Interference with atomic and molecular matter waves is a rich branch of atomic physics and quantum optics. It started with atom diffraction from crystal surfaces and the separated oscillatory fields technique used in atomic clocks. Atom interferometry is now reaching maturity as a powerful art with many applications in modern science. In this review we first describe the basic tools for coherent atom optics including diffraction by nanostructures and laser light, three-grating interferometers, and double wells on AtomChips. Then we review scientific advances in a broad range of fields that have resulted from the application of atom interferometers. These are grouped in three categories: (1) fundamental quantum science, (2) precision metrology and (3) atomic and molecular physics. Although some experiments with Bose Einstein condensates are included, the focus of the review is on linear matter wave optics, i.e. phenomena where each single atom interferes with itself.

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Atom interferometry is the art of coherently manipulating the translational motion of atoms (and molecules) together with the scientific advances that result from applying this art. We begin by stressing that motion here refers to center of mass displacements and that coherently means with respect for (and often based on) the phase of the de Broglie wave that represents this motion. The most pervasive consequence of this coherence is interference, and the most scientifically fruitful application of this interference is in interferometers. In an interferometer atom waves are deliberately offered the option of traversing an apparatus via two or more alternate paths and the resulting interference pattern is observed and exploited for scientific gain. Atom interferometers are now valuable tools for studying fundamental quantum mechanical phenomena, probing atomic and material properties, and measuring inertial displacements.

In historical perspective, coherent atom optics is an extension of techniques that were developed for manipulating internal quantum states of atoms. Broadly speaking, at the start of the 20th century atomic beams were developed to isolate atoms from their environment; this a requirement for maintaining quantum coherence of any sort. Hanle (1924) studied coherent superpositions of atomic internal states that lasted for tens of ns in atomic vapors. But with atomic beams, Stern-Gerlach magnets were used to select and preserve atoms in specific quantum states for several ms. A big step forward was the ability to change atoms’ internal quantum states using RF resonance as demonstrated by Rabi et al. (1938). Subsequently, long-lived coherent superpositions of internal quantum states were intentionally created and detected by Ramsey (1949). The generalization and fruitful application of these techniques has created or advanced a great many scientific and technical fields (e.g. precise frequency standards, nuclear magnetic resonance spectroscopy, and quantum information gates).

Applying these ideas to translational motion required the development of techniques to localize atoms and transfer atoms coherently between two localities. In this view, localities in position and momentum are just another quantum mechanical degree of freedom analogous to discrete internal quantum states. We discuss these coherent atom optics techniques in Section II and the interferometers that result in Section III. Then we discuss applications for atom interferometers in Sections IV, V, and VI.

## A. Interferometers for translational states

Atom Optics is so named because coherent manipulation of atomic motion requires that the atoms be treated as waves. Consequently, many techniques to control atom waves borrow seminal ideas from light optics. To make atom interferometers the following components of an optical interferometer must be replicated:

1. State Selection to localize the initial state (generally in momentum space)
2. Coherent Splitting, typically using diffraction to produce at least two localized maxima of the wave function with a well-defined relative phase
3. Free Propagation so that interactions can be applied to one “arm”, i.e. one of the two localized components of the wave function
4. Coherent Recombination so that phase information gets converted back into state populations
5. Detection of a specific population, so the relative phase of the wavefunction components can be determined from interference fringes.

In hindsight, it is possible to reinterpret much of the work on internal state resonance as an interferometer. In particular, the separated oscillatory fields technique Ramsey (1949) divided a single RF resonance region into two zones that may be regarded as beam splitters. In this experiment a Stern-Gerlach filter (the so-called A magnet in Fig. 1) selects atoms in state $|a\rangle$. The first resonance region (microwave cavity) then excites atoms into a superposition of states $|a\rangle$ and $|b\rangle$. Atoms then travel through a static (C) field in a coherent superposition whose relative phase oscillates freely until the atoms enter the second microwave cavity. If radiation there is in phase with the oscillating superposition, then atoms complete the transition to state $|b\rangle$. But if the radiation...
is half a cycle out of phase then atoms are returned to state $|a\rangle$. After the final state selector, the detected intensity oscillates as a function of microwave frequency. Overall, this method to manipulate the internal states of an atom obviously maps directly onto the steps listed above and can be regarded as the first atom interferometer even though it is more frequently described in terms of resonance of a Bloch vector of an atom moving classically.

B. Preparation. Manipulation. Detection.

Preparation of position states is hindered by the uncertainty principle. As soon as free atoms are localized in position, the attendant momentum uncertainty starts to cause spatial delocalization. On the other hand, preparation in momentum space is free of such back action. Therefore in coherent atom optics, especially with free atoms, it is desirable to reduce the momentum and its uncertainty for an ensemble of atoms. This is colloquially referred to as slowing and cooling the atoms, respectively.

Momentum-state selection can be as simple as two collimating slits that select atoms with limited transverse momentum. Alternatively, and preferably, atoms can be concentrated in phase space by laser cooling and trapping. This is analogous to optical pumping for internal states. In fact, cooling atoms (or ions) in a trap is even more exactly analogous to optical pumping because trapped atoms are in discrete translational states and can ultimately be prepared in the single ground state.

The typical momentum uncertainty achieved with various methods is summarized in Table I. We note that atom interferometers already work with atoms prepared in beams, magneto-optical traps, or Bose Einstein condensates.

Manipulation. In most atom interferometers diffraction or the closely related Raman transitions “split” atoms into a coherent superposition of momentum states that typically differ in momentum by several photon momenta (velocity differences of several cm/sec; e.g. the recoil velocity for Na atoms due to absorbing a 590 nm photon is $v_{\text{rec}} = \hbar k/m_{\text{Na}} = 2.9$ cm/sec and the velocity difference between 0th and 1st diffraction orders for Na atoms transmitted through 100 nm period gratings is $\hbar/(m_{\text{Na}} d) = 17$ cm/sec). As time passes, each atom evolves into a coherent superposition of spatial positions located a distance $\Delta x = (p_2 - p_1)/2m$ apart. Moreover, if the initial preparation was restrictive enough, then the components of each atom’s wavefunction will be distinctly separated in space. Creating such ‘separated beams’ in an interferometer invites the experimenter to deliberately apply different interactions - and hence different phase shifts - to each component of an atom’s wave function.

Observing this phase difference requires recombining the two components of the superposition. This is gen-

\footnote{Original references for cooling and trapping include: supersonic beams [Beijerinck and Verster, 1981; Campargue, 1983], optical molasses [Aspect et al., 1986; Chu et al., 1985], optical traps (Ashkin, 1974; Chu et al., 1986; Miller et al., 1993), magneto optical traps (Raab et al., 1987), magnetic traps (Migdall et al., 1982; Pritchard, 1983), atomic fountains [Kasevich et al., 1989], velocity selective coherent population trapping [Aspect et al., 1988], sideband cooling [Neuhauser et al., 1978; Vuletic et al., 1998; Wineland et al., 1978], cooling to the ground state of a trap [Jessen et al., 1992; Monroe et al., 1993] and Bose Einstein Condensation [Anderson et al., 1995].}
erally achieved by using diffraction or Raman processes again to reverse the momenta of the two states so they subsequently overlap. When this is done, interference fringes are observed and the phase \( \phi_{\text{int}} \) can be determined from their position.

**Detection.** Once information is transferred from the phase of a superposition into the population of observable states by using some kind of beam recombiner, then a state-selective detector is used to measure the output of an interferometer. In analogy with an optical Mach-Zehnder interferometer, the fringes can be observed as atom beam intensity that oscillates between two ‘output’ states by using some kind of beam recombiner, then a state-selective detector is used to measure the output of an interferometer. In analogy with an optical Mach-Zehnder interferometer, the fringes can be observed as atom beam intensity that oscillates between two ‘output’ states as a function of the interaction-induced phase difference \( \phi_{\text{int}} \). Alternatively, fringes can be observed directly in position space either by moiré-filtering with a suitable mask or by directly imaging the atoms. Bragg reflection of laser light can also be used to detect fringes in atomic density. If the interferometer manipulates both the internal and (separated) external states of atoms, then fringes can be detected as oscillations in population of the internal states after recombining the atoms, as in Ramsey’s experiment.

Historically, alkali atoms were the first to be detected efficiently, and this was achieved by counting the ions produced as the atoms ionized on a hot tungsten or rhenium wire\(^2\). Metastable atoms can be detected directly with multi-channel plates because of their stored internal energy. More universal neutral atom detectors use electron bombardment or laser excitation to produce countable ions. Fluorescence or absorption can also reveal fringes, especially if a cycling transition is used with slow atoms.

### C. Scientific promise of atom interferometers

The light interferometers that were developed late in the 19th century by Fizeau (1853), Michelson (1881), Rayleigh (1881), and Fabry and Perot (1899) performed many beautiful experiments and precise measurements that have had a broad impact in physics. Recently, the initial idea from de Broglie and Schrödinger that propagating particles are waves has been combined with technologies to produce interferometers for electrons (Marton et al. 1953, 1954), neutrons (Rauch et al. 1974), and now atoms. Even after the many advances made possible with earlier interferometers, wonderful further scientific advances from atom interferometers have long been anticipated. In fact, the concept of an atom interferometer was patented by Altschuler and Franz (1973) and it has been extensively discussed since. Early proposals for atom interferometers were made by Chebotayev et al. (1985), Clauser (1988, 1989), Keith et al. (1988), Martin et al. (1988), Pritchard (1989), Bordé (1989) and Kasevich and Chu (1991).

Even compared to electron- and neutron-wave physics, interferometry with atoms offers advantages on several fronts: a wider selection of atomic properties, larger cross sections for scattering light, better characterized environmental interactions, higher precision, better portability, and far lower cost. Atomic properties like mass, magnetic moment, and polarizability can be selected over ranges of several orders of magnitude. For example, Cs has 137 times the mass and 89 times the electric polarizability of H and is therefore better suited to measuring inertial effects and detecting weak electric fields. \(^{52}\text{Cr}\) has a magnetic moment of 6 \(\mu_\text{B}\) while \(^{4}\text{He}\) has none. Alkali atoms have \(10^{-9}\) \(\text{cm}^2\) scattering cross sections for resonant light while electrons have a \(10^{-25}\) \(\text{cm}^2\) cross section for the same light (Compton / Thomson Scattering). Hence, interactions of atoms and their environment can be enlarged for better measurements or to study decoherence, or they can be suppressed to measure something else. Furthermore, atoms interact with surfaces and other atomic gasses with potentials that are easily studied by interferometry. Atoms can be manipulated by lasers whose frequency and wavelength are measured with accuracies of \(10^{-15}\) and \(10^{-11}\) respectively, offering far better precision for measurements than the crystals or structures used in other types of interferometer. Finally, atom sources can be as simple as a heated container with a small hole in the side or a pulse of laser light that hits a pellet of the desired material. These sources are far less expensive than nuclear reactors or even 200 keV electron guns. In fact atom interferometers on atom chips can potentially fit in a briefcase.

This richness and versatility is combined with the rewards (and challenges) that stem from the fact that thermal atomic wavelengths are typically 30,000 times smaller than wavelengths for visible light. The power of atom interferometry is that we can measure phase

\[ \langle p^2 \rangle = \langle p \rangle^2 + \langle [p, p] \rangle, \]

\[ \langle [p, p] \rangle = \hbar^2 \left( \frac{\delta}{2\pi} \right)^2, \]

where \(\hbar\) is the reduced Planck constant, \(\langle p \rangle\) is the mean position of the atom, and \(\delta\) is the phase difference.

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\[ \sigma_p = \sqrt{\langle [p, p] \rangle} = \frac{\hbar}{\pi \langle \delta \rangle}, \]

where \(\sigma_p\) is the momentum uncertainty, \(\langle \delta \rangle\) is the phase uncertainty, and \(\hbar\) is the reduced Planck constant.

### Table I: Momentum uncertainty and temperature of atoms prepared with different techniques.

| Atomic Sample                  | \(\sigma_p / \hbar k_{\text{ph}}\) | T/K   |
|-------------------------------|----------------------------------|------|
| Thermal vapor                 | 24,000                           | 500  |
| Effusive beam (longitudinal)  | 8,000                            | 50   |
| Supersonic beam (longitudinal)| 3,000                            | 8    |
| Optical molasses or MOT       | 20                               | 0.00025 |
| Collimated beam (transverse)  | 1                                | \(10^{-6}\) |
| Bose Einstein condensate      | 0.1                              | \(10^{-8}\) |

\[^2\text{Various atom detectors are discussed in }\text{Campargue, 2004; Ramsey, 1983; Scoles, 1988. For hot wire detectors see }\text{Delhuille et al., 2002; Langmuir and Kingdon, 1925, for universal detectors see }\text{DeKieviet et al., 2004; Kuhnke et al., 1993.}\]
shifts $\phi_{int} = \hbar^{-1} \int U dt$ due to very small potential energies. A simple calculation shows that 1000 m/s Na atoms ($E_{kin} \sim 0.1$ eV) acquire a phase shift of 1 rad for a potential of only $U = 6.6 \times 10^{-12}$ eV in a 10 cm interaction region. Such an applied potential corresponds to a refractive index of $|n - 1| = 2.7 \times 10^{-11}$. Measuring the phase shift $\phi_{int}$ to $10^{-3}$ rad corresponds to an energy resolution $U/E \sim 10^{-14}$, or a spectrometer with a linewidth of 10 kHz and spectroscopic precision of Hz/$\sqrt{\tau}$. This with a thermal atomic beam, cold atoms can increase the sensitivity 1000-fold!

As we document in this review, atom interferometers have already measured rotations, gravity, atomic polarization, the fine structure constant, and atom-surface interactions better than previous methods. Yet atom interferometry itself is just over a decade old. The realization of such interferometers started with diffraction gratings that are summarized in Section II of this review. We catalogue atom interferometer types and features in Section III. We discuss fundamental issues such as decoherence in Section IV. Precision measurements are described in Section V, and atomic and molecular physics applications are described in Section VI.

II. ATOM DIFFRACTION

Since half-silvered mirrors do not exist for atoms (solid matter generally absorbs or scatters atoms), beamsplitters for atom interferometers are often based on diffraction. Diffraction itself is an interesting interference effect that has already been cleverly developed for use with atoms. Hence we discuss atom diffraction now, and atom interferometers next (in Section III).

Diffraction occurs when a wave interacts with anything that locally shifts its phase or amplitude (e.g. due to absorption), and is a hallmark of wave propagation and interference. It is generally treated as resulting from the coherent superposition and interference of amplitudes for wave propagation via different paths through the diffracting region that have the same starting and ending points.

A diffraction grating is a periodic diffracting region. Spatial modulation of the wave by the grating generates multiple momentum components for the scattered waves. The fundamental relationship between the momentum transferred to waves in the $n^{th}$ component and the grating period, $d$, is

$$\delta p_n = n \frac{\hbar}{d} = n \hbar G \tag{1}$$

where $G = 2\pi/d$ is the reciprocal lattice vector of the grating, and $\hbar$ is Planck’s constant. When the incoming wave has a narrow transverse momentum distribution centered around $p_{beam}$, this diffraction is generally observed with respect to angle. Since the de Broglie wavelength is $\lambda_{DB} = \hbar/p_{beam}$, the resulting diffraction angles (for nearly normal incidence) are $\theta_n \approx \delta p_n / p_{beam} = n \lambda_{DB} / d \tag{2}$

To observe the interference a grating must be illuminated at least in part coherently, i.e. the incident atom waves must have a well-defined relative phase across several grating periods. That means the transverse coherence length must be larger than a few grating periods, i.e. the transverse momentum distribution must be small enough to resolve the diffraction orders. This is usually accomplished by collimating the incident beam.

A. Early diffraction experiments

The first examples of atom interference were diffraction experiments, and the earliest of these was by Estermann and Stern (1930) just three years after the electron diffraction experiment by Davisson and Germer (1927). Figure 2 shows original data in which helium atoms were reflected and diffracted from the surface of a LiF crystal. The small lattice period of the crystal surface (40 nm) gave large diffraction angles and allowed relaxed collimation. This observation proved that composite particles (atoms) propagate as waves, but this kind

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$^3$ The transverse coherence length is $\ell_{coh} \approx \lambda_{DB}/\theta_{coll}$, where $\lambda_{DB}$ is the de Broglie wavelength and $\theta_{coll}$ is the (local) collimation angle of the beam (the angle subtended by a collimating slit). Since for thermal atomic beams $\lambda_{DB} \sim 10$ pm a collimation of $\theta_{coll} < 10 \mu$rad is required for a 1 $\mu$m coherent illumination.
of reflection-type diffraction grating has not led to a beam splitter suitable for atom interferometry. It did, however, launch an active field of atom diffraction (both elastic and inelastic) for studying surfaces.

