser, a standing evanescent wave is formed. The periodicity is $\lambda/n\sin\theta$ (where n is the refractive index and θ the laser incidence angle), while the evanescent wave extends $\sim\lambda$(nm) into the vacuum (Fig. 10). As a result, atoms incident at near-grazing angles can be diffracted from the periodic evanescent potential, but with much larger diffraction angles due to the grazing-incidence geometry (similar techniques have been employed for X-ray diffraction). The change of momentum ($2\hbar k$) in the x direction, when magnified along the energy conservation circle, can produce diffraction angles of several mrad for thermal atomic beams.

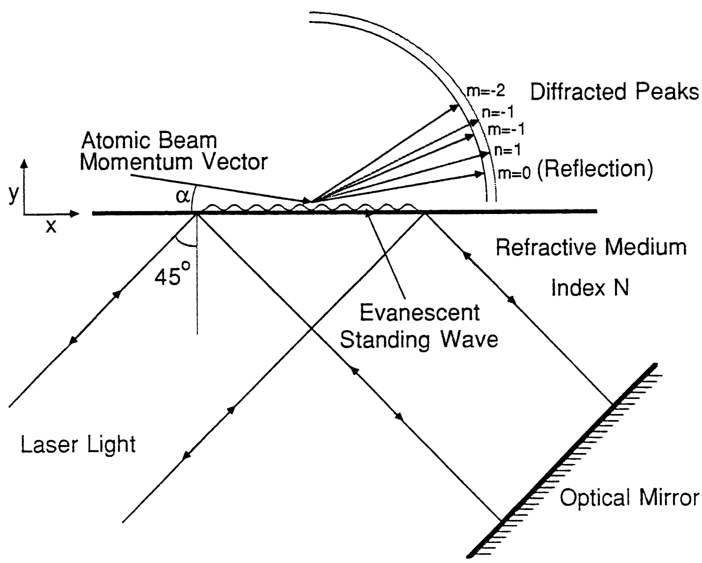


Fig. 10. Evanescent grating showing diffraction into ground (m) and excited (n) momentum states constrained by circles of constant energy (specular reflection, $m = 0$). After Baldwin *et al.* (1990).

The first experiments using standing evanescent waves revealed reflection of sodium atoms from a periodic evanescent mirror, but not diffraction (Hajnal *et al.* 1989; Baldwin *et al.* 1990). The reason for this was thought to be the large Doppler shift of the thermal beam (~1 GHz for 1000 $\mathrm{m\,s^{-1}}$ atoms) which caused the atoms to interact with one laser field, but not the counterpropagating field. Consequently, another experiment was designed using a *moving* evanescent grating, which was achieved by employing two counterpropagating lasers of different frequency (Stenlake *et al.* 1994). The resulting grating could be made to move at any desired speed relative to the thermal atoms, and coherent interaction with the two counterpropagating fields was indeed observed.

(Doppleron resonances were seen in the reflected atom intensity as a function of laser detuning.) However, no diffraction peaks were measured.

By contrast, another experiment using a laser-cooled neon metastable atomic beam ($\sim$25 m s^{-1}) demonstrated first-order diffraction from an evanescent standing wave with $\sim$3% efficiency, and at angular separations up to 48 mrad (Christ *et al.* 1994). The results were in agreement with a theory based on dressed state potentials (Deutschmann *et. al.* 1993; Wallis 1995). According to this theory it would be expected that diffraction using the moving grating (Stenlake *et al.* 1994) should also be observed, given the similarity of the relative velocities in the two situations. However, a further theory (Savage *et al.* 1995), using a solution of the atomic Schrödinger equation in the evanescent field, yields agreement with the moving grating experiment, but conflicting predictions for the neon experiment, with the result that the issue is still unresolved.

Despite the large diffraction angles obtained, the efficiency of the process is at best $\leq$6% according to theory, which limits the usefulness of such a beamsplitter for interferometric applications.

3·2·4 Superposition-state beamsplitters

Using the same apparatus as was used in the large-period standing-wave microlens experiment, a beamsplitter using the **optical Stern–Gerlach effect** has been demonstrated (Sleator *et al.* 1992*b*). The node of the standing wave was used to provide a near-linear gradient to split a beam of metastable helium atoms into coherent superpositions of the 2^3S_1 state. A splitting angle of $\sim$200 mrad ($\sim 8\hbar k$) was achieved, although this was limited by the available laser power since the splitting angle is a continuous function of the field gradient.

The largest splitting observed for an atom optic device was obtained using a **magneto-optic beamsplitter** (Pfau *et al.* 1993). Using a combination of polarisation gradient fields (counter-propagating crossed linearly polarised beams) and a parallel magnetic field, metastable helium atoms were separated by $42\hbar k$. The spatial distribution is shown in Fig. 11, where it is compared with the distribution produced by a standing wave under similar conditions. The major difference is that the splitting in the magneto-optic case is predominantly in the most separated orders, whereas in the grating the population of the orders is relatively even. In this sense the magneto-optic beamsplitter acts somewhat like a blazed grating by producing an adiabatic potential with a triangular modulation. Like the optical Stern–Gerlach experiment, the splitting is limited by the light (and in this case magnetic) field amplitude.

In 1994, an atomic beamsplitter immune to spontaneous emission decoherence was demonstrated (Lawall and Prentiss 1994). This so called **'dark state' beamsplitter** utilised a two-laser scheme tuned slightly to the red and to the blue of the helium 2^3S_1–2^3P_0 transition (Fig. 12). The linking of the slightly off-resonance ground-state levels via the (non-participating) upper state yields superposition states with no excited-state component, but which are separated in momentum by adiabatic interaction with the field. Splittings of $4\hbar k$ due to the Raman process shown in Fig. 12 were observed.