B. Nanostructures

One of the first demonstrations of atom diffraction from macroscopic objects was made by Leavitt and Bills (1969) who observed Fresnel diffraction from a single 20 µm wide slit. With the advent of modern nano technology it became possible to fabricate elaborate arrays of holes and slots in a thin membrane that allow atoms to pass through. These can have feature sizes of 50 nm or below – much smaller than typical transverse coherence in well-collimated atomic beams. Diffraction from a nanofabricated structure – a transmission grating with 200 nm wide slits – was first observed by the Pritchard group at MIT (Keith et al. 1988). This led to many beautiful interference experiments with atoms and molecules.

Nano technology has been used to make single slits, double slits, diffraction gratings, zone plates, hologram masks, mirrors, and phase shifting elements for atom waves. The benefits of using mechanical structures for atom optics include: feature sizes smaller than light wavelengths, arbitrary patterns, rugged designs, and the ability to diffract any atom and or molecule. The primary disadvantage is that atoms stick to (or bounce back from) surfaces, so that most structures serve as absorptive atom optics with a corresponding loss of transmitted intensity.

1. Transmission gratings

After the demonstration of transmission gratings for atom waves by Keith et al. (1988), these gratings have seen numerous applications. A 100-nm period nanostructure grating made at the MIT NanoStructure laboratory (Savas et al. 1997) has been diffracted from similar gratings (Arndt et al. 1999, Brezger et al. 2003, 2002, Bruhl et al. 2004, Chapman et al. 1995a, Hackermüller et al. 2003b, Nairz et al. 2003, Schollkopf and Toennies 1996). Scientific results in this area, such as the study of decoherence and the formation rate of molecules in beams will be discussed in Section IV.

Modification of the diffraction patterns due to van der Waals interaction with the grating bars was first observed by Grisenti et al. (1999). This reduces the flux in the zeroth order, increases flux in most of the higher orders and prevents “missing orders” from occurring (Cronin and Perreau, 2004). Random variations in the grating bar period can be analyzed as Debye Waller damping which preferentially suppresses higher diffraction orders (Grisenti et al. 2000a). Molecular size effects also modify the relative efficiencies as described by Arndt et al. (2000a) and were used to estimate the size of the very weakly bound He2 molecule (Luo et al. 1999, Schollkopf and Toennies 1994, Schattenburg et al. 1994).

Molecules such as 4He2, 4He3 and other 4He clusters, Na2, C60, C70, C60F38, and C44H30N4 have been diffracted from similar gratings (Arndt et al. 1999, Brezger et al. 2003, 2002, Bruhl et al. 2004, Chapman et al. 1995a, Hackermüller et al. 2003b, Nairz et al. 2003, Schollkopf and Toennies 1996).
2. Young’s experiment with atoms

Atomic diffraction from a double slit recapitulates the seminal Young’s double slit experiment in which the diffraction pattern is created by the interference of waves traversing two cleanly separated paths. In that sense it can be seen as a two path interferometer. The atomic version by Carnal and Mlynek (1991) used a mechanical structure with two 1-µm wide slits separated by 8 µm to create the interference (Fig. 4). Diffraction from a single 2-µm wide slit 62 cm from the double slit prepared the atom waves (λdB = 100 pm) to have a transverse coherence length larger than the double slit separation (ℓcoh = zλdB/2w = 15 µm).

In the original experiment, a slit was translated in front of the detector to observe the interference fringes. With a beam brightness of B ≈ 10^{17} s^{-1} cm^{-2} sr^{-1}, the average count rate was about one atom per second. In a later version (see Fig. 5) they used a position sensitive detector to record the whole pattern at once, giving a larger counting rate. Time of flight resolution was added in order to measure the Wigner function of the transmitted atoms (Kurtsiefer et al., 1997).

A two slit experiment using cold Ne* atoms was presented by Shimizu et al. (1992). The atoms were dropped from a magneto-optical trap one meter above a mechanical mask with two slits separated by 6 µm. At the location of the mask the atoms had a speed of 4.5 m/s (λdB = 5 nm) and a speed ratio of v/σv = 20. The mask was equipped with an electrode so that deflection due to an applied electric field gradient could be measured.

3. Charged-wire interferometer

A variation of the atomic Young’s experiment was built by Nowak et al. (1998). A single wire put in a He* beam produces a near-field diffraction pattern. Charging the wire bends the atom trajectories passing around it inward, increasing the interference (Fig. 5) analogous to the charged-wire optical bi-prism interferometer for electrons (Mollenstedt and Duker, 1955).
FIG. 6 A zone plate for focusing atom beams. The plate (inset) has free-standing annular rings and radial support struts. The data shows focused (+1) and defocused (-1) atom beam components. Figure from [Donk et al., 1999].

C. Gratings of light

Laser spectroscopy initially dealt with the internal energy levels of atoms, and coherent phenomena such as non-linear optics. Exploiting the momentum transfer accompanying absorption or emission of light was of little experimental concern until the observation of quantized deflection (=diffraction) in an atom beam by [Moskowitz et al., 1983] and its subsequent application to a BEC by [Ovchinnikov et al., 1999]. Many beautiful experiments with atoms diffracted from standing waves of light have been accomplished since these earliest milestones (e.g. [Delhuille et al., 2002a; Giltner et al., 1995a,b; Koolen et al., 2002; Martin et al., 1995; Rasel et al., 1995; Stenger et al., 1999; Torii et al., 2000]). Now the interaction between light and atoms is recognized as a rich resource for atom diffraction (and interference) experiments; and a unified view of all possible atom diffraction processes using light beams is presented in [Bordé, 1997]. Light waves can act as refractive, reflective and absorptive structures for matter waves, just as glass interacts with light waves.

In an open two-level system the interaction between an atom and the light field (with detuning \( \Delta = \omega_{\text{laser}} - \omega_{\text{atom}} \)) can be described with an effective optical potential of the form [Oberthaler et al., 1996a]

\[
U(x) = \frac{\hbar \Omega_1^2}{4\Delta + i\Gamma} \propto \frac{I(x)}{2\Delta + i\Gamma} \tag{4}
\]

where the (on-resonant) Rabi frequency, \( \Omega_1 = \frac{\mathbf{d}_{\text{ab}} \cdot \mathbf{E}_{\text{optical}}}{\hbar} \), is given by the atomic transition dipole moment and the optical electric field, \( \Gamma \) is the atomic decay rate and \( I(x) \) is the light intensity. The imaginary part of the potential comes from the spontaneous scattering processes, and the real part results from the ac Stark shift. For a more detailed description we point to the vast literature on mechanical effects of light. If the spontaneous decay follows a path to a state which is not detected, the imaginary part of the potential in Eq. (4) is equivalent to absorption. Therefore on-resonant light can be used to create absorptive structures. Light with large detuning produces a nearly real potential and therefore acts as pure phase object. Near-resonant light can have both roles.

The spatial shape of the potential is given by the local light intensity pattern, \( I(x) \), which can be shaped with all the tricks of near and far field optics for light, including holography. The simplest object is a periodic potential created by two beams of light whose interference forms a

4 Of course, theoretical work on quantized momentum transfer from light to matter dates back to Einstein (1917) and Kapitza and Dirac (1932).

5 See for example, Ashkin, 1970, 1980; Dalibard and Cohen-Tannoudji, 1988; Metcalf and van der Stratten, 1999.
standing wave with reciprocal lattice vector
\[ \vec{G} = \vec{k}_1 - \vec{k}_2. \] (5)

This is often called an optical lattice because it is a close realization of the periodic potentials that electrons experience in solid state crystals. Thus, Bloch states can be used to understand atom diffraction (Champenois et al., 2001a; Letokhov et al., 1992). Additional points of view that we shall discuss include the thin-hologram (Raman-Nath approximation) (Meystre, 2001), two-photon Rabi oscillations (Gupta et al., 2001b), and multi beam interference (dynamical diffraction theory).

We distinguish different regimes for atom manipulation, for example (1) thick vs. thin optical lattices, (2) weakly perturbing vs. strongly channeling lattices, (3) on- vs. off-resonant light, and (4) static vs. time-dependent optical potentials. These are discussed and interrelated in (Bernet et al., 2000; Champenois et al., 2001a; Gupta et al., 2001b; Keller et al., 1999; Morsch and Oberthaler, 2006; Oberthaler et al., 1999, 1996a). We include a summary chart (Figure 8) that catalogues different effects caused by gratings of light.

Since light gratings can fill space, they can function as either thin or thick optical elements. As in light optics, for a thin optical element the extent of the grating along the propagation direction has no influence on the final diffraction (interference). But in a thick element the full propagation of the wave throughout the diffracting structure must be considered. In a grating, the relevant scale is set by the grating period \(d\) and the atomic de Broglie wavelength \(\lambda_{\text{dB}}\). If a grating is thicker than \(d^2/\lambda_{\text{dB}}\) (half the Talbot length) it is considered thick, and the characteristics observed are Bragg scattering or channeling, depending on the height of the potentials. If the grating is thinner than \(d^2/\lambda_{\text{dB}}\), it can be analyzed in the Raman-Nath limit, and it produces a symmetric distribution of intensity into each pair of diffraction orders of opposite sign \((\pm N)\). The thin vs. thick transition is labeled “first focus line” in Figure 8.

The second distinction, mostly relevant for thick gratings, has to do with the strength of the potential. One must determine if the potential is only a perturbation, or if the potential modulations are larger then the typical transverse energy scale of the atomic beam or the characteristic energy scale of the grating,
\[ E_G = \frac{\hbar^2 G^2}{2m} = 4\hbar\omega_{\text{rec}}, \] (6)

associated with one grating momentum unit \(\hbar G\). \(\hbar\omega_{\text{rec}}\) is an atom’s ‘recoil energy’ due to absorbing (or emitting) a photon. For weak potentials, \(U \ll E_G\), one observes Bragg scattering. The dispersion relation looks like that of a free particle with avoided crossings at the edges of the zone boundaries. Strong potentials, with \(U \gg E_G\), cause channeling. The dispersion relations are nearly flat, and atoms are tightly bound in the wells.

**FIG. 8** (color online) Dimensionless parameter space for atom diffraction. The vertical axis (optical potential in units of \(E_G\)) and horizontal axis (interaction time in units of \(\omega_{\text{rec}}^{-1}\)) are independent of atomic transition dipole moment and atomic mass (see Equations 4 and 6). Under the ‘first focus line’ the RNA (Equation 8) is satisfied. ‘KD’ labels curves corresponding to conditions that maximize Kapitza Dirac diffraction into orders 1 through 10 in order from bottom to top (see Equation 7). ‘Bragg’ indicates curves that correspond to conditions for complete (\(\pi\)-pulse) Bragg reflection into orders 1 through 10 (see Equations 11 and 12). The vertical dashed line indicates the Talbot time \(\tau_T\) (discussed in Section II.D.). For detuning of \(\Delta = 100\Gamma\), the average number of spontaneously scattered photons per atom is greater than one above the line marked \(N_s = 1\). Experiment conditions are shown as points. ◊: Kapitza-Dirac diffraction of an atomic beam (Gould et al., 1988). •, △, ◇: Bragg diffraction of an atomic beam (Martin et al., 1988; Giltner et al., 1995a; Koolen et al., 2002) respectively. ♦: Bragg diffraction of a BEC (Kozuma et al., 1999a) (Bragg spectroscopy of a BEC (Stenger et al., 1999) at \(2\omega_{\text{rec}} = 80\) would appear to the right of the charted regions, near the first-order Bragg curve). ▲: Transition from Kapitza-Dirac diffraction to oscillation of a BEC in a standing wave light pulse (Ovchinnikov et al., 1999). ■: Coherent channeling. Figure adapted from (Gupta et al., 2001b) and (Keller et al., 1999).

1. Thin gratings: Kapitza-Dirac scattering

If atoms are exposed to a standing wave of off-resonant light for a short time \(\tau\), the resulting optical potential due to the standing wave acts as a thin phase grating with period \(d = \lambda_{\text{ph}}/2\). Atom waves are diffracted by this grating so that many momentum states (each differing by \(\hbar G\)) are populated as shown in Figure 9 (left...
FIG. 9 (color online) Comparison between diffraction from a thick and a thin grating. (a) Kapitza Dirac (KD) diffraction, discussed in Section II.C.1. (b) Bragg Diffraction, discussed in Section II.C.3. The top row shows the essential difference: thick vs. thin gratings. The bottom row shows data obtained by the Pritchard group for KD and Bragg diffraction (Gould et al., 1986; Martin et al., 1988).

This is known as Kapitza-Dirac scattering\(^6\), and occurs in the Raman-Nath limit. The probability of finding atoms in the \(N\)th diffracted state is given by the Fourier transform of the imprinted phase shift, resulting in the equation (Gupta et al., 2001b)

\[
P_{N}^{\text{KD, thin}} = J_{N}^{2} \left( \frac{\Omega_{1}^{2} \tau}{2 \Delta} \right).
\]  

Here \(J_{N}\) is an \(N\)th order Bessel function, and \(\tau\) is the duration that the optical intensity is experienced by the atoms. As defined near Equation 3, \(\Omega_{1} = d_{ab} E_{\text{optical}} / \hbar\). Equation 7 is valid for normal incidence; Henkel et al. (1994) considered all angles of incidence.

The Raman-Nath approximation (RNA) is valid provided the transverse motion of the atoms remains small. Approximating the potential from a standing wave as parabolic near a minimum leads to the condition for the RNA to be valid:

\[
\tau < \frac{\tau_{\text{osc}}}{4} = \frac{1}{2 \sqrt{\Omega_{R} E_{G} \hbar}}
\]  

where \(\Omega_{R} = \sqrt{|\Omega_{1}|^{2} + \Delta^{2}}\) is the generalized Rabi frequency. If the interaction time is longer than this, Eq. 7 is no longer valid, and population transfers to states with the largest momenta (large \(N\)) are suppressed (Keller et al., 1993; Meystre, 2001; Moharam and Young, 1978; Raman and Nath, 1953; Wilkens et al., 1991).

Early attempts to observe the Kapitza-Dirac (KD) effect with electrons were controversial [see discussion in (Batelaan, 2000; Freimund et al., 2001)], and attempts with atoms were unable to eliminate the effects of spontaneous emission (Arimondo et al., 1979)\(^7\). The first observation of Kapitza-Dirac scattering by Moskwowitz et al. (1983), and Gould et al. (1986) was therefore a breakthrough: it showed a symmetric double maximum and also revealed that momentum transfer was quantized in units of \(2 \hbar k_{\text{light}}\), thereby indicating a coherent process. Moreover, these experiments showed that quantized momentum transfer (i.e. coherent diffraction) is possible even if the interaction time, \(\tau\), is much larger than the atoms’ radiative lifetime, provided that the radiation is detuned from resonance.

With a BEC Kapitza-Dirac scattering was first observed at NIST by Ovchinnikov et al. (1999) and has subsequently become an everyday tool for manipulating BEC’s. More recently, a series of light pulses separated in time [by about one eighth of the Talbot time (\(\tau_{T} = 2d^{2} m / \hbar\))] have been used to diffract atoms with high efficiency into only the ±1 orders (Wang et al., 2005; Wu et al., 2005b).

2. Diffraction with on-resonant light

Tuning the light frequency of a standing light wave to resonance with an atomic transition (\(\Delta = 0\)) can make an ‘absorptive’ grating with light. This is possible when the spontaneous decay of the excited state proceeds mainly to an internal state which is not detected. (If the excited state decays back to the ground state, this process produces decoherence and diffusion in momentum space.) For a thin standing wave the atomic transmission is given by

\[
T(x) = \exp \left[ -\frac{\kappa}{2} [1 + \cos(Gx)] \right],
\]  

where the absorption depth for atoms passing through the antinodes is \(\kappa\). For sufficiently large absorption only

---

\(^6\) The original proposal by Kapitza and Dirac (1933) was for Bragg reflection of electrons by a standing wave of light (Batelaan, 2000; Freimund et al., 2001). However, “Kapitza-Dirac scattering” is now most commonly used in the literature to describe diffraction of atoms by a thin grating of light.

\(^7\) In fact, T. Oka made a wager with DEP that the MIT experiments would continue to show a maximum at zero deflection, rather than revealing two maxima displaced from the center as predicted.
atoms passing near the intensity nodes survive in their original state and the atom density evolves into a comb of narrow peaks. Since the ‘absorption’ involves spontaneous emission such light structures have been called measurement induced gratings. As with all thin gratings, the diffraction pattern is then given by the scaled Fourier transform of the transmission function.

Such gratings have been used for a series of near-field (atom lithography; Talbot effect) and far-field (diffraction; interferometry) experiments, and an example is shown in Figure 10 (Abfalterer et al., 1997). These experiments demonstrate that transmission of atoms through the nodes of the ‘absorptive’ light masks is a coherent process.

3. Thick gratings: Bragg diffraction

If the standing wave is thick, one must consider the full propagation of the matter wave inside the periodic potential. The physics is characterized by multi wave (beam) interference. For two limiting cases one can regain simple models. For weak potentials, Bragg scattering; and for strong potentials, coherent channeling.

When an atomic matter wave impinges on a thick but weak light crystal, diffraction occurs only at specific angles, the Bragg angles $\theta_B$ defined by the Bragg condition

$$N\lambda_{dB} = \lambda_{ph}\sin(\theta_B).$$

(Bragg scattering, as shown in Figures 9 (right column) transfers atoms with momentum $-p_x$ into a state with a single new momentum, $p_x = -p_x + nhG$. Momentum states in this case are defined in the frame of the standing wave in direct analogy to electron or neutron scattering from perfect crystals. Bragg scattering was first observed at MIT (Martin et al., 1988) and first observed with atoms in a Bose Einstein condensate at NIST (Kozuma et al., 1999a). Higher order Bragg pulses transfer multiples of $NhG$ of momentum, and this has been demonstrated up to 8th order with an atomic beam (Giltner et al., 1995b; Koolen et al., 2002). Reviews of Bragg scattering appear in (Bernet et al., 2000; Durr and Rempe, 1999; Gupta et al., 2001b; Oberthaler et al., 1999).

The Bragg scattering process can be understood in terms of absorption followed by stimulated emission (Figure 11). Viewing Bragg scattering as a two-photon transition from the initial ground state with momentum to a final ground state (with new momentum) illuminates the close connection with a Raman transition. (Gupta et al., 2001b). As a result of the coherently driven 2-photon transition, the probability amplitude oscillates between the two momentum states $|g, -nhG\rangle$ and $|g, +nhG\rangle$ in a manner analogous to the Rabi oscillation of atomic population between two resonantly coupled states. The probability for Bragg scattering of atoms from off-resonant standing waves of light is

$$P^{\text{Bragg}}_{N=1}(\tau) = \sin^2\left(\frac{\Omega_1^2\tau}{4\Delta}\right)$$

The oscillation between the two Bragg-coupled states ($N = 0$ and $N = 1$) is known as the Pendellösung and has been observed for atoms (Koolen et al., 2002; Martin et al., 1988; Oberthaler et al., 1999), neutrons (Shull, 1968), electrons, and x-rays. The nice feature with atoms is that the strength of the grating can be controlled by the intensity of the light.

The probability for $N$th order Bragg diffraction is

$$P^{\text{Bragg}}_N(\tau) = \sin^2\left(\frac{\Omega_1^2N\tau}{24N^{-3/2}|(N-1)!!|\Delta\omega_{rec}^{-1}}\right)$$

FIG. 10 (color online) Diffraction from a measurement-induced grating. (a) Schematic of two on-resonant standing waves of light. The first causes atom diffraction. The second can be translated to analyze near-field atomic flux. (b) Periodic structure in the transmitted atomic beam. (c) Far-field atom diffraction from a measurement induced grating. Figure from [Abfalterer et al., 1997].

FIG. 11 Energy states on the energy-momentum dispersion curve associated with Bragg diffraction. Versions of this classic figure are found in (Bordé, 1997; Giltner et al., 1995a; Gupta et al., 2001b; Kozuma et al., 1999a; Martin et al., 1988).
where we have assumed $\Delta \gg N^2\omega_{rec}$.

Bragg diffraction of atoms from off-resonant standing waves of light is often used for studying a BEC’s velocity distribution because the velocity selectivity of the Bragg condition (Blakie and Ballagh, 2000; Carusotto et al., 2000, Kozma et al., 1999a, Stamper-Kurn et al., 2001; Stenger et al., 1999). $\sigma_v$ is improved by increasing the duration of interaction with the grating, as can be deduced from the time-energy uncertainty principle, $\sigma_v = 2/(\tau G)$ (Blakie and Ballagh, 1999a, Kozma et al., 1999a, Stamper-Kurn et al., 2001; Stenger et al., 1999). For first-order Bragg diffraction, the minimum interaction time required to suppress all but one diffraction order is $\tau > h/E_G \approx 10$μsec; so to observe Bragg scattering with a 1000 m/s Na atom beam typically requires standing waves nearly 1-cm thick. However, $\tau$ can be substantially increased with cold atoms, and $\sigma_v$ less than 1/30 of the recoil velocity has been observed. For higher order Bragg diffraction the interaction time must be $\tau > \pi/(2(N-1)\omega_{rec})$.

Bragg scattering can be described as a multi beam interference as treated in the dynamical diffraction theory developed for neutron scattering. Inside the crystal one has two waves, the refracted incident ‘forward’ wave ($k_F$) and the diffracted ‘Bragg’ wave ($k_B$). These form a standing atomic wave field, and the diffraction condition ($k_B - k_F = G$) implies that the standing atomic wave has the same periodicity as the standing light wave. At any location inside the lattice, the exact location of atomic probability density depends on $k_F$, $k_B$ and the phase difference between these two waves.

For incidence exactly on the Bragg condition the nodal planes of the two wave fields are parallel to the lattice planes. The eigen-states of the atomic wave field in the light crystal are the two Bloch states, one exhibiting maximal ($\Psi_{max}$) the other minimal ($\Psi_{min}$) interaction.

$$\Psi_{max} = \frac{1}{2} \left[ e^{i\frac{Gx}{2}} + e^{-i\frac{Gx}{2}} \right] = \cos \left( \frac{G}{2} x \right),$$

$$\Psi_{min} = \frac{1}{2} \left[ e^{i\frac{Gx}{2}} - e^{-i\frac{Gx}{2}} \right] = i \sin \left( \frac{G}{2} x \right).$$

For $\Psi_{max}$ the antinodes of the atomic wave field coincide with the planes of maximal light intensity, for $\Psi_{min}$ the antinodes of atomic wave fields are at the nodes of the standing light wave. These states are very closely related to the coupled and non-coupled states in velocity selective coherent population trapping (VSCPT) (Aspect et al., 1988).

The total wave function is that superposition of $\Psi_{max}$ and $\Psi_{min}$ which satisfies the initial boundary condition. The incoming wave is projected onto the two Bloch states which propagate through the crystal accumulating a relative phase shift. At the exit, the final populations in the two beams is determined by interference and depends on this relative phase (following equation 11).

Bragg scattering can also be observed with absorptive, on-resonant light structures (Oberthaler et al., 1996a) and combinations of both on and off-resonant light fields (Keller et al., 1997). One remarkable phenomenon is that the total number of atoms transmitted through a weak on-resonant standing light wave increases if the incident angle fulfills the Bragg condition, as shown in Fig. 12. This observation is similar to what Bornmann (1941) discovered for x rays and called anomalous transmission.

The observed anomalous transmission effect can easily be understood in the framework of the two beam approximation outlined above. The rate of de-population of the atomic state is proportional to the light intensity seen by the atoms and therefore to the overlap between the atom wave field with the standing light field. The minimally coupled state $\Psi_{min}$ will propagate much further into the crystal than $\Psi_{max}$. At the exit phase the propagating wave field will be nearly pure $\Psi_{min}$. As a consequence one sees two output beams of (nearly) equal intensity.

Inserting an absorptive mask (Abfalterer et al., 1997) inside the light crystal allows one to observe the standing matter wave pattern inside the crystal (Oberthaler et al., 1999, 1996a) and verify the relative positions between the light field and $\Psi_{min}$.

Indeed, tailored complex potentials for atoms can be made out of combinations of bi-chromatic standing waves (Keller et al., 1997). For example, a superposition of standing waves (one on- and one off-resonance) with a phase shift $\Delta \varphi = \pm \pi/2$ results in a combined potential of $U(x) = U_0 e^{\pm iGx}$ which, in contrast to a standing
FIG. 13 Observation of long lasting Bloch oscillations in Cs where the interaction was switched off by tuning the scattering length close to zero by applying a magnetic field to 17.12 G (adapted from Gustavsson et al. (2007)).

wave, has only one momentum component. Such a potential can therefore only diffract in one direction. As this predicts, various diffraction orders can be suppressed by adjusting the phase difference between the absorptive and the refractive grating. The lack of symmetry is referred to as a violation of Friedel’s law. The asymmetry in the observed patterns can also be understood as an interference effect between diffraction at refractive and absorptive “subcrystals” spatially displaced with respect to each other (Keller et al., 1997).

4. Bloch Oscillations

Bloch oscillations were predicted by Bloch (1929) and Zener (1934) as an interference phenomenon in connection with the electronic transport in crystal lattices, but can in general also be observed in any system where accelerated matter waves move through a periodic potential. In a simple physical picture the Bloch oscillations can be viewed as repeated Bragg reflection from an accelerating grating. To observe high contrast Bloch oscillations it is desirable to prepare the initial sample well localized in momentum space, with a width of the momentum distribution close to the Brillouin-Zone. Therefore to each other (Keller et al., 1997).

5. Coherent channeling

When the lattice potential becomes higher then $E_G$ (Eq. 16) the atoms can be localized in the standing light wave. Atoms impinging on such a strong light crystal are then guided in the troughs through the crystal, and can interfere afterwards. Such guiding is called channeling. Channeling of electron beams (Joy et al., 1982) and ion beams (Feldman, 1982) in material crystals is related to channeling of atoms in optical lattices (Horne et al., 1999; Keller et al., 1999; Salomon et al., 1987). If the process is coherent one can observe a diffraction pattern reminiscent of the KD diffraction from a thin grating. See Figure 14.

D. The Talbot effect

We now turn from far-field atom diffraction to the near-field region, where a host of different interference effects occur. The well-known optical self imaging of a grating discovered by Talbot in 1832 is most important. It has many applications in image processing and synthesis, photo-lithography, optical testing and optical metrology (Patorski, 1989), and has proven to be a powerful tool for interference experiments with matter waves.

Plane waves incident on a periodic structure form a “self-image” of the structure at the Talbot distance $L_T = 2d^2/\lambda dB$ and again at integer multiples of the Talbot length. At half the Talbot distance a similar self-image is formed but displaced by half a period. At certain intermediate distances higher-order Talbot images are formed. These have a spatial frequency that is higher than the original grating by a ratio of small integers. The position and contrast of the sub-period images are determined by Fresnel diffraction as discussed in (Clauser and Li, 1994) and (Clauser and Reinisch, 1992). The replica (Fresnel) images and higher-
Talbot fringes were first observed with an atom beam and nanostructure gratings by Chapman et al. (1995) and higher-order Talbot fringes were observed by Nowak et al. (1997) (see Figure 15). The Talbot effect has also been studied with on-resonant light (Turlapov et al., 2003, 2005), and Talbot revivals have been observed in the time-evolution of atom clouds after pulses of off-resonant standing waves of light (Cahn et al., 1997; Deng et al., 1999). The Talbot time is $\tau_T = L_T/v = 2d^2/m/h$.

Rohwedder (2001) proposed detecting the Talbot effect for atoms trapped in wave guides, and Ruostekoski et al. (2001) discussed the formation of vortices in BEC as a result of the Talbot effect. Proposals to use the Talbot effect to study the state of electromagnetic fields in cavities are discussed in Rohwedder et al. (1999) and Rohwedder and Santos (2000). Using the Talbot effect with multiple phase gratings has been proposed as a way to make more efficient beam splitters for atom waves (Rohwedder, 1999, 2000), and this is related to the standing-wave light-pulse sequence described in Wu et al. (2005b).

The Lau effect is a closely related phenomenon in which incoherent light incident on two gratings causes fringes on a distant screen, provided that the gratings are separated by a half-integer multiple of the Talbot length. References for the Lau effect in light optics include Bartelt and Jahns, 1979, Jahns and Lohmann, 1973, Lau, 1948, Patorski, 1989. In essence, for the Lau effect the first grating serves as an array of mutually incoherent sources and Fresnel diffraction from the second grating makes the pattern on the screen. This forms the basis for Talbot-Lau interferometers which we discuss in Section III.

An especially promising application of Talbot (or Lau) imaging with atoms is atom lithography as demonstrated in McClelland et al. (2004) Timp et al. (1992) and many others. For reviews see Bell et al. (1999), Meschede and Metcalf, 2003. It is possible to write smaller gratings and features using the reduced period intermediate images discussed above. Similar Fourier images have been used for x-rays to write half-period gratings (Flanders et al., 1979) and to construct x-ray interferometers (David et al., 2002; Momose et al., 2003; Weitkamp et al., 2005). Grating self-images may also be used in quantum optics experiments to produce a periodic atom density in an optical resonator.

E. Time-dependent diffraction

Many new interference effects arise when the diffracting structures are modulated in time, a situation we have not considered previously (except for revivals at the Talbot time after pulsed gratings). These new effects arise with matter waves because the vacuum is dispersive for atoms - particles with shorter wavelength (higher energy) propagate faster than those with longer wavelengths. In contrast, for light in vacuum all wavelengths propagate at a constant speed, $c$.

Two matter wave components interfering at $(x,t)$ may have propagated from the same $x'$ but originated from there at different times $t'$ (if they have different velocity)! Time-dependent boundary conditions can cause matter wave diffraction phenomena in time that are similar to spatial diffraction phenomena arising from spatially dependent boundary conditions. This was first discussed in a seminal paper by Moshinsky (1952), who argued that after opening a shutter one should observe a rise in the matter wave intensity with Fresnel fringes in time, similar to the diffraction of an edge in space. He called this very general phenomena *diffraction in time*. Similarly, the opening and closing of a shutter results in a single slit diffraction in time; two successive openings makes a double slit; and a periodic change in the opening of the slit produces a diffraction pattern in time. With diffraction in time, new frequency (energy) components are created (as in an acoustic-optic modulator), resulting in com-
components with new momenta. In analogy to diffraction in space one finds that diffraction in time has both near-field and far-field regimes. One also observes Raman Nath and Bragg regimes, depending on the duration of the interaction and the amount of energy (frequency) transfer.

1. Vibrating mirrors

Even though diffraction in time of matter waves was predicted in 1952 the first experimental demonstrations had to wait until the late 1980’s. The experimental difficulty in seeing diffraction in time is that the time scale for switching has to be faster than the inverse frequency (energy) width of the incident matter wave. This condition is the time equivalent to coherent illumination of adjacent slits in spatial diffraction. The first (explicit) experiments demonstrating diffraction in time used ultra-cold neutrons reflecting from vibrating mirrors (Felber et al., 1990; Hamilton et al., 1987; Hils et al., 1998). The side-bands of the momentum components were observed.

A study of diffraction and interference in time was performed by the group of J. Dalibard at the ENS in Paris using ultracold atoms reflecting from a switchable atom mirror (Arndt et al., 1996; Steane et al., 1995; Szriftgiser et al., 1996). Ultra cold Cs atoms ($T \sim 3.6 \mu K$) released from an optical molasses fell 3 mm, and were reflected from an evanescent light mirror. By pulsing the evanescent light field one can switch the mirror on and off, creating time-dependent apertures that are diffractive structures in the spirit of Moshinsky (1952).

Even for these ultra cold Cs atoms the energy spread (7 MHz) is too large for the time-diffraction experiment, so a very narrow energy window was selected by two (0.4 ms) temporal slits. The first slit was positioned 26 ms after the atoms were released. Switching on the mirror a second time, 52 ms later, selected a very narrow energy slice in the same way as a two-slit collimation selects a very narrow transverse velocity slice. The arrival time of the atoms at the final “screen” was measured by fluorescence induced by a light sheet.

If the second slit is very narrow (<10 μs) one observes single slit diffraction in time; if the mirror is pulsed on twice within the coherence time of the atomic ensemble one observes double slit interference in time; and many pulses lead to a time-dependent flux analogous to a grating diffraction pattern as shown in Fig. 16. From the measurement of the arrival times the energy distribution can be reconstructed. Similar diffraction in time is observed when a BEC is reflected from a vibrating mirror (Colombe et al., 2005).