In more recent experiments (Lawall *et al.* 1994) using a helium metastable atomic trap, an ultracold source of atoms was created using **velocity-selective coherent population trapping (VSCPT)** in two dimensions (Fig. 13). A similar

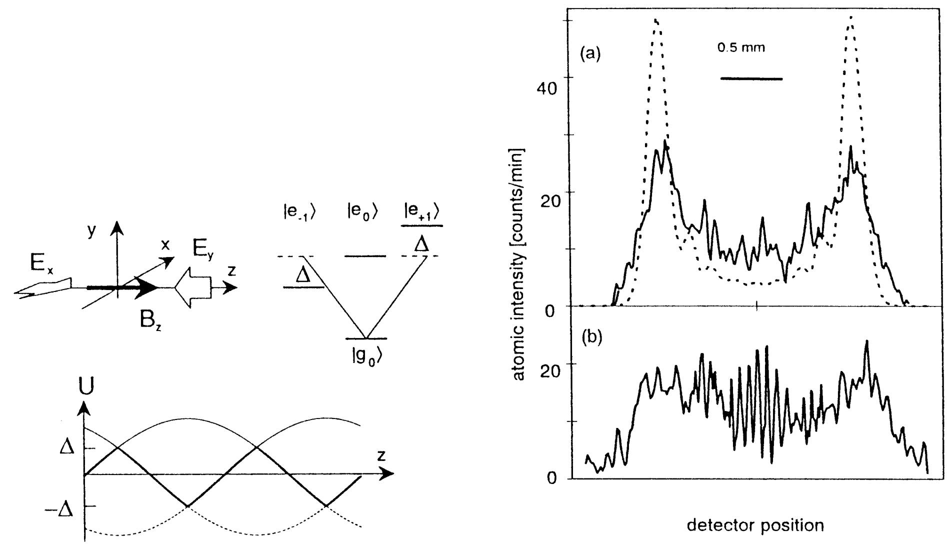


Fig. 11. *Left*: Magneto-optic beamsplitter geometry and energy levels. *Right*: (*a*) results and theory (dashed line), compared to standing-wave diffraction grating results (*b*). After Pfau *et al.* (1993).

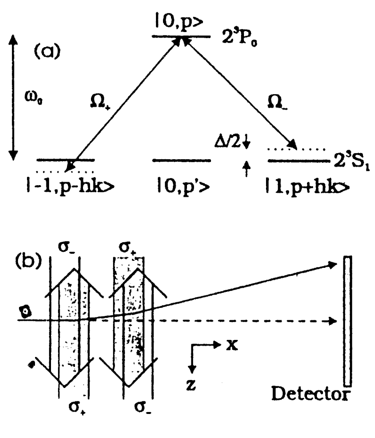


Fig. 12. Dark state beamsplitter: (*a*) the principal transitions and (*b*) the experiment. After Lawall and Prentiss (1994).

Raman transition to that in Fig. 12 was used in the VSCPT process, which was switched on as the MOT was switched off. The Raman process produced a separation of the superposition states in momentum space which were allowed to fall under gravity as shown in Fig. 13. These states each had a velocity spread of $\sim 2\cdot 3\ \mathrm{cm\,s^{-1}}$ ($\sim v_r/4$) yielding a de Broglie wavelength of $\sim 4\ \mu$m. The result was a two-dimensional beamsplitter with very large spatial separations — of the order of centimetres — creating the possibility of a large-area interferometer. Very recent experiments have extended this technique to three dimensions (Lawall *et al.* 1995).

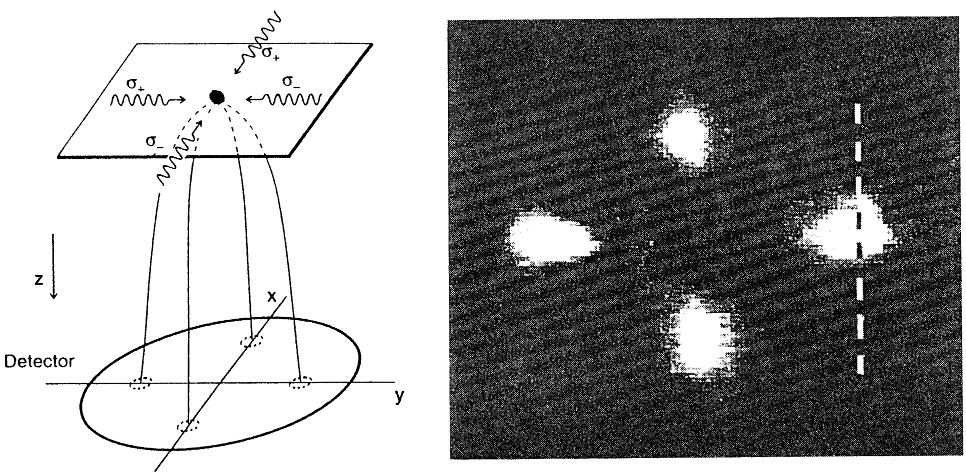


Fig. 13. VSCPT experiment (*left*) and resulting image, showing spatial separation of the de Broglie wavepacket in the detector plane (*right*). After Lawall *et al.* (1994).

3·3 Interferometers

The primary application of atomic beamsplitters is in atom interferometry, where the atomic de Broglie wave is coherently split along two separate pathways and then recombined using a second beamsplitter. Following recombination, the fringe pattern produced by altering the relative phase of the partial waves traversing one arm of the interferometer can be detected. To date, atom interferometers have been used to measure a wide range of effects, including rotational acceleration, collisional phase shifts (refractive index), the acceleration due to gravity, dc field gradients, ac and dc polarisabilities, the recoil of the atom, and geometric phase.

One of the important requirements for atom interferometry is a significant spatial or angular separation of the two arms of the interferometer. This is necessary to improve the sensitivity of field gradient measurements, to enable scattering targets or field sources to be placed in the beam, or to increase the area required for sensitive rotation measurements. The separation requirement is the motivation behind the development of large-angle beamsplitters. Similarly, there has been considerable emphasis on cooled atomic sources both for producing atoms with large de Broglie wavelengths for diffractive beamsplitters, and for experiments where the splitting angle is dependent upon the initial longitudinal velocity of the atoms.

The principles behind atom interferometry are not discussed here, as they are presented elsewhere in this Workshop. The following sections describe the various types of atom interferometry experiments to date, and their applications.

3·3·1 Young's two-slit interferometer

The earliest demonstrations of atom interferometers used mechanical components, one being the Young's two-slit experiment (Carnal and Mlynek 1991) shown in Fig. 14. A helium metastable beam was cooled to temperatures as low as 20 K to increase the de Broglie wavelength and reduce the spread in longitudinal

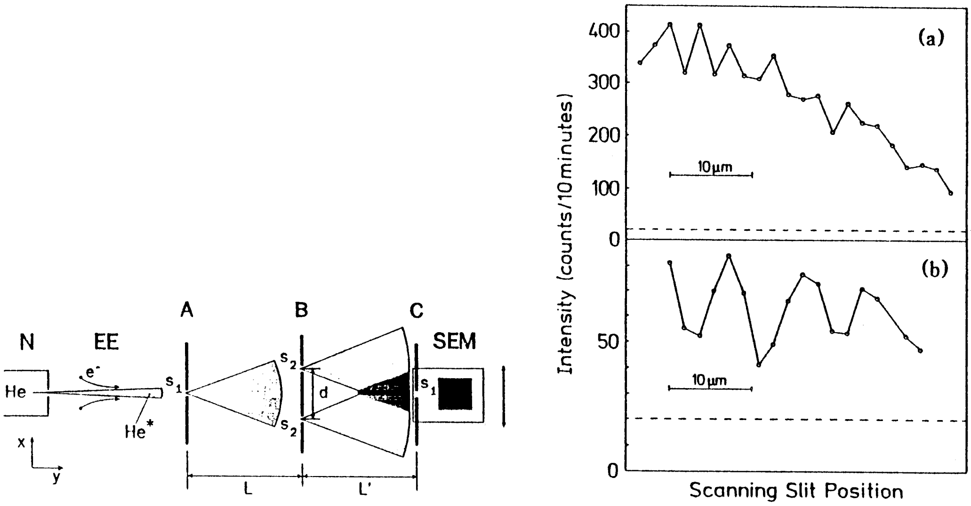


Fig. 14. Young's two-slit (s2) experiment (*left*), with resulting interference fringes (*right*) for (*a*) $\lambda_{dB} = 0 \cdot 56$ Å and (*b*) $\lambda_{dB} = 1 \cdot 03$ Å. After Carnal and Mlynek (1991).

velocity ($\delta v/v$ ~15) of atoms in the beam. A source size of 2 μm was used and two slits 1 μm wide and 8 μm apart were placed 64 cm downstream. To improve the detection effectiveness, a grating with 1 μm slits and the same periodicity as the diffraction pattern (8 μm) was placed 64 cm from the slits. Fringe visibility was 60% of that expected from a simple Fraunhofer diffraction model.

A similar experiment has been performed using laser-cooled neon atoms dropped onto a pair of slits from a MOT (Shimizu *et al.* 1992). A 20 μm point source was created by focusing a laser tuned to a non-cooling transition into the MOT, producing spontaneous decay to another metastable state and thereby releasing those atoms from the trap. These atoms then fell onto two 2 μm slits placed 6 μm apart, reaching a velocity of 0–2 m s^{-1} ($\lambda_{dB} > 10$ nm) and producing a fringe pattern with a spacing of several 100 μm. The experiment was also used to show the effect of a static electric field on the interference pattern.

Despite the relative simplicity of such experiments, the spatial separation of the two paths is very small, which limits the usefulness of two-slit interferometry in many applications.

3·3·2 Matter grating interferometer

The matter grating beamsplitter described in Section 3·2·1 has been applied to create the three-grating interferometer shown in Fig. 15 (Keith *et al.* 1991). The first grating was used to separate the two beam paths, the second to recombine them, and the third to act as a mask to sample the interference pattern. A supersonic sodium beam seeded in argon was used to increase the collimation and velocity bunching of the sodium atoms (λ_{dB} ~0·016 nm). Initial experiments utilising 400 nm period gratings with 40 μm openings produced fringe separations of 27 μm. However, there were stringent requirements on the stability of this system (the three gratings had to be stationary to within 1/4 period over the sampling times of hundreds of seconds). This was achieved by using passive and active (laser) vibration stabilisation systems.

Variations of this interferometer have been used for a number of important applications. In 1995, the complex index of refraction of sodium atoms passing through different gases (ranging from rare gases to ammonia) was measured by placing them in one arm of the interferometer (Schmiedmayer *et al.* 1995). Since then, the same interferometer with the two arms isolated by a metal foil was used to measure the electric polarisability of sodium, resulting in an order of magnitude improvement on the existing accuracy (Ekstrom *et al.* 1995). Very recently, Na_2 molecules in a jet were separated from sodium atoms using light forces, and then used in the first matter interferometer experiment with molecules to measure their refractive index in neon (Chapman *et al.* 1995).

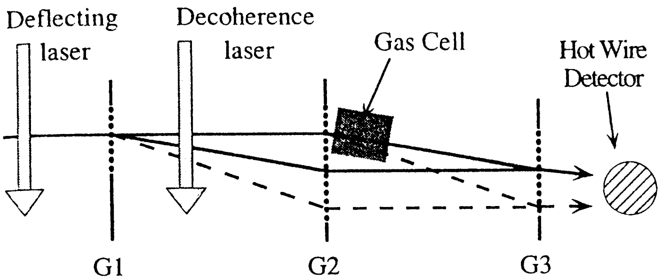


Fig. 15. The three-grating (G) experiment, with gas cell used for refractive index measurements in one arm of the resulting interferometer. After Chapman *et al.* (1995).

3·3·3 Static field interferometer

The first use of static fields to create interference between atomic internal states occurred in 1982 when the technique was used to determine the Lamb shift and hyperfine splitting in hydrogen (Sokolov and Yakovlov 1982). In a similar experiment known as the **longitudinal Stern–Gerlach interferometer** (Robert *et al.* 1991), a beam of hydrogen atoms are Zeeman-polarised by a transverse magnetic field into the $2S_{1/2}$ ($F = 1$, $m_F = 0, 1$) states before passing non-adiabatically through a longitudinal magnetic field, creating a coherent superposition of spin states (Fig. 16). The atoms then pass through an interaction region where in one experiment, two oppositely directed current-carrying wires induced a differential phase shift in the superposition states. The states were then recombined and analysed using a reverse arrangement of the first part of the interferometer. In this way, a topological phase shift of the Aharanov–Anandan type was measured (Miniatura *et al.* 1992).