Because the interaction time between the atoms and the mirror potential (<1 μs) was always much smaller then the modulation time scale (>10 μs), these experiments are in the ‘thin grating’ (Raman-Nath) regime for diffraction in time.

2. Oscillating potentials

When matter waves traverse a time-modulated potential one can observe coherent exchange of energy between the oscillating field and the matter wave. This was demonstrated in a neutron interference experiment (Summhammer et al., 1995) where a oscillating magnetic potential was applied to one path of a neutron interferometer. Coherent exchange of up to 5 quanta $\hbar \omega$ was observed in the interference patterns, even though the transit time through the oscillating potential was much shorter than the oscillation period.
3. Modulated light crystals

The time equivalent of spatial Bragg scattering can be reached if the interaction time between the atoms and the potential is long enough to accommodate many cycles of modulation. When a light crystal is modulated much faster than the transit time, momentum is transferred in reciprocal lattice vector units and energy in sidebands at the modulation frequency. This leads to Bragg diffraction at two new incident angles.

Bragg scattering in time can be understood as a transition between two energy and momentum states. The intensity modulation frequency of the standing light wave compensates the detuning of the Bragg angle. The frequency of the de Broglie wave diffracted at the new Bragg angles is shifted by \( \pm \hbar \omega_{\text{mod}} \) (Bernet et al., 2000, 1996). Thus, an amplitude modulated light crystal realizes a coherent frequency shifter for a continuous atomic beam. It acts on matter waves just as an acousto-optic modulator acts on photons, shifting the frequency (kinetic energy) and requiring an accompanying momentum (direction) change.

In a complementary point of view, the new Bragg angles can be understood from looking at the light crystal itself. The modulation creates side bands \( \pm \omega_{\text{mod}} \) on the laser light, creating moving crystals which come from the interference between the carrier and the side bands. Bragg diffraction from the moving crystals occurs where the Bragg condition is fulfilled in the frame co-moving with the crystal, resulting in diffraction of the incident beam to new incident angles.

The coherent frequency shift of the Bragg diffracted atoms can be measured by interferometric superposition with the transmitted beam. Directly behind the light crystal the two outgoing beams form an atomic interference pattern which can be probed by a thin absorptive light grating (Abfalterer et al., 1997). Since the energy of the diffracted atoms is shifted by \( \hbar \omega_{\text{mod}} \), the atomic interference pattern continuously moves; this results in a temporally oscillating atomic transmission through the absorption grating (Figure 17).

Starting from this basic principle of frequency shifting by diffraction from a time dependent light crystal many other time dependent interference phenomena were studied for matter waves (Bernet et al., 2000, 1999). Light crystals are an ideal tool for these experiments since one can easily tailor potentials by controlling the laser intensity and frequency and create more complex structures by superimposing different independently controlled crystals.

For example using light from two different lasers one can create two coinciding light crystals generated in front of the retro-reflection mirror. Varying detuning and phase between the two modulated crystals creates situations where diffraction is completely suppressed, or where either the frequency unshifted or the frequency shifted order is suppressed (Figure 18). The combination of real and imaginary potentials can produce a driving potential of the form \( U(t) \sim e^{\pm i\omega_{\text{mod}} t} \) which contains only positive (negative) frequency components respectively. Such a modulation can only drive transitions up in energy (or down in energy).

F. Summary of diffractive Atom Optics

To summarize, in Section II we have reviewed atom diffraction from nanostructures and standing waves of light. Nanostructures absorb atoms, can be arbitrarily patterned (e.g., holograms) and affect all atomic and molecular species. Standing waves of light can make a phase (or in some cases amplitude) grating for a particular species of atom in a specific state. Light gratings

![Figure 18](color online) Diffraction in time from two superimposed light crystals with a controlled relative phase between the modulations. (Left) two off-resonant light crystals are superimposed. The relative phase of the temporal modulation controls the intensity of the frequency shifted and unshifted Bragg beams. (Right) an on-resonant and an off-resonant crystal are superimposed. The relative phase controls the time-dependent potential. For phase \( \pi/3 \) (\( 3\pi/2 \)) only frequency up (down) shifted components appear. Figure adapted from (Bernet et al., 2000).
FIG. 19 Summary of diffraction efficiency for atoms $|\psi_{in}/\psi_{out}|$ from different types of gratings. (a) nanostructures with $C_3=0$, (b) standing waves of on-resonant light, (c) Kapitza-Dirac (thin phase mask) diffraction, and (d) Bragg (thick crystal) scattering. The x-axis is proportional to the intensity of the light (or the open fraction in the case of nanostructures).

FIG. 20 Momentum diagrams for cases: (A) A thick grating, (B) A thin grating, (C) A thick pulsed grating (D) A thick harmonically modulated grating. (Bernet et al. 2000)

can be thick or thin, strong or weak, and can be modulated in time. Both types of gratings exhibit interesting and useful interference phenomena in both the near- and far-field regimes.

Figure 19 summarizes the diffraction efficiency of four different kinds of time-independent gratings: two absorbing gratings (nanostructures and standing waves of on-resonant light) and two non-dissipative gratings (in the Kapitza Dirac and Bragg regimes). These efficiencies are given by equations 3, 7, 11, and the Fourier transform of equation 9.

Figure 20 summarizes thick and thin gratings in space and also in time with Ewald constructions to denote energy and momentum of the diffracted and incident atom waves. The diffraction from (modulated) standing waves of light can also be summarized with the Bloch band spectroscopy picture (Bernet et al. 2000; Champenois et al. 2001a).

G. Other coherent beam splitters

Whereas diffraction occurs without changing the atom’s internal state, another important class of beam splitters uses laser or RF transitions that do change atoms’ internal state while transferring momentum. Therefore, as they coherently split atomic wavefunctions into two (or more) pieces they cause entanglement between the atomic motion and the internal atomic states. Important examples that are used in atom interferometry include absorption from a traveling wave of light (Borde 1989, 1997), stimulated Raman transitions (Kasevich and Chu 1992) and longitudinal RF spectroscopy (Gupta et al. 2001a). The longitudinal Stern-Gerlach effect (Miniatura et al. 1991) also causes entanglement between motion and internal degrees of freedom. We discuss these in Section III on atom interferometry.

Potentials that change slowly from single-well to double-well represent an entirely new type of beam splitter that is more applicable to trapped atoms than propagating light. We discuss this tool for coherent splitting of atomic wavefunctions in the next chapter on atom interferometry.

Reflecting surfaces have been used for atom diffraction, atom holography, and Young’s experiment with atoms, e.g. in Christ et al. 1994; Cognet et al. 1998; Deutschmann et al. 1993; Gunther et al. 2001, 2003; Landragin et al. 1997; Shimizu and Fujita, 2002b), and Esteve et al. 2004; Kohno et al. 2003 respectively. The challenges of using reflection-type atom optical elements include low reflection probability and strict requirements for flatness in order to maintain atom wave coherence. Still, the toolkit for coherent atom optics is expanded by quantum reflection, in which atom waves reflect from an attractive potential, and also classical reflection, where repulsive potentials can be formed with evanescent waves of blue-detuned light or engineered magnetic domains. Various mirrors for atoms are discussed in Berkhout et al. 1983; Fortagh and Zimmermann 2003; Henkel et al. 1999, 1997; Kaiser et al. 1996; Marani et al. 2000; Savalli et al. 2002; Shimizu, 2001; Shimizu and Fujita, 2002a).

Other beam splitters for atoms that have not been used for atom interferometer experiments will not be discussed in this review.
III. ATOM INTERFEROMETERS

A. Introduction

The essential features of interferometers generally and atom interferometers in particular are listed in the succession of five steps: (1) prepare the initial state, (2) split the wavefunctions coherently into two or more states, (3) apply interactions that affect the two states differentially, generally due to their different spatial location, (4) recombine these components coherently, and (5) measure the phase shift of the detected fringes.

The crucial step of coherent splitting (2) has been accomplished for atom interferometers using diffraction gratings, photon absorption, Raman transitions, longitudinal Stern-Gerlach magnets and even physical separation of confined atoms into multiple potential wells. In the following we discuss these in the framework of the interferometers in which they have been used, and review the basic features of several atom interferometer designs. A detailed survey of scientific research with atom interferometers is given in Sections IV, V, and VI.

1. General design considerations

When designing and building interferometers for atoms and molecules, one must consider key differences between matter waves and light. The dispersion relations, the coherence properties, and our tools to control the two different kinds of waves are among the important differences.

One striking difference is the fact that matter waves have short deBroglie wavelengths (~10 pm for thermal atoms up to ~1 μm for ultracold atoms), and also have a very short coherence lengths (~100 pm for thermal atomic beams, and seldom larger than 10 μm even for atom lasers or BEC). This requires that the period and the position of the interference fringes must be independent of the deBroglie wavelength of the incident atoms. In optical parlance this is a property of white light interferometers.

A second concern with atoms is that they interact strongly with each other. Therefore matter waves are often non-linear, especially in the cases where the atoms have significant density as in a BEC or atom laser.

A third distinguishing feature is that atoms can be trapped. This leads to a new class of interferometers for confined particles, which we discuss at the end of this section.

2. White light interferometry

The challenge of building a white light interferometer for matter waves is most frequently met by the 3-grating Mach Zehnder (MZ) layout. This design was used for the first electron interferometer by [Martoni (1952)], for the first neutron interferometer by [Rauch et al. (1974)], and for the first atom interferometer that spatially separated the atoms by [Keith et al. (1991)]. In the MZ interferometer the role of splitter and recombiner is taken up by diffraction gratings. They also serve as the mirrors that redirect the separating atom waves back together. (In fact simple mirrors won’t serve this purpose if the initial state is not extremely well collimated. This is because most interferometer designs that employ simple mirrors will make the fringe phase strongly correlated with input beam position and direction.) In their seminal work [Simpson (1954)], noted that with grating interferometers

“the fringe spacing is independent of wavelength. This ‘achromatic’ behavior ... appears to be characteristic of instruments using diffraction for beam splitting.”

The explanation is that diffraction separates the split states by the lattice momentum, then reverses this momentum difference prior to recombination. Faster atoms will diffract to smaller angles resulting in less transverse separation downstream, but will produce the same size fringes upon recombining with their smaller angle due to their shorter deBroglie wavelength. For three evenly spaced gratings, the fringe phase is independent of incident wavelength, surprisingly also for asymmetric designs (such as that in Fig 21b) where the intensity maximum for different wavelengths occurs at different distances off the symmetry axis.

Many diffraction-based interferometers produce fringes when illuminated with a source whose transverse coherence length is much less than its (large) physical width, or even the grating period. Under such conditions, the different diffraction orders will not be separated, so diffraction can not be resolved and it will not be possible to exploit the physical separation of the orders to apply an interaction to only one arm of the interferometer. Nevertheless, high contrast fringes will still be formed.

The three grating interferometer produces a “position echo” as discussed by [Chebotayev et al. (1985)]. Starting at one grating opening, one arm evolves laterally with $hG$ more momentum for some time, the momenta are reversed, and the other arm evolves with the same momentum excess for the same time, coming back together with the first arm at the third grating. If the gratings are registered, an atom’s trapezoidal pattern starts at a slot on the first grating, is centered on either a middle grating slot or groove, and recombines in a slot at the third grating. Not surprisingly, spin-echo and time-domain echo techniques (discussed below) also offer possibilities for building an interferometer that works even with a distribution of incident transverse atomic momenta.

---

9 The popular design in figure 21 is asymmetric because the interferometer paths are formed by diffraction orders 0 and 1 for one arm, and orders 1 and -1 for the other.
3. Types and categories

A large variety of atom and molecule interferometers have been built since 1991. The list includes Mach Zehnder, Talbot-Lau, optical Ramsey-Bordé, and stimulated Raman transition interferometers. There are also longitudinal Stern-Gerlach, and longitudinal RF interferometers. Some of these designs render the interference fringes in position space. Some make fringes in momentum space. Still other designs make the interference fringes observable in internal atomic state space. We catalogue these interferometers briefly here according to their features before examining each in detail throughout this section.

(1) Internal state changing interferometers are one broad category. Some beam splitters change atom’s internal state, analogous to a polarizing beam splitter in light optics. For example, stimulated Raman transitions entangle internal and external states, so atoms in these interferometers are in a coherent superposition of different momentum-spin states.

(2) Time-domain vs. space-domain is another broad classification. In a time-domain interferometer, the beam splitters are pulsed so all atoms interact with the gratings and the interferometer for the same amount of time.

(3) Near-field (Talbot-Lau) and far-field (Mach Zehnder) classification applies for diffractive atom optics. Near-field interferometers can function even with poorly collimated beams, but the gratings in a Talbot-Lau interferometer (TLI) must be separated by precise multiples of the Talbot length or else the contrast degrades.

(4) Separated path interferometers are a special category of atom interferometer in which the paths are sufficiently physically separated that the atom wave in one arm can be isolated and interactions can be applied to it alone.

(5) Freely propagating cold atoms can have long times of flight (∼1/2 s) as compared to thermal atom beams (∼1 ms). Confinement in a trap during the interferometer operation may soon provide even longer interaction times.

(6) Atom traps and waveguides offer the possibility of making confined atom interferometers in which the atom wavefunction is split in coordinate space rather than momentum space. Obviously, the ability to interfere atoms that are spatially confined in all three dimensions throughout the entire interferometer is unprecedented with light interferometers. Additional topologies such as multiple wells and ring-traps and longitudinal waveguides have also been demonstrated.

Finally, we distinguish single atom interferometers from those in which (non-linear) collective effects are significant. Even atoms launched from a magneto-optical trap are generally not dense enough to cause significant non-linear effects. Interferometry with Bose-Einstein condensates (or atom lasers) on the other hand can show non-linear atom optics phenomena that range in significance from phase noise to number squeezing and Josephson oscillations.

These distinctions – (1) internal state changing vs. state preserving, (2) space-domain vs. time-domain, (3) near-field vs. far-field, (4) separated path or not, (5) trapped or freely propagating, (6) dilute vs. dense – all affect the performance of atom interferometers for different applications.

Since the first atom interferometers were built for Na, Cs, Mg, and He* in 1991, others have been made for Ar*, Ca, H* He, K, Li, Ne*, Rb atoms, and He2, Li2, Na2, I2, C60, C70, C60F48, and C44H30N4 molecules. Interferometers starting with trapped atoms have been made for Ca, Cs, He*, Mg, Na, and Rb and interferometers using Bose-Einstein condensates have been demonstrated with Na and Rb.

B. Three-Grating Interferometers

The simplest white light interferometer is a Mach Zehnder interferometer built from 3 diffraction gratings. The first grating acting as a beam splitter, the second as a redirector, reversing the (transverse) momentum of the beam, and the 3rd as a recombiner or analyzer of the interference.

1. Mechanical gratings

The first 3-grating Mach-Zehnder interferometer for atoms was built by Keith et al. [1991] using three 0.4-μm period nano fabricated diffraction gratings. Starting from a supersonic Na source with a brightness of $B \approx 10^{19} \text{s}^{-1}\text{cm}^{-2}\text{sr}^{-1}$ the average count rate $<I>$, in the interference pattern was 300 atoms per second. Since then, gratings of 100 nm period have been used to generate fringes with up to 300,000 atoms per sec.

We use this design (shown in Fig. 21) to illustrate how a standing wave interference pattern is formed by the two running waves. Starting with a common beam that is incident on two gratings (G1 and G2), one wave is formed by 0th and 1st order diffraction, while the other is formed by -1st and +1st order diffraction. The difference in momentum is thus one unit of $\hbar G \hat{x}$. So we describe the incident running waves by the functions $\psi_1$ and $\psi_2 e^{iGx_\perp \Delta \phi_{int}}$. These running waves differ in momentum explicitly by $\hbar G \hat{x}$ due to diffraction. The waves also differ in phase by $\Delta \phi_{int}$ due to different interactions along the two paths.

In the zone where these coherent running waves overlap, the atom beam intensity is

$$I(x) = |\psi_1 + \psi_2 e^{i\Delta \phi_{int} e^{iGx}}|^2$$

$$I(x) = <I> + <I>C \cos(\Delta \phi_{int} + Gx). \quad (14)$$

This interference pattern is a standing wave in space but is unchanged in time. The fringes have a period
FIG. 21 (color online) Three grating Mach-Zehnder atom interferometers. (a) Atom Interferometer setup used in [Keith et al. (1991)]. (b) Interference fringe data and best fit with \( \langle I \rangle = 157,000 \text{ counts per second and } C = 0.42 \). A total of 5 seconds of data are shown and the uncertainty in phase calculated by equation 19 is \( \sigma_\phi = 2.7 \times 10^{-3} \text{ radians.} \) (c) Average intensity \( \langle I \rangle \) and contrast \( C \) as a function of detector position [under different conditions than (b)].

of \( d = G/(2\pi) \) (just like the gratings), and a spatial offset in \( \hat{x} \) (i.e. a phase) that depends on the location of the two gratings \( G_1 \) and \( G_2 \) as well as the interaction phase \( \Delta \phi_{\text{int}} \). Equation 14 is a general result, and the fringes can be detected in many different ways.

The intensity pattern has a mean intensity and contrast

\[
\langle I \rangle = |\psi_1|^2 + |\psi_2|^2
\]

\[
C = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} = \frac{\psi_1^* \psi_2 + \psi_2^* \psi_1}{|\psi_1|^2 + |\psi_2|^2}.
\]

If one of the interfering beams is much stronger then the other, for example \( |\psi_1|^2 \gg |\psi_2|^2 \), then the contrast of the interference pattern scales like

\[
C \sim \frac{2|\psi_2|}{|\psi_1|} = 2\sqrt{\frac{I_2}{I_1}}.
\]

Consequently one can observe 20\% (2\%) contrast for an intensity ratio of 100:1 (10^4:1) in the interfering beams.

If the waves are not perfectly coherent, then the incoherent part adds to the overall intensity, and the contrast is diminished. If more than two components overlap, the situation is somewhat more complicated.

The spatial oscillations in intensity can be detected, for example, by measuring the atom flux transmitted through a third (absorbing) grating (G3). In this case G3 acts as a mask to transmit (or block) the spatially structured wave intensity. By translating G3 along \( x \) one obtains a moiré filtered interference pattern which is also sinusoidal and has a mean intensity and contrast

\[
\langle I \rangle = \frac{w_3}{d} \langle \hat{I} \rangle,
\]

\[
C = \frac{\sin(Gw_3/2)}{(Gw_3/2)} \tilde{C}.
\]

where \( \hat{I} \) and \( \tilde{C} \) refer to the intensity and contrast just prior to the mask. The phase of the filtered interference pattern is given by

\[
\phi = G(x_1 - 2x_2 + x_3) + \Delta \phi_{\text{int}}
\]

where \( x_1, x_2, \) and \( x_3 \) are the relative positions of gratings 1, 2 and 3 with respect to an inertial frame of reference [Schmiedmayer et al. (1997)].

The phase \( \phi \) will have a statistical variance, \( \sigma_\phi^2 \), in the simplest case due to shot noise (counting statistics) [Lenef et al., 1997; Schmiedmayer et al., 1997] given by

\[
(\sigma_\phi)^2 \equiv \langle (\phi - \langle \phi \rangle)^2 \rangle = \frac{1}{C^2 N}
\]

where \( N \) is the total number of atoms counted. For discussion of how phase fluctuations depend on atom-atom interactions within the interferometer see [Pezze and Smerzi, 2006; Scully and Dowling, 1993; Search and Meystre, 2003]. To minimize the uncertainty in measured phase we therefore seek to maximize \( C^2 N \times C^2 \langle I \rangle \) by choosing the open fractions \( w_i/d \) for the three gratings, where \( w_i \) is the window size for the \( i^{th} \) grating and \( d \) is the grating period. The open fractions that maximize \( C^2 \langle I \rangle \) are \( (w_1/d, w_2/d, w_3/d) = (0.56, 0.50, 0.37) \). With these open fractions, the theoretical value of \( C = \)
FIG. 22 Atom interferometers based on three standing waves of light. (a) Atom beam and three Kapitza-Dirac gratings. (b) Atom interference patterns for both output ports demonstrate complementary intensity variations. This is a consequence of atom number conservation. Figures a and b reproduced from (Rasel et al., 1995). (c) Interferometer based on three Bragg gratings. Dashed line shows the path of auxiliary optical interferometer used for stabilization. (d) Intensity fluctuations in beam A vs. position of the Bragg gratings. For second order Bragg diffraction, fringes of half the period are formed. Figures c and d reproduced from (Giltner et al., 1995a). (e) Schematic of the $\pi/2 - \pi - \pi/2$ Bragg interferometer for atoms in a BEC falling from a trap. (f) Absorption images and density profiles demonstrating different outputs of the interferometer. Figures e and f reproduced from (Tori et al., 2000).

0.67 and $\langle I\rangle/I_{\text{inc}} = 0.015$. If vdW interactions between atoms and gratings are included, then open fractions of the first two gratings should be increased for best performance (Cronin et al., 2005).

There are in fact several different interferometers formed by the gratings. For example, the 1st and 2nd orders can recombine in a skew diamond to produce another interferometer with the white fringe property. Additional mirror images of these interferometers make contrast peaks on either side of the original beam axis, as shown in Fig. 21. All those interferometers can have fringes with the same phase, and consequently one can therefore build interferometers with wide uncollimated beams which have high count rate, but lower contrast. (The contrast is reduced because additional beam components such as the zeroth order transmission through each grating will also be detected.)

Mechanical gratings with much larger periods have been used to make interferometers in the extreme limit of non-separated beams. We discuss these in the Talbot-Lau interferometer section ahead.

For well-collimated incoming beams, the interfering paths can be separated at the 2nd grating. For example in the interferometer built at MIT the beams at the second (middle) grating have widths of 30 $\mu$m and can be separated by 100 $\mu$m (using 100-nm period gratings and 1000 m/s sodium atoms ($\lambda_{dB} = 16$ pm). Details of this apparatus, including the auxiliary laser interferometer used for alignment and the requirements for vibration isolation, are given in (Schmiedmayer et al., 1997).

This geometry was used in the first atom interferometer with physical isolation of the spatially separated paths. Isolation was provided by inserting a 10 cm long metal foil between the two paths, so that the electric or magnetic field or gas pressure could be varied on the left or right arm separately. This resulted in measurements of atomic polarizability (Ekstrom et al., 1995), the index of refraction due to dilute gasses (Roberts et al., 2002; Schmiedmayer et al., 1995), contrast interferometry using magnetic rephasing (Schmiedmayer et al., 1994), and diffraction phases induced by van der Waals interactions (Perreault and Cronin, 2005, 2006). In experiments not explicitly needing separated beams, this apparatus has been used to measure phase shifts due to rotations (Lenef et al., 1997) and to study decoherence due to scattering photons and background gas (Chapman et al., 1995b; Kokorowski et al., 2001; Uys et al., 2003). This apparatus was also used to perform the first separated beam experiments with molecules (Na$_2$) (Chapman et al., 1995a).

An interferometer with similar nanogratings was developed at the MPI in Göttingen and used to measure the polarizability of He and He$_2$ (Toennies, 2001).

2. Interferometers with light gratings

One can also build MZ interferometers with gratings made from light (Fig. 22). These light gratings are generally near-resonant standing waves that make species-
specific phase gratings. Because they transmit all the atoms, light gratings are more efficient than material gratings.

The third grating in a light interferometer can function in many ways to enable detection of the fringes. It can recombine atom waves so their relative phase dictates the probability to find atoms in one output port (beam) or another. Alternatively, fringes in position space can be detected with fluorescence from a resonant standing wave. Another detection scheme uses backward Bragg scattering of laser light from the density fringes. This can be used in multi-path interferometers where phase shifts affect the contrast of the fringes. (We discuss such *contrast interferometry* in the next section.) Detecting the direction of exiting beams requires that the incident beams must be collimated well enough to resolve diffraction, and may well ensure that the beams are spatially separated in the interferometer.

Rasel *et al.* (1995) used light gratings in the Kapitza-Dirac regime with a 5 μm-wide collimated beam. Many different interferometers were formed, due to symmetric KD diffraction into the many orders. Two slits after the interferometer served to select both the specific interferometer, and the momentum of the outgoing beam (ports 1 and 2 in Figure 22). Fringes with 10% contrast show complementary intensity variations, as expected from particle number conservation in a MZ interferometer with phase gratings.

It is even more efficient to use Bragg diffraction because no atoms are lost to ‘unwanted’ orders. Giltner *et al.* (1995a) used Bragg diffraction and a Ne* beam and obtained contrast of C=63%. Higher order Bragg diffraction was also used to demonstrate smaller period interference fringes shown in Figure 22. A Bragg scattering interferometer for Li atoms with a contrast of 0.84 and a count rate of 17 kc/s was recently used to measure the polarizability of Li atoms (Delhalle *et al.*, 2002; Miffre *et al.*, 2006).

3. Time domain and contrast interferometers

Light gratings can easily be turned on and off, allowing one to control the interaction times of atoms with the three gratings. Thus, independent of initial longitudinal momentum, all atoms will see an equal interaction and will subsequently separate equally (since they have the same momentum transferred by the grating). Such interferometers are especially valuable in precision experiments since time is so easily measured accurately. This consideration also applies to optical Raman pulses, which will be discussed in a later section. Torii *et al.* (2000) made a 3-grating interferometer for ultra cold atoms by pulsing gratings thrice in time. These pulsed gratings are turned on for a duration long enough to produce Bragg diffracted momentum states. This duration does not affect the precise timing between interactions, but is long enough that diffusion in time is unimportant. Their fringes were read out in momentum space by measuring the atom cloud position in absorption images taken shortly after the third grating pulse. Atoms released from a BEC were used insuring that the momentum spread of the cloud was smaller than a photon recoil momentum $\hbar k_{ph}$ thus allowing resolution of the output states. More examples of time-domain interferometers based on three diffraction gratings include Gupta *et al.* 2002 [Wang *et al.*, 2003].

Gupta *et al.* (2002) used one Kapitza-Dirac pulse followed by a second order Bragg pulse to make an interferometer with *three* paths as shown in Fig. 23. One can understand this arrangement as two separate two-path interferometers whose density fringes overlap. Because the phase of each two-path interferometer changes in time in opposite directions, the two density gratings move in and out of register as time (and phase) increase, hence the contrast oscillates rapidly with time. This interferometer has been used to measure $\hbar/m_{Na}$ to a precision of 7 ppm. This demonstrates the utility of *contrast interferometry* in which measurements of contrast, not phase, are used. Contrast interferometry was pioneered in Schmiedmayer *et al.* (1994) where interference patterns from atoms with different magnetic sublevels moved in and out of register.

This contrast interferometer design offers several advantages compared to phase measurements made with a regular interferometer. First, the fringe phase can be accurately determined in a single “shot”, eliminating effects of shot to shot atom intensity fluctuations. Sec-
ond, most experimental sources of phase noise affect each two-path interferometer in the same way they move the fringes but don’t change the contrast. For example, measurements with the interferometer in [Gupta et al., 2002] were nearly insensitive to vibrations, rotation, accelerations, and magnetic field gradients. A relative phase shift between the two interferometers can be caused however, by diffraction phases [Buchner et al., 2003]. If the Kapitza-Dirac pulse causes a phase shift between the 0th and 1st diffraction order, then the contrast does not peak at exactly 2\(T\), where \(T\) is the time between diffraction grating pulses. Hence, fluctuations in the intensity of light used for the KD pulse can then lead to fluctuations in the time at which the total contrast peak is visible.

Gupta et al. [2002] detected the contrast of the fringes in space by measuring the intensity of reflected (Bragg diffracted) light probing the fringes in space. The intensity of reflected light can be continuously monitored as the two sets of interference fringes pass through each other in time. This causes oscillations in the intensity of reflected light as shown in Fig. 23.

4. Talbot-Lau (near field) interferometer

We now turn to near-field interferometers. As discussed in Section II D, a high degree of spatial coherence is needed to create recurring self-images of a grating due to near-field diffraction (the Talbot effect). But completely incoherent light can still produce fringes downstream of a grating pair (the Lau effect). When two gratings with equal period (\(d\)) are separated by a distance \(L_1\), the Lau fringe contrast is maximum at a distance beyond

\[
L_2 = \frac{L_1L_T \frac{n}{m}}{L_1 - L_T \frac{m}{n}}
\]

where \(L_T = 2d^2/\lambda_{dB}\) is the Talbot length and the integers \(n\) and \(m\) refer to the \(n\)th revival of the \(m\)th higher-order Fourier image. The fringe period is then

\[
d' = dL_2 + 1\frac{L_1}{mL_1}.
\]

If a 3rd grating is used as a mask to filter these fringes, then a single large-area integrating detector can be used to monitor the fringes. This 3-grating arrangement is a Talbot-Lau Interferometer (TLI). A typical TLI uses three identical gratings and \(L_1 = L_2 = L_T/2\) with \(n = 1\) and \(m = 2\).

The first grating can be regarded as an array of small but mutually incoherent sources of diverging waves. Shortly after the second grating near-field diffraction causes any shadow effects to become blurred out. At a distance \(L_2\) from the second grating, spatial structure in the intensity starts to reemerge. The intensity oscillations observed with a TLI are not a ray-optics phenomenon; they are due to wave interference for the multiple paths shown in Figure 24. Evidence for this is that \(L_2\) depends on \(\lambda_{dB}\) (and hence a fairly monochromatic velocity distribution is needed for optimum contrast).

The second grating can be a phase grating, but the first and third gratings must be amplitude gratings. The theory of this interferometer is discussed in [Batelaan et al., 1997; Brezger et al., 2002; Clauser and Li, 1994b; 1997; Clauser and Reinisch, 1992].

A famous feature of a TLI is that the contrast is unaffected by the beam width. A large transverse momentum spread in the beam is also tolerated. Hence much larger count rates can be obtained with a TLI.

Furthermore, in a TLI the relationship \(L_1 = L_2 = L_T/2\) means that the maximum grating period is \(d < \sqrt{L_1\lambda_{dB}} \sim M^{-1/4}\) where \(M\) represents mass for a thermal beam. In comparison, for a MZI with resolved paths the requirement is \(d < \lambda_{dB}L/(\Delta x) \sim M^{-1/2}\) where \(\Delta x\) is the width of the beam and \(L\) is the spacing between gratings. Thus the TLI design is preferable for massive particles.

A Talbot-Lau interferometer was first built for atoms by Clauser and Li [1994b] using a slow beam of potassium atoms. The experiment used gratings with a period of \(d = 100\ \mu m\), and a count rate of \(<I> = 4 \times 10^7\) atoms/sec was achieved. The source brightness was 2500 times weaker than in the 3 grating Mach Zehnder interferometer of [Keith et al. (1991)], but the signal was about 3000 times stronger. Because of its attractive transmission features, and the favorable scaling properties with \(\lambda_{dB}\), the TLI has been used to observe interference fringes with complex molecules such as \(C_{60}, C_{70}, C_{60}F_{18}\), and \(C_{60}H_{30}N_{4}\) [Brezger et al., 2002; Hackermuller et al., 2003]. Of course, the TLI does not separate the orders - indeed components of the wave function are only
displaced by one grating period at the Talbot length. Even though the TLI interferometer cannot offer separated paths, it is still sensitive to inertial forces, decoherence, and field gradients (Clauser and Li, 1994; Hackermüller et al., 2004; Hornberger et al., 2003). Cahn et al. (1997) used the phrase “time domain interferometry” to describe a Talbot-Lau interferometer that consists of two (Kapitza-Dirac) gratings pulsed in time, and renders interference fringes in position space. A third pulse of light, a traveling wave, was Bragg reflected by the atomic density pattern and thus served as the detection scheme for fringes. The atom fringe contrast even with an ‘uncollimated cloud’ of atoms. Talbot Lau interferometry with (pulsed) light gratings has also been explored by (Cohen et al., 2000; Deng et al., 1999; Turlapov et al., 2003, 2005; Weed et al., 2006; Wu et al., 2005a).

C. Interferometers with path-entangled states

In some interferometers, the internal state of the atoms depends on the path through the interferometer. Hence the state of the atom is entangled with the path. This usually occurs when the RF or laser photons that cause a transition between internal states also impart momentum, thus creating such entanglement.

Such entanglement has implications both for what the interferometer can measure, and for how the interference can be detected. Detection is the more obvious; if recombination results in oscillations between two internal states, then state-sensitive detection can reveal the fringes without need for the atom paths to be spatially resolved. The influence of having different internal states in the middle of the interferometer is more subtle. Many atomic properties such as polarizability and scattering lengths depend on the state; hence such interferometers naturally measure the difference of that property between the states which is generally less informative than the property in one state.