3·3·4 Raman light pulse interferometer

The application of laser-based interferometric techniques is often limited by the absolute stability of the laser frequency, in analogous fashion to the mechanical stability of matter gratings. One way around this problem is to use a Raman transition linking two lower-state levels — a scheme which requires that only the relative (not the absolute) frequency of the two lasers be stable (Kasevich *et al.*

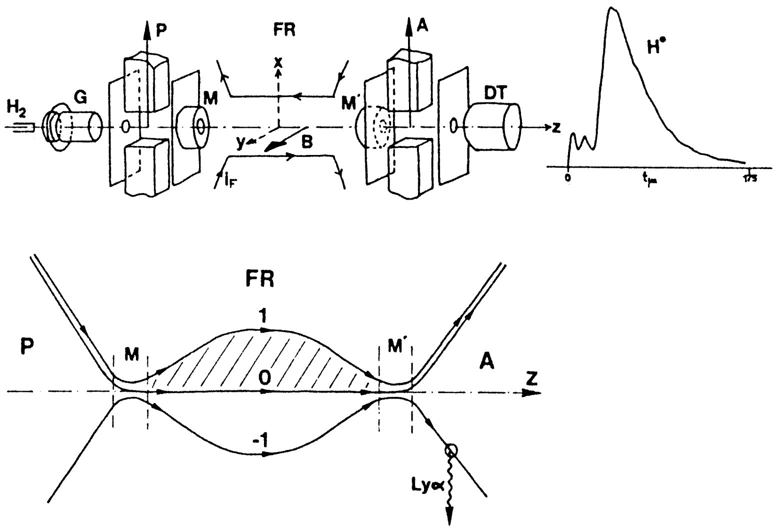


Fig. 16. Longitudinal Stern–Gerlach experiment, showing the variation of the hydrogen Zeeman hyperfine structure in the magnetic field gradients (mixing regions M). After Chormaic *et al.* (1992).

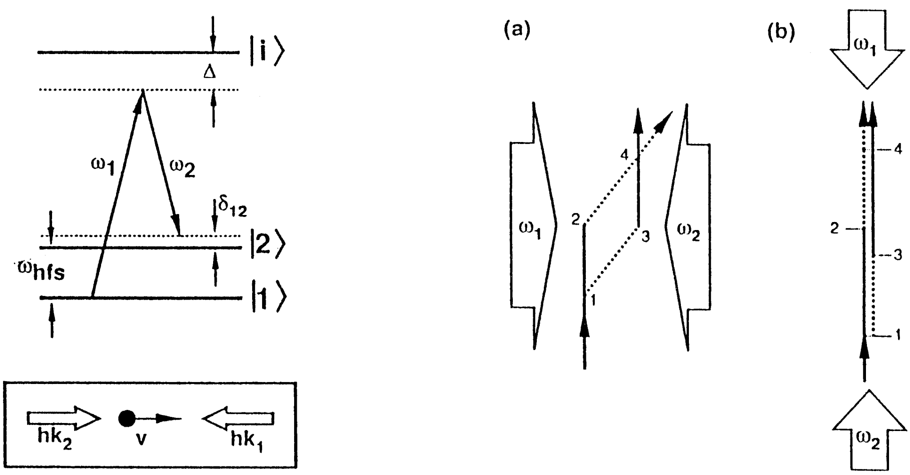


Fig. 17. Raman light pulse interferometer, showing transition levels (*left*) and beam geometries (*right*) for (*a*) an open area interferometer and (*b*) a linear gravimeter. After Kasevich and Chu (1992).

1991). The diagram in Fig. 17 shows the transition scheme employed, as well as the physical orientation of the lasers — used either in Mach–Zehnder or linear (gravitational) configurations.

A series of pulses are used to produce a separation of superposition states according to the momentum transferred in the Raman process (Kasevich and Chu 1991). The first pulse is a $\pi/2$ pulse which excites atoms initially in the $|1, p\rangle$

state into a coherent superposition of states $|1, p\rangle$ and $|2, p+\hbar k\rangle$, where p is the initial atomic momentum in the direction of laser ω_1, and $k = k_1 + k_2$ (since the two lasers are counterpropagating). The two states then separate by a distance $\hbar kT/m$ after propagating for a time T, following which a π pulse reverses the two states. After a further time T, the two reversed states catch up with each other. A second $\pi/2$ pulse is then applied that causes the two wavepackets to remix and interfere, after which they are detected, e.g. by measuring the number of atoms in state 2. The separation can occur either transverse to or along the atomic propagation axis, creating either an interferometer with area or one in linear geometry.

The Raman transition frequencies can be tightly controlled, e.g. by locking the beat frequency between two narrowband cw systems. By detuning slightly from resonance (δ_{12}) the Raman transition can be made velocity-dependent, and consequently this interferometer can be used to measure gravitational acceleration. The sensitivity of the measurement can be extended by launching the atoms vertically from a trap to produce an atomic fountain (Kasevich *et al.* 1989), where the ballistic trajectory results in long integration times.

Using such a technique with a caesium fountain (Kasevich and Chu 1992), the fractional change in the acceleration due to gravity has been measured to an accuracy of 3×10^{-8}, which approaches that of existing gravimetric measurements. The same system has also been used to measure photon recoil with a precision of 10^{-7}, thereby providing information contributing to the determination of the fine-structure constant α (Weiss *et al.* 1994).

3·3·5 Optical Ramsey interferometer

The Raman interferometer described above uses a similar principle to the Ramsey technique of separated oscillatory fields. One of the first demonstrations of atom interferometry utilised this technique to spatially separate superposition states in a calcium atomic beam (Riehle *et al.* 1991). A set of four laser fields providing $\pi/2$ pulses was applied in the configuration shown in Fig. 18.

Incoming atoms in the ground state are excited into a superposition state by the first pulse, with the excited-state component experiencing a momentum kick ($\hbar k$). A second pulse splits the states again, followed by third and fourth pulses in the opposite direction. The geometry of the momentum kicks yields two Mach–Zehnder interferometer combinations for different components of the states (solid and dashed path lines in Fig. 18), which when recombined yield interference patterns.

The path difference of the asymmetric arms results in chromatic (transverse velocity-dependent) dephasing. Consequently, the atomic beam has to be collimated to better than 1 mrad. Furthermore, species such as calcium and magnesium with long excited state lifetimes ($\sim$0·4 ms and $\sim$4·6 ms respectively) are required for such experiments due to the extended transit time in the arms of the interferometer. This is one disadvantage of the technique that is overcome by the Raman method, which exploits a transition between two ground states.