1. Optical Ramsey-Bordé interferometers

When a traveling wave of resonant light intersects a two-level atom, the atom is put into a superposition of ground and excited states in which the photon absorbed in promoting the atom to the excited state has added its momentum to that of the ground state, resulting in a differential momentum of $\hbar k_{ph}$ between ground and excited state (Fig. 25a).

\[
|a, p\rangle \rightarrow \sin(\theta)|a, p\rangle + \cos(\theta)|b, p + \hbar k_{ph}\rangle
\]  

(22)

Bordé’s seminal 1989 paper that Optical Ramsey spectroscopy by four traveling laser fields is an atom interferometer when taking the momentum transfer in the excitation process into account (Bordé, 1989). Such an experiment is now often called a Ramsey-Bordé interferometer. In comparison, the classic Chebotayev paper (Chebotayev et al., 1985) focused on Kapitza-Dirac or Bragg diffraction gratings that preserve atoms’ internal state. A unified description of these cases is found in (Bordé, 1997).

If the excitation is on resonance, the fraction of amplitude that is deflected by the transition is determined by the pulse area $\theta = \int \Omega_1 dt$ where $\Omega_1 = d_{ab} \cdot E_0 / \hbar$ is the bare Rabi frequency. A Ramsey-Bordé $\pi$-pulse (named for the condition $\theta = \pi$) results in an equal splitting of the amplitude between states $|a\rangle$ and $|b\rangle$ by resonant light. If the excitation is detuned by $\Delta$

\[
P_b(t) = \frac{1}{2} \left( \frac{\Omega_1}{\Omega_R} \right)^2 \left[ 1 - \cos(\Omega_R t) \right],
\]  

(23)

where $\Omega_R = \sqrt{\Omega_1^2 + \Delta^2}$ is the generalized Rabi frequency. When the detuning grows the oscillations become more rapid and less complete.

For an optical Ramsey-Bordé interferometer to work, the lifetime of the excited state must be comparable to the transit time through the interferometer in order to avoid coherence-destroying spontaneous decay of state $|b\rangle$ (see Section IV.B. on decoherence). Consequently optical Ramsey-Bordé interferometers are generally used with long-lived, metastable excited states such as the 1S-2S transition in H, or the lowest-lying intercombination lines of Mg or Ca (Gross et al., 1998; Morinaga et al., 1989; Oates et al., 1994; Ruschewitz et al., 1998).

In the 4 zone Ramsey-Bordé interferometer atoms passing through the first laser beam are put in a superposition of internal states $|a\rangle$ and $|b\rangle$. Several possible paths exit this apparatus, but only the paths shown in Fig. 25 cause interference fringes in the populations (outputs I and II of figure 26). Oscillations in the state $|b\rangle$ population are controlled by the phase of the laser at each of the 4 zones, therefore the simplest way to produce fringes is to adjust the laser frequency. Additional phase
FIG. 26 Ramsey-Bordé Interferometer. (Left) In the first interaction zone the matter wave is coherently split into two partial waves with internal states $|a,m\rangle$ and $|b,m\rangle$ corresponding to energy levels $a$ and $b$ respectively, and the number $m$ of photon momenta transferred to the atom. (Right) Fringe shifts due to rotation at different rates. Figures and caption reproduced from Riehle et al. (1991).

shifts in the fringes can be caused by any interaction that affects the internal states differentially, for example magnetic fields. Because of the photon recoil, the two paths are also separated in space and are therefore sensitive to field gradients and inertial displacements.

This 4 zone design of a Ramsey-Bordé interferometer was realized by Riehle et al. (1991) who also demonstrated the linear increase of phase shift with rotation rate $\Omega$. The data shown in Fig. 26 are the first demonstration of the Sagnac effect for atom interferometers.

Since then many Ramsey-Bordé interferometers were employed for H, Mg, and Ca atoms and I$_2$ molecules for precision experiments such as high resolution spectroscopy (Degenhartd et al., 2005; Gross et al., 1998; Hempel et al., 2002; Huber et al., 1998; Keupp et al., 2005; Kisters et al., 1994; Oates et al., 1999; Sengstock et al., 1993; Sterr et al., 2004; Wilpers et al., 2002) and fundamental studies such as geometric phases, and light shift potentials (Mei et al., 2000; Muller et al., 1993; Yanagimachi et al., 2002), transition Stark shifts (Morinaga et al., 1993; Rieger et al., 1993) and multiple beam high-finesse atom interferometry (Hinderthur et al., 1997, 1998; Ruschewitz et al., 1998; Weitz et al., 1996) and molecule interferometry (Bordé et al., 1994).

2. Raman interferometry

A similar beam splitter can be implemented using Raman transitions between two low-lying (e.g., hyperfine) states in a three-level atoms (Fig. 25b). The superposition is now between two long-lived states and can be driven with lasers tuned off-resonant from the excited state so that spontaneous emission is no obstacle to coherence time. For building an atom interferometer one has to transfer momentum during the Raman transition. Consequently two counter propagating running waves$^{10}$ ($\omega_1$ and $\omega_2$) of light with frequencies tuned to Raman resonance ($\hbar \omega_1 - \hbar \omega_1 = E_a - E_c = \Delta E_{bd}$) are used to stimulate Raman transitions between two hyperfine states.

FIG. 27 Raman pulse interferometer. (a) Transverse splitting and (b) longitudinal splitting of atoms with a $\pi/2 - \pi - \pi/2$ pulse interferometer. The mechanical recoil from the first $\pi/2$ pulse (at position 1) coherently splits the atomic wave packet. The $\pi$ pulse (positions 2 and 3) redirects each wave packet’s trajectory. By adjusting the phase of the second $\pi/2$ pulse (position 4), the atom can be put into either $|1\rangle$ or $|2\rangle$. In the experiment, the atoms were prepared in the $|1\rangle$ state (solid lines) and detected in the $|2\rangle$ state (dashed lines). (Bottom) Interferometer fringes are observed by scanning the frequency of the Raman laser beams. Figures reproduced from Kasevich and Chu (1991).

$^{10}$ Counter-propagating light beams make Doppler sensitive transitions that are highly selective for atomic velocity; co-propagating light beams make Doppler insensitive transitions. Doppler sensitive Raman transitions can prepare atoms with a momentum uncertainty of less than a photon recoil [Kasevich et al., 1991].
states $|a\rangle$ and $|c\rangle$ (Fig. 25). Absorption from one light beam and stimulated emission into the other gives atoms a momentum kick of $h\Delta k = h\Delta k_1 + h\Delta k_2 \sim 2h\Delta k_{ph}$. Since the hyperfine splitting $\Delta E_{hf} \ll h\omega_{1,2}$ is much smaller than the energy of either of the photons ($h\omega_{1,2}$) the momentum transfer can be approximated by $2h\Delta k_{ph}$ (reduced by the cosine of the half-angle between light beams).

Transfer of amplitude from $|a\rangle$ to state $|c\rangle$ mimics the dynamics of a driven 2 level system with coupling frequency equal to the product of the individual Rabi frequencies divided by $\Delta$ (see Fig. 25).

An alternative to Raman transitions is Stimulated Adiabatic Rapid Passage STIRAP described by Gaubatz et al. (1990) and Bergmann et al. (1998). This process is more controllable since it does not depend so critically on laser power. The method is based on adiabatic change of a “dark state” and has the disadvantage that only one superposition of the two states survives (the other decays spontaneously) hence its application to interferometry gives only one output state.

Starting with laser-cooled sodium atoms launched from a trap, Kasevich and Chu (1991, 1992) demonstrated an interferometer based on stimulated Raman transitions by employing a $\pi/2 - \pi - \pi/2$ sequence (Fig. 27). The $\pi/2$ pulses act as beam splitters, and the $\pi$ pulse acts to completely change the state and reverse the differential momentum in each arm of the interferometer in essence a three-grating interferometer. Similar to the Ramsey-Bordé interferometer, the paths have internal state labels. The interference is detected as oscillations in the population of the different internal states after the interferometer, as measured with state-sensitive fluorescence or ionization. Since the gratings are pulsed in time such an arrangement is a time domain interferometer. These experiments employed atomic fountains for Na (Kasevich and Chu, 1991, 1992) or Cs atoms (Peters et al., 1999) to permit longer interaction times. In the first experiments (with Na) a time delay between pulses of 100 msec gave a wavepacket separation of 6 mm (cf. 66 $\mu$m for thermal beams with fabricated gratings (Keith et al., 1991)). Chu and coworkers have refined this technique to get high contrast (C=65%) fringes with a count rate of $\langle f \rangle = 10^6$ atoms per second. This allowed measurements of $g$ at the part-per-billion level (Peters et al., 1999, 2001). The theory of this interferometer is discussed in detail by Young et al. (1997) and Kasevich and Chu (1992). Higher order Raman transitions can be stimulated with multiple pulses, and momentum differences of $60 h\Delta k_{ph}$ have been used for interferometry (Weiss et al., 1993).

A beam experiment using the same kind of Raman transitions was used by Gustavson et al. (1997, 2000) to measure rotation rates, and achieved short-term sensitivity to rotations of $6 \times 10^{-10}$ (rad/s)/$\sqrt{\text{Hz}}$ as discussed in Section V.A.. In this configuration, the gratings were not pulsed, so this was a space domain interferometer.

We discuss several other applications of this kind of interferometer, like precise measurements of gravity gradients (McGuirk et al., 2002; Snadden et al., 1998), Newton’s constant $G$, and the value of $h/M$ (Peters et al., 1997; Weiss et al., 1993) in Section V on precision measurements.

D. Longitudinal interferometry

The standard description of Ramsey’s separated fields experiment treats the longitudinal motion classically and as being the same for both states. This is obviously incorrect if the states have different magnetic moments and the beam passes into a region with a different magnetic field - the field gradient puts a different force on components with different magnetic moments, and could even reflect one state but not the other. Another source of longitudinal energy shift is excitation by RF radiation whose frequency is below (or above) resonance; the remaining energy to excite the atom comes from (or goes into) the kinetic energy of the excited state component. In fact, the transition can be made by a gyrating field with zero temporal frequency, especially if the beam is moving fast so that the spin can’t follow the field as it passes. We discuss these cases below.

1. Stern Gerlach interferometry

While a Stern-Gerlach magnet can entangle an atom’s spin and momentum transverse to the beam velocity, it is difficult to redirect and recombine amplitudes along these two paths (Englert et al., 1988; Reinisch, 1999; Schwinger et al., 1988; Scully et al., 1989). In a different geometry, atoms in a beam can be split longitudinally, so that components of each atom are separated along the direction of the beam velocity. This is easy to accomplish, and has the advantage (for interferometry) that the two paths overlap (DeKieviet et al., 1993; Miniatura et al., 1991; Robert et al., 1991).

A longitudinal Stern-Gerlach interferometer from Robert et al. (1991) is shown in Fig. 28. A partially polarized beam of metastable hydrogen atoms in the state $2s_{1/2}, F=1$ ($\lambda_{AB} = 40$ pm) is prepared in a linear superposition of magnetic sub-levels by a non-adiabatic passage (projection on the new eigen-states) through a magnetic field perpendicular to the atomic beam. The magnetic field gradient along the beam shifts the longitudinal momentum of different atomic center of mass wave packets proportionally to their magnetic state. Next, the different magnetic sub-levels enter a constant magnetic field region, and after 10 cm are recombined again in a region identical to the one used as a beam splitter. Finally, an analyzing magnetic field selects a particular magnetic polarization, whose intensity is then measured by detecting Lyman-α photons emitted in the decay of the $2p_{1/2}$ state to the ground state. A typical interference pattern is shown in Fig. 28 (Chormaic et al., 1993; Robert et al., 1992).
Interference fringes are obtained in the beam intensity by changing the magnetic field strength, and arise from the different potentials experienced by the magnetic sublevels in the region of constant magnetic field. The longitudinal Stern-Gerlach interferometer was applied to demonstrate the effect of topological phases on the atomic wavefunction for a non-adiabatic cyclic evolution (Miniatura et al., 1992).

2. Spin echo

Along similar lines, DeKieviet et al. (1997) developed an atomic beam spin-echo (ABSE) interferometer with $^3$He atoms. Following the Stern-Gerlach arrangement described above one can apply a reversed field (or a $\pi$-pulse) and extend this type of interferometer with an “echo”, in complete analogy to the spin echo technique used for neutrons [Mezei, 1993]. The $^3$He ABSE has the advantage that $^3$He can reflect from a surface at grazing incidence, and therefore can be applied as interferometric probe of surfaces [DeKieviet et al., 2000a, 1997, 1995].

![FIG. 28](https://example.com/fig28.png)

**FIG. 28** Longitudinal Stern Gerlach interferometer. (a) Experimental setup: source G, polarizing and analyzing magnetic fields P and A, mixers M and M’, frame FR with current $i_F$ creating a magnetic field $B$, detector DT. (b) The energy landscape for the Zeeman states (-1,0,1) of H* ($2s_{1/2}$, $F = 1$) along axis Z. (c) Interference pattern obtained with a transverse magnetic field in region FR. Figure from Chormaic et al. (1993).

![FIG. 29](https://example.com/fig29.png)

**FIG. 29** (color online) Atomic Beam Spin Echo interference technique for a spin-1/2 particle. (a) Schematic of setup: upon entering spin echo field 1, the linearly polarized wave packet $|\uparrow\rangle$ is split into two polarizations $|\rightarrow\rangle$ and $|\leftarrow\rangle$, having different energies in the longitudinal magnetic field. By inverting the direction of the spin echo field 2 with respect to the first one, the Zeeman states $|\rightarrow\rangle$ and $|\leftarrow\rangle$ exchange roles (like a $\pi$-flip). At the end they overlap and coherently add up to $|\uparrow\rangle$ or $|\downarrow\rangle$ depending on the phase shift. The initial linearly polarized wave packet reappears as an echo. (b) Experimental ABSE data using a 4 K beam of $^3$He atoms. Plotted is the beam averaged linear polarization as a function of the spin echo field. (spin rotation): when spin echo field is off, the interference pattern is generated through Stern-Gerlach interferometry. (spin echo): when the same (but inverted) current is applied through both spin echo coils an echo appears. Figure courtesy of M. DeKieviet Zielonkowski et al., 1998).

In a quantum mechanical picture, the Larmor precession can be viewed as a magnetic birefringence (Fig. 29). Note that the Zeeman states $|\rightarrow\rangle$ and $|\leftarrow\rangle$ arrive with some time delay $\tau_{SE}$ (spin echo time) at the scattering center, which allows time-correlation spectroscopy of the sample. The contrast in the measured echo signal depends then on the degree to which the Zeeman states are scattered coherently. For non-static samples this will depend on $\tau_{SE}$ (see Fig. 29b). The interference contrast directly measures the correlation function $I(q, \tau_{SE})$ in the time domain, which is the Fourier transform of the scattering function $S(q, \tau_{SE})$ ($q$ is determined by the scattering geometry). ABSE with $^3$He atoms has been successfully applied in surface science as an appealing alternative to time-of-flight experiments. The spin echo experiment is much more sensitive, with an energy resolution extending into the sub-neV-range.
ABSE is not restricted to longitudinal interferometry; depending on the direction of the magnetic field gradient, the paths of the magnetic sub-states may diverge perpendicular to the beam direction. Using atomic hydrogen with a de Broglie wavelength of around 100 pm, Lang (1998) measured a transverse spin echo interference signal for path separations exceeding 100 nm.

In an entirely optical setup a spin echo was demonstrated through hyperfine pumping a thermal beam of lithium atoms (Zielonkowski et al., 1998). Here, the spin echo is induced via a “virtual magnetic field”, by applying a short pulse of intense, far detuned photons. The light causes a shift in the hyperfine levels that depends linearly on the quantum number \( m_F \), just like Zeeman splitting (Cohen-Tannoudji and Dupont-Roc, 1972; Rosatzin et al., 1999).

3. Longitudinal RF interferometry

Dhirani et al. (1997) showed that a detuned radiofrequency field constitutes a beamsplitter in longitudinal momentum space for atoms. If an atom makes a transition to an excited quantum state by absorbing a quantum of off resonant RF radiation, then its longitudinal velocity is changed such that total energy is conserved.