Nevertheless, Ramsey interferometers have found a number of useful applications. They have been employed to measure rotational acceleration using the Sagnac effect (Riehle *et al.* 1991), which was achieved by fitting the entire experiment onto a rotating table fed by an umbilical cord comprising fibre optic and electrical

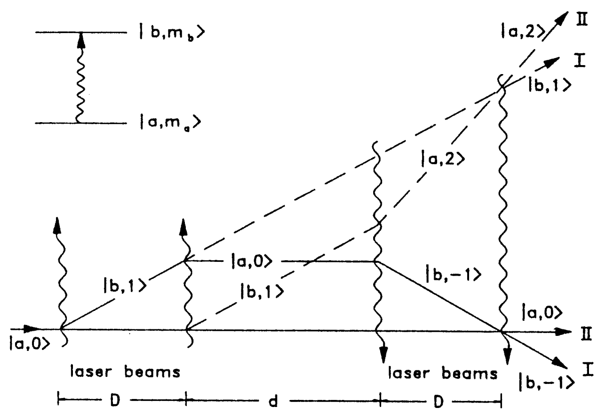


Fig. 18. Optical Ramsey interferometer showing laser configuration and two separate Mach–Zehnder interferometer paths (solid and dotted lines) for atoms leaving in the excited state (I) or ground state (II) ports. After Riehle *et al.* (1991).

cables. Another experiment has been used to measure the dc polarisability of magnesium (Rieger *et al.* 1993), while both experiments have provided measurements of the ac Stark effect (Riehle *et al.* 1992; Sterr *et al.* 1992).

4. SECOND-ORDER ATOM OPTICS

The exploitation of wave properties in atom optics has seen a surge of activity aimed at developing the analogues of optical devices. However, there are fewer analogues for which the motion of photons or atoms is quantised, and invariably these have been more difficult to implement. Nevertheless there are a number of experiments which have already investigated the quantum regime for atomic de Broglie waves.

4·1 Bose–Einstein Condensation

Perhaps the most topical and exciting development of recent physics, let alone in atom optics, has been the first demonstration of **Bose–Einstein condensation** (BEC) (Anderson *et al.* 1995; Collins 1995; Hecht 1995*a*, 1995*b*; Griffin 1995). The theoretical developments behind this long-standing prediction for a novel state of matter will not be discussed here, since this topic is treated elsewhere in this issue (Zhang 1996, present issue p. 819). However, the underlying principle is the following: atomic bosons are cooled to below the temperature at which the de Broglie wave becomes larger than the interparticle separation, at which point they are predicted to condense into the lowest quantum mechanical energy state.

The first observation of this prediction was for Rb^{87} atoms loaded from a MOT into a magnetic trap in which they were evaporatively cooled (Anderson *et al.* 1995). The characteristic sudden phase change to a low-velocity, high-density state below a certain temperature (170 nK), and the anisotropic velocity distribution reflecting the shape of the potential, were positive indications that condensation had occurred. Temperatures as low as 20 nK were obtained, and the condensate was observed for periods of more than 15 s.

A criterion normally thought necessary for BEC was the presence of a repulsive potential for atoms at the small separations required for condensation (i.e. a positive s-wave scattering length, so that the atoms do not coalesce into molecular or other non-BEC states). It came as some surprise, then, when Li^7 atoms — which have a negative (i.e. attractive) scattering length — were also claimed to have undergone BEC (Bradley *et al.* 1995). This result has produced a flurry of activity around the world to try and realise BEC in other species (more recently in sodium — Davis *et al.* 1995), irrespective of the sign of the predicted scattering length. This field of atom optics — realising the coldest temperatures ever generated — will be a 'hot' topic for some time to come.

4·2 Quantised Motion in Potential Light Wells

Claims for another new state of matter have recently been made in the first demonstration of atoms trapped in a **periodic potential lattice of light** (Stein 1994; Collins 1993). The lattice is formed by three-dimensional interference of standing laser light waves, which generates an array of small potential wells into which atoms can be localised. However, the occupancy of the lattice sites (with separations of the order of half the atomic wavelength) is extremely low, making such 'atom crystals' unsuited to experiments on BEC.

Nevertheless, the atoms may exist in eigenstates of the potential wells in which their motion can be quantised. Demonstration of this effect has been performed by inducing transitions between the quantised levels, firstly in one-dimensional standing waves. These initial experiments used either resonance fluorescence (Jessen *et al.* 1992), or Raman transitions which showed both gain and absorption between the different levels (Verkerk *et al.* 1992). These experiments have since been generalised to two- (Hemmerich and Hansch 1993) and three- (Hemmerich *et al.* 1993; Grynberg *et al.* 1993) dimensional atomic lattices.

In more recent experiments (Moore *et al.* 1994), quantised motion in a one-dimensional standing wave has been used to study the effects of **quantum chaos**, a field covered elsewhere in this issue (Chen *et al.* 1996, p. 777). A cloud of cold atoms released from a MOT was placed in a standing wave formed by two lasers. The phase of one laser was modulated so as to impose a steady-state velocity distribution which was shown to differ markedly from the thermal distribution in the MOT. The form of the distribution indicated that **dynamic localisation** (Graham *et al.* 1992) had occurred in the periodic potential.

4·3 Cavities

The wavelike nature of atoms raises the possibility of confinement in an atomic cavity (Balykin and Letokhov 1989*b*; Wilkens *et al.* 1993). Furthermore, there is the opportunity for the atomic motion to be quantised in such a cavity in which the atom can exist in eigenstates of the cavity potential.

A number of schemes have been proposed for a closed cavity using purely reflective mirrors based on evanescent laser light fields. However, these schemes necessitate a beamsplitter or some other arrangement to introduce atoms into the cavity.

4·3·1 The gravity cavity

Alternatively, by utilising a single curved evanescent mirror as one reflective element, and the earth's gravitational potential as the other, a 'gravity cavity' (Wallis *et al.* 1992) can be created into which atoms can be dropped from a trap (Fig. 19). Such an arrangement has the advantage that since the velocity of the released atoms can be made very small (as determined by the distance from which the atoms are dropped onto the surface), the de Broglie wavelength can be made very large. Furthermore, the evanescent field strength required for such cold atoms is feasible using cw laser intensities enhanced by waveguide surface coatings (Esslinger *et al.* 1993; Feron *et al.* 1993; Seifert *et al.* 1994*a*; Kaiser *et al.* 1994; Seifert *et al.* 1994*b*).

An early experiment was performed using a flat evanescent field from which two bounces were observed for sodium atoms reflected from this **atomic 'trampoline'**

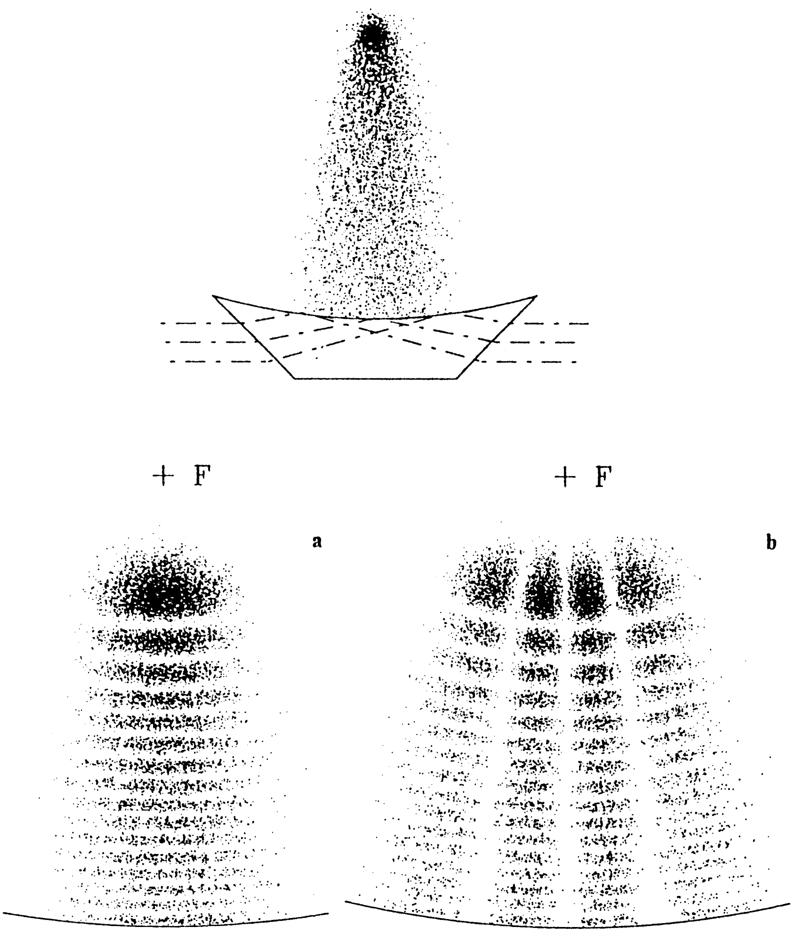


Fig. 19. Gravity cavity schematic (top), showing computed longitudinal (left) and transverse (right) cavity modes. After Wallis *et al.* (1992).

(Kasevich *et al.* 1990). However, the atoms soon left the reflecting region since their trajectories were not confined in the horizontal dimension.

The first realisation of a **gravity cavity** employed a concave spherical evanescent field to reflect atoms dropped from a caesium trap, thereby producing stable trajectories which were able to sustain more than ten bounces (Aminoff *et al.* 1993). [Similar observations were reported for sodium reflected from a curved evanescent surface, but only a few bounces were observed (Helmerson *et al.* 1992).]

The main reason for losses were trajectory walkoff from the finite mirror area, and stray light from the mirror surface resulting in diffusion. The effective confinement potentials were $\sim$5 μK in the horizontal direction and 1 mK in the vertical direction.

However, evidence of cavity mode structure has yet to be observed to demonstrate quantised motion. Furthermore, confinement and loading issues need to be addressed before mode occupancy increases to the level where, for example, Bose–Einstein condensation might be expected.

In some very recent experiments using a gravity cavity (Steane *et al.* 1995), a cold cloud of atoms was dropped onto the reflecting evanescent surface. During the second bounce the evanescent field intensity was modulated, forming the temporal equivalent of a spatially periodic grating. The atomic translational energy was observed to be modulated by the atomic mirror vibrational frequency, producing a number of sidebands propagating at different velocities. The coherent splitting thereby produced has important potential applications to atom interferometry, to the realisation of **modulator devices for atoms** similar to those used for light, or to study the effects of quantum chaos as described in the last section.

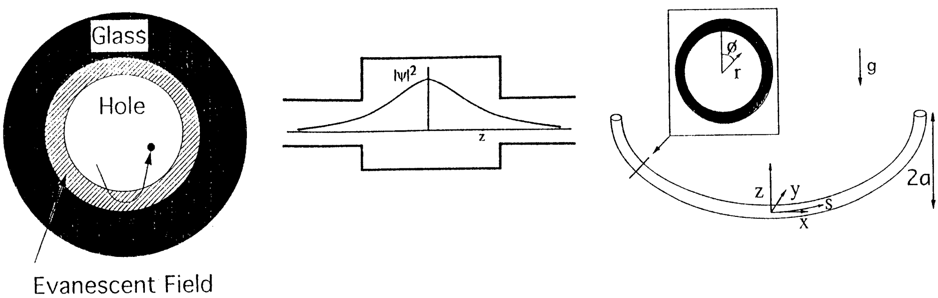


Fig. 20. Fibre optic waveguide (left), stepped cavity (centre) and U-tube cavity (right). After Savage *et al.* (1993) and Harris and Savage (1995).

4·3·2 Hollow optical fibres

Evanescent fields have also been proposed to guide atoms along hollow optical fibres (Ol'Shanii *et al.* 1993; Marksteiner *et al.* 1994; Ito *et al.* 1995). Using blue-detuned laser light, atoms could be confined to the dark region near the centre of the fibre where spontaneous emission is minimised (Fig. 20). If the fibre hollow core diameter is of the order of the de Broglie wavelength, **waveguiding** is predicted to occur in an analogous fashion to that of fibre optics for light.

The first experimental demonstration of fibre guiding has been achieved using rubidium atoms which were guided along a red-detuned laser introduced *inside* the hollow fibre core (Renn *et al.* 1995). Although evanescent fields were not employed in this experiment, the atoms were guided around bends, with up to 18 reflections being experienced from the guiding potential. In a more recent experiment, blue-detuned evanescent light fields were used to guide the rubidium atoms inside the fibre (Renn *et al.* 1996).

By using stepped evanescent potentials (Fig. 20), it may also be possible to create a cavity within the fibre itself that would reflect atoms at the potential barriers, and support those modes whose de Broglie wavelength was resonant with the step separation (Savage *et al.* 1993). Alternatively, the fibre may be bent into a U-shape (Fig. 20), and atoms dropped into the fibre would be confined to oscillate under gravity within the **fibre cavity** (Harris and Savage 1995).

4·3·3 Lasers for atoms?

The demonstration of atom cavities raises the question: is it possible to create coherent atomic sources, possibly leading to a 'laser' for atoms? Clearly, partially transmitting cavities (e.g. in which atoms in cavity modes tunnel through light potentials) could be used to increase the coherence of an atomic source, in much the same way as a Fabry–Perot etalon increases the coherence of a broadband light source. However, the demonstration of gain in an atomic cavity is another question.