Using two such beam splitters Smith et al. (1998) constructed a longitudinal atom interferometer in a generalization of Ramsey’s separated oscillatory fields (SOF) configuration. This technique is referred to as differentially tuned separated oscillatory fields, or DSOF. Oscillations in excited state population both in time and space occur after an atom beam passes the two DSOF regions. To measure the phase and amplitude of these oscillations, a third oscillatory field and a state selective detector were used as shown in Fig. 30.

This interferometer is well suited to studying the longitudinal coherence properties of matter-wave beams. Scanning the position of the third oscillating field demonstrates that the DSOF system can produce or detect coherent momentum superpositions.

The envelope of the fringes in space Fig. 30 indicates the velocity width of the atom beam was 36 ± 4 m/s and the fringe period in space indicates the most probable beam velocity was 1080 ± 3 m/s. An argon seeded supersonic source of sodium atoms was used.

The same DSOF arrangement was used to demonstrate the absence of off-diagonal elements in the density matrix in a supersonic atom beam, thus showing that there are no coherent wave packets emerging from this source. (Rubenstein et al., 1999a). In a further demonstration, the DSOF longitudinal interferometer was used to measure the complete longitudinal density matrix of a deliberately modulated atom beam (Dhirani et al., 1997; Rubenstein et al., 1999b). A fully quantum mechanical treatment of this system was developed for this analysis (Kokorowski et al., 1998), and these experiments are summarized by Kokorowski et al. (2000).

4. Stückelberg interferometers

Stückelberg oscillations occur when a level-crossing for internal states acts as a beam splitter. For example, if an atom can change its internal state on the way either to or from a reflecting surface, then two amplitudes for making a transition will interfere. Oscillations in the probability for state-changing atomic reflection can thus be regarded as longitudinal interferometry. One application is to survey the van der Waals potential near surfaces (Cognet et al., 1998; Marani et al., 2000).

E. Coherent reflection

Here we briefly list more experiments in which reflected de Broglie waves are demonstrably coherent. Shimizu demonstrated reflection mode holograms (Shimizu and Fujita, 2002b) and a reflection-mode double slit experiment (Kohno et al., 2003). Westbook used a Raman-pulse atom interferometer to study coherent reflection from an evanescent light field (Esteve et al., 2001) as shown in Figure 61. Dekieviet used a longitudinal Stern-Gerlach interferometer to study quan-
tum reflection of $^3$He. Druzhinina and DeKieviet (2003). Zimmermann used a chip-integrated magnetic grating to diffract and interfere reflected BEC’s (Fortagh and Zimmermann, 2007; Gunther et al., 2007).

FIG. 31 An atom mirror inside an interferometer. (a) Diagram of the interferometer. The arrows represent Raman $\pi/2$ pulses which create superpositions of different internal states and momenta. The atomic mirror is an evanescent wave at the surface of a glass prism represented by the trapezoid. The letters a, b, c and d, label the 4 possible paths. (b) Fringes obtained by scanning the pulse separation T with the mirror (filled symbols) and without the mirror (open symbols). Figures from Esteve et al., 2004.

F. Confined Atom Interferometers with BEC’s

In this section we discuss a different type of interferometer, where the atoms are confined in a 3-dimensional potential well during the splitting of their wave function and application of the interaction. In this new type of splitting process, the single trap holding the ultra cold gas of atoms (or BEC) is continuously deformed into two adjacent potential wells, each containing a part of the wave function. Thus the splitting step in the interferometer occurs in position space.

This splitting in position space is in sharp contrast to previously discussed atom and most optical interferometers, in which the splitting process occurs in momentum space. Using diffraction gratings or pulses of light transfers momentum; similarly a partially reflecting surface changes the momentum of the reflected, but not the transmitted, beam. The two maxima then separate to a varying extent in position space only because the wave is split in momentum space. In the trapped atom interferometers discussed here the atom waves remain confined and are separated by moving the potential wells apart.

Important advantages of confined atom interferometers are manifold. The confinement can support the atoms against gravity, offering potentially unlimited experiment times with obvious advantages for precision experiments. The location of the atom wave can be known very precisely. This is essential in experiments studying atom-surface interactions like the Casimir potential, or for studying spatially varying fields or interactions with small objects that are coupled to the atoms via an evanescent wave. If a BEC is confined, the large scale coherence allows new ways to measure the relative phase of two condensates using just a small sample of the atoms. Additionally, confined atom interferometers, especially those using atom chips, can be small and portable.

Confined atom experiments differ qualitatively from the many experiments that have been carried out using BEC’s as a bright source of cold atoms propagating in free space (Gupta et al., 2002; Torii et al., 2000). In those the physics is dominated by single-particle dynamics and does not exploit the particular coherence properties of BECs. In the interferometers described here, the intrinsic properties of the BEC allow novel measurements, and create new problems to be overcome.

Confined atom interferometers naturally operate with significant density to achieve the advantages of large signals, from which several disadvantages follow. First of all, the matter wave optics becomes non linear. The atom-atom interactions lead to a mean field potential (the chemical potential in a BEC) that can cause a relative frequency shift between atoms in the two wells. In addition the potential wells have to be controlled very accurately in stiffness and depth, to prevent additional sources of systematic frequency shifts. (In waveguide interferometers where the atoms are confined only in two directions, any residual potential roughness gives additional problems.)

Splitting a condensate coherently produces a state whose relative phase is specified at the expense of a superposition of number states with different relative populations because of the (approximate) number-phase uncertainty relation. Knowing the relative phase of two condensates requires an uncertainty in the relative number of atoms in each well, even though the total number may be certain. The wave function in each well is therefore a coherent superposition of states with different relative mean field interactions (different relative chemical potentials) and therefore evolve at different rates. The resulting dephasing limits the coherence time to less than 50 ms for a typical million-atom BEC (with diluteness parameter, $na^3 \approx 10^{-4}$).

In addition one has to carefully consider the collective excitations of the condensate (e.g. sound or shape oscillations) which may arise if the potential changes too suddenly. This can be overcome by applying techniques from coherent control as shown in Hohenester et al. (2007).
Recombining the split double well into a single trap allows in principle the readout of the relative phase as a relative population difference between ground state and first excited state (Andersson et al. 2002; Hinds et al. 2001). In the recombination, the non linear interactions lead to creation of (fast moving) solitons. These can enhance the sensitivity (Negretti and Henkel 2004) of phase measurements, but are much harder to control. Consequently the experiments recombine the split waves by releasing them from the trap, then free expansion reduces the non-linearity and facilitates the overlap.

Confined atom interferometers have so far come in two types: BEC’s confined to waveguides (i.e. in two dimensions) which are described in the next sub section, and those confined in traps (i.e. in all three dimensions) using focused light beams (subsection 2) and magnetic fields generated by atom chips (subsection 3). Finally in the last subsection we describe an example where it is possible to establish and read out the relative phase of two condensates that do not overlap during the entire process and discuss whether this can be seen as a type of interferometry involving two classical objects.

1. Interference with guided atoms

Given the existence of optical interferometers using fiber optical wave guides, and the success in confining and guiding ultra cold atoms, it is natural to consider similar designs for atoms. While preliminary theoretical study shows that special designs should allow multi-mode interferometers (Andersson et al. 2002), no interferometer devices involving atom waveguide beam splitters have been demonstrated.

The first waveguide atom interferometer, by Wang et al (2005) and improved on by Garcia et al (2006), was designed to test coherent propagation in atom waveguides, not waveguide beamsplitters. It was a familiar three grating interferometer in which pulsed light gratings split and recombined a BEC confined in a weakly confining (magnetic) guide along the axis. The BEC is split at $t = 0$ into two momentum components $\pm 2\hbar k_L$ using a double pulse of a standing light wave. A Bragg scattering pulse at $t = T/2$ then reverses the momentum of the atoms and the wave packets propagate back. At $t = T$ the split wave packets overlap and a third recombining double pulse completes the interferometer. The output port is given by the momentum of the atoms as detected by imaging (typically 10 ms) after release from the guide. To apply a phase shift between the two arms of the interferometer, a magnetic field gradient was turned on for a short ($500 \mu$s) time while the atom clouds were separated. In the original experiment (Wang et al. 2005) the propagation time in the interferometer was varied from $T = 1 \text{ ms}$ to $T = 10 \text{ ms}$. The contrast of the fringes was as high as 100% for $T = 1 \text{ ms}$, but dropped to 20% for $T = 10 \text{ ms}$. The degradation of the contrast is mainly due to the non linear term coming from the interaction between the atoms. By reducing the transverse confinement and consequently the non linear interaction (Garcia et al. 2006) reached much longer coherent propagation up to 180 $\mu$m and times up to 50 ms.

There is ample optical precedent for waveguide interferometers using 2-dimensional confinement since there is wide application of optical fiber interferometers both scientifically and commercially. On the other hand, interferometry with 3-dimensionally trapped atoms has no precedent in light optics\(^\text{11}\).

2. Coherent splitting in a double well

Three dimensional trapped atom interferometers are a qualitatively new type of interferometer without precedent in optics since it is not possible to trap photons, move the trap around, and then somehow recombine the photons. A trapped atom interferometer does just that.

Coherent splitting of the wave function by slowly deforming a single trap into a double well is the generic trapped atom beam splitter, achieving physical separation of two wavefunction components that start with the same phase. When the two wells are well separated, an interaction may be applied to either. Finally the split atoms in the two wells are recombined to observe the interference.

\(^{11}\) One could argue that a Fabry-Perot is an (imperfect) trap for photons and that the LIGO interferometer which uses Fabry-Perot interferometers nested in a Michelson interferometer is not far from this precedent.
FIG. 33 Top: Optical double-well potential. (a) Schematic diagram of the optical setup for the double-well potential. The insert shows an absorption image of two well-separated condensates in the double-well potential (he field of view is 70 × 300 µm). (b) Energy diagram, including the atomic mean field, for the initial single-well trap with $d=6$ µm and for the final double-well trap with $d=13$ µm ($U_0=5$kHz, atomic mean field energy $\sim 3$kHz, potential “barrier”). (c) Absorption image of fringes created by condensates released from the double-well potential immediately after splitting (30 ms of ballistic expansion, field of view 600 × 350µm). (c) Density profile obtained by integrating the absorption signal between the dashed lines. Figure and caption adapted from Shin et al. (2004).

Such coherent splitting was first demonstrated by Shin et al. (2004) who split a BEC by deforming an optical single-well potential into a double-well potential. A BEC was first loaded into the single trap and allowed 15 sec to damp its excitations. The splitting was done over 5 ms, slowly enough compared to a 600 Hz transverse oscillation frequency in the trap not to excite substantial transverse excitation of the two new condensates, but not slowly enough that the mean field interaction would cause the atom to divide exactly evenly between the two wells (with exactly $N/2$ on each side there would be no number uncertainty and hence the relative phase would have been indeterminate).

The interferometer was completed by releasing the trapped separated BEC’s and determining their relative phase from the resulting fringes. Releasing the condensates dramatically lowers the mean field interaction prior to overlap, hence averting problems arising from the non-linearity of atom optics. Another big advantage is that overlapping two BEC’s produces high contrast fringes, enabling an accurate determination of the phase from each “shot” of the interferometer.

Observing the fringes in repeated experiments, starting with fresh condensates each time, addressed the key question: is the relative phase between the split condensates random or consistent from shot to shot? There had been some theoretical controversy on this subject. The fringes observed when the load, split and immediate release sequence was repeated were in the same place, showing that the relative phase between the two condensates was consistent, i.e. that is can be controlled deterministically. It was also shown that the phase evolved coherently for up to 5 ms.

The condensates were separated by 13 µm in these experiments, and the single atom tunneling rate between the two wells was estimated to be $5 \times 10^{-4}$ s$^{-1}$, sufficient to uncouple the BEC’s in separated wells and let their phases evolve independently. It was verified that each condensate evolved phase independently and was phase shifted as expected by a local Stark shift.

This experiment showed definitively that splitting the well led to BEC’s with a common phase, introduced a new method to determine the phase that was not affected by mean field interactions, and showed that coherence could be maintained for several oscillation periods of transverse condensate motion.

3. Interferometry on atom chips

The combination of well established tools for atom cooling and manipulation with state-of-the-art microfabrication technology has led to the development of atom chips (Folman et al., 2002). Atoms are manipulated by electric, magnetic and optical fields created by microfabricated structures containing conductors designed to produce the desired magnetic and electric fields. Technology, atom chip based atom interferometers promise to be relatively inexpensive and presumably are relatively robust. Atom chips have been demonstrated to be capable of quickly creating BEC’s and also of complex manipulation of ultra cold atoms on a micro scale. We trace here the development of techniques to coherently split the condensate and perform atom interferometry.

Many basic interferometer designs and beam splitters on an atom chip were conceived and tested (Folman et al., 2002). Most of them rely on splitting a magnetic potential in multi-wire geometry. The first experiments demonstrating splitting, but not coherence, were carried out in Innsbruck 1996-1999 with splitting a guide with a Y-shaped wire (Cassettari et al., 2000a,b) and a trap with a 2-wire configuration (Folman et al., 2002).

At MIT interference with random phase using such
FIG. 34 (color online) Coherent splitting with an RF induced double well on an atom chip. (a) A wire trap is split by coupling the magnetic substates by RF radiation. To achieve the correct orientation (splitting orthogonal to gravity) the trap is rotated and placed directly over the RF wire. (b, c) The energy landscape before and after splitting. (d) Interference is observed by switching the trap off, and letting the atomic cloud overlap in time of flight. The image integrates over the length of the condensate. (e) Observed distribution of fringe phase and contrast obtained from multiple experiments [Schumm et al. 2005].

A two wire setup was observed by Shin et al. (2005). Simultaneously the first coherent splitting of trapped micro manipulated atoms on atom chip was achieved by Schumm et al. (2005) at Heidelberg, using radio frequency induced adiabatic potentials [Colombe et al. 2004, Lesanovsky et al. 2006a; Zobay and Garraway, 1998]. Analyzing interference patterns formed after combining the two clouds in time-of-flight expansion, demonstrated that the splitting is coherent (i.e. phase preserving) Figure 34.

The splitting using radio frequency induced adiabatic potentials as developed in Heidelberg overcomes the disadvantages of the 2 wire setup: weak confinement during the splitting, and extreme sensitivity to magnetic field fluctuations. The new method allows very well controlled splitting over a large range of distances - from 2 to 80 \( \mu m \) - thus accessing the tunneling regime as well as completely isolated sites.

The Heidelberg experiments [Hofferberth et al. 2006; Schumm et al. 2005] are remarkable since they were performed with 1d BEC (chemical potential \( \mu < \hbar \omega \perp \)) much longer then the phase coherence length. Nevertheless the interference patterns persist for as long as the condensate. All different regimes from physically connected to totally separated 1d BECs were accessible, and phase locking by coherent tunneling in the intermediate regime could be demonstrated.

With continued progress on these topics, together with techniques for reducing dephasing of interferometers using BECs, interferometers using confined atoms hold the promise to be employed as highly sensitive devices that will allow exploration of a large variety of physics questions. These range from exploring of atom-surface interactions to the intrinsic phase dynamics in complex interacting (low dimensional) quantum systems and the influence of the coupling to an external `environment' (decoherence).

IV. FUNDAMENTAL STUDIES

In this chapter, we address two questions that lay people often ask once they have understood the basic ideas of atom interferometry: “Can you make interferometers with any object, people for example?” and “Of what use are atom interferometers?” We discuss the limits to particle size in section A, experiments that probe the transition from quantum behavior to classical behavior via the process of decoherence in B, and how the ideas of single particle coherence can be extended in D. The question of utility is first addressed in section C, where we show that measurable phase shifts arise not only from potential differences, but from “weirder” things like the Aharonov-Bohm effect and topological transport in general. Then we describe how atom interference can be used to study four different features of many-body systems in section E, and finally address fundamental tests of charge equality for protons and electrons. The actual order of the sections does not reflect the answers to these questions in sequence, however; rather the first three address single particle questions, section D addresses extensions of coherence first to extended single particles, and then to multi-particle systems, and section E is devoted to describing studies of many particle systems that reveal many-particle coherence and decoherence processes, or in which atom interference is the tool that enabled the study of their collective properties.

A. Basic questions: How large a particle can interfere?

When the first atom interferometers were demonstrated, some of our colleagues expressed surprise that “composite” particles would give such high contrast fringes. These sentiments are in line with the idea that there exists a quantum-classical boundary and that somehow there must be a limit on the number or spacing of internal states (i.e. the “complexity”) for particles in an interferometer. Perhaps the mass, the size of a molecule, or the strength of interactions with the environment can limit or eliminate the interference. In this section we investigate the limits to coherent manipulation of the cen-
tering of mass motion of larger and more complex particles, and point to some interesting open problems. We shall first consider practical limits set by particle size, grating size, and interactions with the grating, and then move on to more fundamental limits determined by interactions with the surrounding environment.