This speculative topic has given rise to a number of suggestions, such as the use of state-switching techniques to dump atoms from a non-cavity mode state into an already partially occupied cavity-mode. The hope then is that the coherence of cavity mode atoms is transferred to the switched atoms, thereby producing gain. Still other ideas revolve around Bose–Einstein condensation of atoms as a means of generating a coherent atomic source. Although no experiments have yet been attempted in these areas, with the history of rapid evolution in atom optics, the future realisation of such speculative ideas may not be too far away.

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APPENDIX: ATOM OPTICS IN AUSTRALASIA

Not surprisingly, given the strength of atomic physics and laser science in Australasia, there has been considerable activity in the field of atom optics in this region. From the early experiments involving the University of Melbourne and the Australian National University in the late 1980s (Hajnal and Opat 1989; Hajnal *et al.* 1989; Baldwin *et al.* 1990), there has been a growth of experimental and theoretical activity in many centres which has contributed substantially to this field. A synopsis of these developments has been compiled below by institution, together with a contact name, and is an updated version of that given by Bachor and Baldwin (1994).

The group at the **University of Melbourne** (G. Opat) and **CSIRO Division of Materials Science and Technology** (P. Hannaford) is currently developing an atom matter-wave interferometer based on spatially separated beams of laser-cooled atoms as a highly sensitive inertial sensor of gravity fields, and for conducting various fundamental physics experiments of the type previously performed using neutron interferometry. A novel approach for producing the atomic-optical elements, which is based on spatially varying periodic magnetic fields generated on a flat surface, is being developed. This method does not rely on light fields and hence avoids the complication of spontaneous emission.

To date, samples of laser-cooled caesium atoms have been captured in a MOT, further cooled in optical molasses to about 13 μK, and then allowed to free-fall to generate a beam of near-monochromatic, slowly moving atoms. Experiments have included the observation of Stern–Gerlach deflection of a beam of slowly moving atoms by the inhomogeneous magnetic field from a current-carrying wire. The spatial distribution of the falling atoms shows well resolved structure corresponding to the individual magnetic substates. The single current-carrying wire can be considered as a simple atom-optical element using static magnetic fields, with the obvious extension to an array of wires to produce a flat mirror for beams of slowly moving atoms. Very recent experiments include the observation of specular reflection of a beam of free-falling laser-cooled caesium atoms from a planar magnetostatic mirror, consisting of an array of permanent rare-earth magnets of alternating polarity. Three bounces from the mirror have so far been observed, with reflectivities approaching 100%.

At the University of Melbourne (A. Roberts) computational techniques originally used in electron diffraction have been adapted to the situation of atoms in light fields. Members of the optics group are using scanning near-field optical microscopy to study evanescent fields. The aim is to design fields with sub-wavelength structure to be used as optical elements for atom optics.

Another group at the University of Melbourne (R. Scholten) is exploiting the small dimensions of light waves and atomic de Broglie waves to explore the manipulation of atomic beams at nanoscopic dimensions. Highly collimated atomic beams will be necessary, and these will be produced using polarisation-gradient laser cooling. Effective beam collimation requires laser intensities significantly higher than those typically used for three-dimensional cooling and trapping. Cooling of atomic beams will be studied in this previously unexplored regime. Standing waves will also be used to focus atomic beams into lines and spots as small as 10 nm across. Laser beams with phase singularities, such as doughnut beam modes, will be produced using holographic techniques and then used to control and focus atomic beams.

At the **Australian National University** there are currently two experimental laboratories engaged in a collaborative research program into atom optics, supported by an in-house theoretical program (C. Savage). The first laboratory, located in the Department of Physics in the Faculties (H. Bachor), has two facilities for atom optics experiments: an atomic beam line and an ultracold, slow atom launch facility. The other laboratory, in the Research School of Physical Sciences and Engineering (K. Baldwin), is developing a high-brightness source of cooled, metastable helium atoms for lithography, atom optics and atomic physics experiments.

Experiments in the Faculties have been concerned with developing atomic beamsplitters for use in atom interferometry, and have centred around the use of evanescent diffraction gratings backed by a numerical modelling program. Initial studies using thermal sodium beams and dye laser technology employed a moving grating to demonstrate coherent interaction of the standing evanescent field with atoms moving at similar velocities. Another series of experiments using standing laser light fields in free space have demonstrated controlled atom deflection and the realisation of a variable focal length lens for atoms. However, the use of thermal beams for atom optics experiments under these conditions is restricted, so a source of laser-cooled atoms has been developed. A caesium trapping and launching facility has been constructed to allow atoms cooled using diode lasers to be launched with velocities of a few $\mathrm{m\,s^{-1}}$, considerably slower than for atoms in thermal beams. The first experiment will involve diffracting these slow atoms from an evanescent light grating.

The high-brightness helium metastable source in the Research School also uses diode lasers to collimate, focus and cool the excited atoms into an intense beam which will then be used to interact with prepared surfaces for lithography applications. The same source will also be used to inject atoms into hollow optical fibres which will employ evanescent fields to guide the atoms, thereby creating a flexible atomic waveguide for lithography and other applications. The He metastable beam will also become a high-density target for atomic physics scattering experiments to measure excited-state cross sections for electron–atom and atom–atom collisions.

The group at the **University of Otago** (W. Sandle) is interested in the nonlinear optical properties of cold, dense samples of atoms. Such clouds of atoms have little or no Doppler broadening and could be used to provide an enhanced nonlinear interaction. A prototype MOT has been built as a source of sodium atoms which will be placed inside a cavity to study optical bistability and other nonlinear interactions of the laser-driven, cooled atoms within the cavity field.

The group at the **CSIRO National Measurement Laboratory** (P. Fisk) is investigating the microwave resonances of trapped ions as a promising new frequency standard. In the CSIRO laboratory the 12·6 GHz ground-state hyperfine transition in ytterbium-171 ions confined in a linear Paul trap are interrogated using the microwave-optical double resonance technique. This work uses a sapphire-loaded superconducting cryogenic resonator from the University of Western Australia as a local oscillator, and thereby achieves very high short-term microwave phase stability. An Allan variance deviation of $6\times10^{-14}\ \tau^{-1/2}$ for integration times of $\tau < 1000$ s has been demonstrated, which is significantly better than contemporary caesium clocks, and is currently the best performance ever demonstrated in a passive atomic frequency standard. The absolute accuracy of the two prototype ion trap standards currently in operation is better than 1 part in 10^{13}. Laser cooling of the ions has been achieved to <1 K and it is ultimately intended to use these techniques to eliminate microwave frequency shifts due to the second-order Doppler effect.

The group at **Griffith University** (W. MacGillivray) is developing a technique using laser deflection of an atomic beam to determine the state of the atoms as they enter the interaction region. A theoretical model has been derived which predicts that the optical force exerted on an atom is dependent on the exact description of its initial quantum state. This model has been used to design experiments in which the initial state of the atom is deduced from measurements of its deflection. The information that will be determined includes not only the population states of the atoms but also the initial coherences or superposition states. The feasibility of the method has been demonstrated recently by observing a difference in the atomic deflection when Na atoms were prepared in different ground states by optical pumping. Current work centres on measurements of ground-state populations and coherences prepared by magnetic pumping using an RF field. Ultimately, this is to be used to determine scattering parameters for electron excitation of metastable atoms.

The group at the **University of Queensland** is exploring light forces both experimentally and theoretically. In the experiments the idea of optical tweezers is greatly extended (H. Rubenstein-Dunlop). Micron-sized particles are also trapped using highly focused beams with a central intensity minimum. The group has expertise in producing such laser beams using holographic techniques, yielding holograms of high efficiency. In addition, rotation of trapped particles inside a defocused doughnut beam has been observed and it has been verified that a transfer of angular momentum is occurring from the laser beam to the particle. This effect could have wide reaching applications for the active driving of a rotational motion by light. The group is exploring the possibility of using an optically trapped particle as a force sensor for a scanning force microscope. It has been demonstrated that an improvment of at least one order of magnitude in compliance is achievable.

The same group at the University of Queensland is planning to use optical phase-singular fields for manipulation and confinement of atomic trajectories of cold atoms. In particular, the group will study the atom–field dynamics of a system comprising of an atomic wave packet with large de Broglie wavelength and an optical field which has a radial exponential potential. The beam profiles designed for specific trapping strategies will be produced by passing the laser beam through computer-generated holograms. At the present stage the group has finalised the construction of a MOT and cold rubidium atoms have been localised. The trap consists of two external cavity diode lasers stabilised to about 1 MHz. A detection system has been designed and the first successful measurements of the temperature of the trapped atoms have been performed using the method of ballistic expansion detected by an intensified CCD camera. This type of detection allows real-time two-dimensional imaging of the expanding cloud. The lowest temperature measured to date is 15 μK.

The theoretical work is concerned with quantum properties of the motion of atoms (G. Milburn). A two-level atom moving either inside a standing wave or in an evanescent field experiences a nonlinear potential. Situations such as a nonlinear driven pendulum are possible which can exhibit chaotic behaviour. In contrast to mechanical systems, the motion of the atom has to be quantised and thus a quantum chaotic system can be investigated. Presently the effects of spontaneous emission are being investigated. It is hoped that the dynamics of the quantum motion dominates over such dissipative effects and that atom optics can be regarded as a test case for the chaotic behaviour of a quantum system. Recently a group at the University of Texas at Austin obtained clear experimental evidence of dynamic localisation, one of the more surprising predictions of quantum chaology. The group at the University of Queensland is currently constructing a detailed theoretical model of the effects of laser noise on the results obtained in the Austin experiment.

The group at the **University of Auckland** (D. Walls) is investigating a number of theoretical aspects of atom optics. The recent experimental achievement of Bose–Einstein condensation of atoms shows how atoms can behave like photons statistically as well as in their wavelike behaviour. The next step would be to create an atomaser, a device which produces a coherent beam of atoms like a laser beam of photons. The group is undertaking theoretical studies of different models of atomasers, in collaboration with workers in Europe.

Bichromatic standing-wave fields can be used to create appropriately shaped potentials for the splitting and focusing of beams of three-level atoms. The work is a theoretical inquiry into the expected performance of such optical elements, and the effect of various noise sources.

Using an intense evanescent light wave as the lower mirror, and the gravitational force as the upper mirror, a vertical cavity for storing atoms for long periods of time can be constructed. Effects of measurement, spontaneous emission and dispersion in such cavities are being studied.

The Auckland group has also been investigating the use of the fluorescence from atoms cooled with 'dark state' laser cooling schemes for the measurement of small forces. The effect of an external force on both the time-dependent and steady-state fluorescence, and also the steady-state momentum distribution, have been studied theoretically.

Presently the University of Auckland is setting up a laboratory which will trap and cool atoms with lasers. At present they are stabilising laser diodes to a caesium transition and the construction of a MOT is well under way. Numerous experiments are planned with the trapped and super-cooled (sub-millikelvin) atoms. For example, the group plans to construct an optical lattice with additional laser beams by modulating the lattice one can examine quantum chaotic effects. An industrial application of the MOT is planned: the construction of a wavelength standard for telecommunication fibre networks. They also hope to frequency-stabilise an erbium-doped fibre amplifier with internal gratings to the $1 \cdot 5\,\mu$m line of trapped and cooled rubidium atoms. Rubidium also has a line at $1 \cdot 3\,\mu$m, and it could prove very fruitful to lock a praseodymium-doped fluoride fibre amplifier or appropriate semiconductor laser to that rubidium line.

Finally, at **Macquarie University** (B. Sanders) theoretical research is in progress in related situations showing the quantum nature of the movement of atoms in light fields. For example, very slow, extremely well collimated atomic beams could show quantum tunnelling effects, which are studied using a vector Schrödinger equation. On the other hand, dense ultracold clouds of atoms should have interesting properties once the mean distance between atoms is less than a de Broglie wavelength. For this situation an appropriate quantum field theory has been developed which predicts novel effects such as the formation of atomic solitons.

The group at Macquarie University are developing rigorous theoretical techniques for describing experiments involving ultracold atoms. These atoms are linked by quantum coherence into a 'superatom', and this Bose–Einstein condensate has been realised experimentally in 1995. Interesting effects are being explored, including generation of atomic pulses in atom cavities, determination of the conditions for ultracold atomic soliton propagation in laser beams, diffraction of these condensates from optical standing waves, and the stability of the condensate in the presence of a laser beam is being studied.

Atom optics is also being pursued by studying velocity selection methods for atom waves. Resonant tunnelling is seen to occur for atoms propagating transversely through laser beams. Very slow, well collimated atoms can undergo quantum tunnelling through laser beams which form classical potential barriers. By exploiting this quantum coherence, velocity selection becomes possible, and this technique could provide a way to produce exotic atomic waves.

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