Experiments with Na$_2$ molecules (Chapman et al., 1995a) demonstrate that particles with many internal states show interference fringes even if the paths go on opposite sides of a thin conductor. These experiments also confirm what the first atom interferometers showed: interference fringes can be observed when the size of the particle is considerably larger than both its de Broglie wavelength and its coherence length. For example in the separated beam interferometer with Na$_2$ $\lambda_{\text{dB}} \approx 10$ pm and the coherence length $\lambda_{\text{coh}} \approx 100$ pm are both much smaller than the size of the molecule ($\sim 400$ pm). For the experiments with $C_{60}$ or larger molecules the parameters are even more extreme (Arndt et al., 2000; 2001; 1999; Brezger et al., 2003; Clauser, 1997; Hackermüller et al., 2003).

Perhaps a bit more surprising is the observation of fringes in Talbot-Lau interferometers with hot particles like $C_{60}$, the surprise being that they have a spontaneous emission rate fast enough to emit IR photons during the interference process. But since the maximum separation of the paths in these experiments (about a grating period) is much less than the wavelength of the IR radiation, a few photons of emitted radiation cannot be used to localize the molecule to one path or the other (Hackermüller et al., 2004; Hornberger, 2006). Thus the interference is between two spatially separated paths along which the molecule emitted a photon and changed from internal state $|i\rangle$ to final state $|f\rangle$. Interestingly, IR emission would localize a molecule on one side or the other of a conducting plate, so hot molecule interference would not occur between paths separated by a conductor\(^{12}\). This makes an important point: information left in the environment is sufficient to destroy the coherence; no actual measurement by a macroscopic apparatus is necessary.

Even though a particle’s size itself poses no fundamental limit to matter wave interferometry, there are more practical limitations to interferometry with large particles, such as 1. the time required to propagate through an interferometer, 2. the requirement that the particles fit through the openings on material gratings without undue effects from Van der Waals interactions, and 3. whether laser-based beamsplitters can work with particles larger than the laser wavelength.

The time it takes a diffracted particle (with one grating momentum, $hG$) to move one grating period sets the characteristic time for interference of a particle of mass $m$,

$$t_{\text{char}} = \frac{d}{hG/m} = \frac{md^2}{\hbar} = \frac{\hbar}{2E_G}$$

(24)

where $E_G$ is defined as in Eq. 6. For a grating period 100 nm and a flight time of one second this limits the mass to $\sim 10^{-17}$ g, or about one million Na atoms. Such a cluster would have a size of $\sim 30$ nm and would just fit through the gratings. For the 0.01s flight times characteristic of current Talbot-Lau interferometers, this limit would be around atomic mass $10^5$, about an order of magnitude heavier than current practice. Increasing the time by an impractical factor (e.g. to a year, with concomitant inertial stabilization of the gratings) does not improve the mass limit proportionately. The reason is that the grating period has to be increased to accommodate the diameter of the particle (Hegerfeldt and Kohler, 1998; 2003; Schmiedmayer et al., 1997; Schollkopf et al., 1998) which grows as $m^{1/3}$. Thus a year-long interferometer can barely interfere a large bacterium as pointed out by Schmiedmayer et al. (1997).

While this discussion of size/mass limits applies quite accurately to Talbot-Lau interferometers, the requirements of a separated beam interferometer are several times more stringent. In order to separate the paths the beam must be collimated to better than the diffraction momentum, which requires that the beam (and its transverse coherence length) be several grating periods wide. To separate these wider beams, the particles must propagate for several characteristic times. Even worse, the flux of particles will be dramatically reduced due to the tight collimation. In contrast, Talbot-Lau interferometers have no restriction on their width. Not surprisingly they are the interferometer of choice for demonstrating interference of heavy particles. And even with them, it will be some time before sentient beings can be sent through an interferometer and subsequently asked which path they took.

While equation \(^{23}\) shows that if molecules spend too little time in the interferometer, they will not exhibit quantum interference (Oberthaler et al., 1999); on the other hand, if particles spend too long interacting with mechanical gratings, they will interact with the grating bars, or be diffracted into very high orders. This is because of Van der Waals or Casimir-Polder interactions between molecules and the grating bars (Grisenti et al., 1999). To keep half the diffracted molecules in the central $n$ orders requires

$$\left| \frac{\partial}{\partial r} V(r) \right|_{r=d/8} < \frac{h\nu}{d^2}$$

(25)

where $V(r)$ is the atom-surface interaction potential. Equation \(^{23}\) assumes a grating with an open fraction of 50% and a grating thickness equal to the grating period ($d$) (Perreault et al., 2005; Hornberger et al., 2004) and Brezger et al. (2003) discussed how the useful range of molecular velocities for a TLI gets severely restricted for

\(^{12}\) Of course a separated path interferometer, not a Talbot-Lau interferometer would be needed for this experiment.
large molecules or small gratings. Van der Waals interactions also set a minimum mechanical grating period for Sagnac gyroscopes. For a large Sagnac response factor, one would naturally select small grating periods. However, Van der Waals interactions cause the uncertainty of a Sagnac rotation sensor to increase if grating periods smaller than 44 nm are used with 1000 m/s Na atoms. For helium atoms, which have much weaker vdW interactions, the optimum grating period for a rotation sensor is 8 nm, about ten times smaller than current practice. This is discussed for a MZI by Cronin et al. (2004).

These limitations from grating bars and Van der Waals interactions have lead to proposals for Talbot-Lau interferometers for large molecules based on light gratings (Brezger et al., 2003). If the particle’s size is a large fraction of the wavelength, the light forces will have gradients inside the particle that will excite the collective oscillations of the particle unless the turn on/off time extends over many periods of oscillation. For even larger homogeneous particles the light force averages out to nearly zero. This can be overcome by localizing the interaction [e.g. with a color center (Hornberger et al., 2004; Nairz et al., 2001)] or by making particles with periodic structure on the scale of the wavelength. Nevertheless the question of how much internal excitation will occur still remains to be answered. Finally, it should be possible to impart lots of momentum with long wavelength photons by using multi-photon processes.

B. Decoherence

Quantum mechanics makes assertions so at odds with everyday experience, that the mechanisms by which a quantum mechanical treatment of macroscopic objects reduce to purely classical behavior have long been considered a fascinating topic. Indeed wrestling with this problem has led a number of scientists to make radical suggestions for changes in quantum theory itself (e.g. spontaneous projection, pilot wave, etc.) or the nature of reality (many worlds, etc.). Observation of decoherence, and the suppression, avoidance, control and correction of decoherence mechanisms is a busy field made especially topical by the fruits of, and need for, advances in quantum computation and nanotechnology.

Atom interferometry is based on coherence and therefore is sensitive to interactions that upset this coherence. Relative to neutrons, atoms have large polarizability, magnetic moment, and scattering cross sections and are therefore both more sensitive to, and easy to use as quantitative probes for, decoherence processes. In this section we discuss atom interferometry’s historical role in gedanken experiments about quantum uncertainty and its present role in providing an environment in which clean quantitative tests of decoherence is possible.

1. Interference and ‘Welcher Weg’ information

Perhaps the first general realization about interference fringes was that they can easily be destroyed by interactions that, even in principle, allow one to determine which path an atom took through the interferometer. This is deeply rooted in Bohr’s principle of complementarity which forbids simultaneous observation of the wave and particle behaviors. It is best illustrated in the debate between Einstein and Bohr on the question ‘can one know which path the particle took and still observe the interference of the waves?’ (Bohr, 1949; Wooters and Zurek, 1973). Einstein proposed the famous recoiling-slit experiment to gently measure which path the particle took through a two-path interferometer. In reply Bohr pointed out that the slit itself must also obey the laws of quantum mechanics and therefore is subject to the Heisenberg uncertainty principle. He showed quantitatively that if the initial momentum of the slit-assembly is known well enough to permit the recoil measurement of which path the particle took, then the initial position of the slit must have been so uncertain that fringes would be unobservable.

According to Feynman, this experiment “has in it the heart of quantum mechanics. In reality it contains the only mystery.” (Feynman et al., 1963). (Subsequently Feynman acknowledged that entanglement was another mystery.) In 1960, Feynman proposed a related gedanken experiment in which a perfect light microscope (i.e. one fundamentally limited by Heisenberg uncertainty) is used to determine “which-way” information in a two-slit electron interferometer by analyzing a single scattered photon (Feynman et al., 1965). In Feynman’s analysis of this gedanken experiment, electron interference (a manifestly wave-like behavior) is destroyed when the separation of the interfering paths exceeds the wavelength of the probe (i.e. when it is possible to resolve on which path the electron traversed). In fact the contrast is lost whether or not anyone actually looks with the microscope; the ability in principle to identify the electron’s path is enough to destroy the interference pattern. Feynman concludes, “If an apparatus is capable of determining which hole the electron goes through, it cannot be so delicate that it does not disturb the pattern in an essential way.”

More recently, a quantitative duality relation was derived by (Jaeger et al., 1993) and (Englert, 1996) to quantify how much ‘which-path’ knowledge \( K \) can be obtained and how much contrast \( C \) can be observed at the output of an interferometer.

\[
K^2 + C^2 \leq 1
\]  

(26)

It is based on the analysis of a detector that quantifies how well the two paths can be distinguished. The detector could be similar to Feynman’s light microscope, as studied theoretically by Geotsch and Graham (1996); Holland et al. (1996b); Stern et al. (1990);
Modern decoherence theories no longer invoke Bohr’s collapse postulate, and they do not rely on the uncertainty principle. Instead they treat quantum systems (such as atoms in an interferometer) as being coupled to their environment (including the which-way detector) together as one combined (open) quantum system. In this view, the interaction between the observed quantum system and its (quantum) environment is a unitary process that causes entanglement so that the state of the observed quantum system becomes correlated with the quantum state of the environment. Then a measurement made on the environment allows inferences on the quantum system. For example, if a photon in the environment allows an inference of which path the atom took, then a trace over the environment would reduce the coherence remaining in the atom density matrix, even if the coupling interaction were now turned off. For more details we refer the reader to a set of excellent articles by Joos and Zeh (1985); Tan and Walls (1993); Tegmark (1993); Wiseman et al. (1997) and examined experimentally by Chapman et al. (1995b); Clauser and Li (1994b); Kokorowski et al. (2001); Mei and Weitz (2001). Alternatively the detector could monitor spin polarization or the internal state of atoms as proposed by Scully et al. (1991), discussed by Badurek and Rauch (2000); Engert et al. (2000); Luis and Sanchez-Soto. (1998) and examined experimentally by Durr et al. (1998a,b); Durr and Rempe (2000a). We also note the similarity with many neutron spin-superposition experiments (Badurek et al. 1983, 1988; Bonse and Rauch 1979; Summhammer et al. 1983).

Since atoms couple strongly to electromagnetic fields in a well-understood way, atom interferometers provide ideal tools for studying decoherence.

2. Internal state marking

The simplest way of measuring an atom’s ‘path’ through the interferometer is by marking it with an internal state of the atom. This is analogous to an interferometer for light where the polarization is rotated in one arm. Measuring the internal state of the atom then determines which path it took, and consequently destroys the interference.

For example, Durr et al. (1998a,b) studied the complementary nature of fringe contrast and path information by using atoms prepared in a superposition of internal states before they pass through an interferometer for their external (center of mass) states. The interferometer was based on Bragg diffraction gratings that affect the internal states differently so that the interferometer paths became correlated with internal states. This caused a controllable amount of contrast loss, based on how well the internal states labeled which path the atom took.

These experiments are very similar to earlier neutron interferometer experiments where loss of interference caused by correlations between spin polarization and interferometer path was studied (Badurek et al. 1983). In both the atom and neutron experiments the coherence can be retrieved (Durr and Rempe 2000a,b; Summhammer et al. 1983) by projecting the internal state vector onto a measurement basis that does not allow one to distinguish the encoded internal states. The path information is thereby erased and the full interference contrast regained. This is a nice demonstration that interference will be lost if the internal states contain which-path information; the loss of interference occurs without invoking any coupling to an external environment.

To substantiate that there is no coupling to the environment, note that the transitions to prepare the internal state label are driven with microwave fields that are in coherent states with large photon number uncertainty, and hence one can not use a measurement of the microwave field itself to get information about whether the atom absorbed a single photon on the labeled path. Thus no information about the internal state is transferred to the environment. The coherence is not really gone, it is hidden behind the choice of what to measure (interference or path). One can easily get it back by rotating the basis for the measurement, so that the ‘which path information’ is erased, as it was done in the beautiful experiments by Badurek et al. (1983); Durr and Rempe (2000a,b).

This is different from the decoherence described by the recoiling slit or Feynman’s microscope discussed above. There one has to look into the environment to get the coherence back. One has to find the other part of the entangled state.

3. Coupling to an environment

We now discuss situations in which the interferometer looses coherence because of coupling to the environment. It is closely related to modern theories of decoherence as will become obvious. As an example, consider that the initial state involves an atom traversing an interferometer and a well-collimated photon incident on the atom; then the final state may involve an atom at the detector and a photon in the environment traveling toward infinity. This is a prototypical example of an interferometer that becomes entangled with an external environment or particle. The interaction and its strength is well known, but the final state is unknown.

a. Decoherence in Diffraction Several experiments have demonstrated decoherence due to spontaneous emission of light quanta. Gould et al. (1991); Keller et al. (2000); Pfau et al. (1994) used atom diffraction patterns caused by diffraction from a grating to observe how the spatial coherence of an atom beam gets reduced by spontaneous...
emission of a photon. A good picture is that the recoil from the spontaneously emitted photon shifts the momentum of each atom randomly, along with its individual diffraction patterns. Since the direction of the final photon is random, these experiments revealed a decrease of contrast of the summed patterns. There was a transition from diffraction to diffusion with increasing probability of spontaneous emission. In a similar spirit, the visibility in the diffraction patterns of fullerenes $C_{60}$ and $C_{70}$ has been used to bound the amount of decoherence for the molecule waves caused by emitting thermal photons (Hackermuller et al., 2004).

All of these experiments can be perfectly explained by the random momentum kicks given by the spontaneously emitted photons. Interestingly the result is the same regardless of the place of the photon emission, as long as it is at or upstream of the grating. Consequently the effect is the same as if the incident beam had a wider transverse momentum distribution, with associated smaller transverse coherence length.

b. Decoherence in Talbot Lau interferometer In a three grating Talbot Lau interferometer, Clauer and Li (1994) showed that resonant laser light scattered from atoms in the middle of the interferometer can destroy fringe contrast. This experiment actually detected the fringes by selectively destroying the contrast for different velocity classes that were Doppler shifted into resonance with a laser beam.

More recently, but in a similar spirit, Mei and Weitz (2001) demonstrated that photon scattering in a multiple beam Ramsey interferometer also leads to decoherence for the atoms that scatter light. Furthermore, because some of the multiple paths in this experiment cause fringes that are out of phase with the other two-path combinations, it was shown that decoherence of one beam can either increase or decrease the net contrast.

Hackermuller et al. (2004) observed decoherence of internally hot fullerene matter waves caused by emission of radiation in a Talbot-Lau interferometer. This experiment is remarkable, since the emission spectrum of the hot fullerene is very close to thermal radiation, and in that sense looks more like a (mesoscopic) classical particle which ‘cools’ internally by emitting photons during the flight in the TLI.

All of these experiments can again be perfectly explained by the (classical) random momentum kicks given by the spontaneously emitted photons.

c. Photon scattering in an Interferometer Chapman et al. (1995) studied the loss of coherence in a Mach-Zehnder interferometer when each atom scattered exactly one photon. Loss of contrast was observed which depended on the separation between the two interferometer paths at the point of photon scattering. This is a close realization of Feynman’s gedanken experiment, and we will discuss it below in detail.

d. Scattering from background Gas in an Interferometer Scattering from a background gas of massive atoms or molecules has also been used to cause a controlled amount of decoherence. Collisional decoherence was observed by Hackermuller et al. (2003a), Hornberger et al. (2003) with Talbot-Lau atom interferometer, and similar work with a Mach-Zehnder interferometer (Uys et al., 2005) is shown in Figure 35.

It is interesting to note the difference between the decoherence due to photon scattering and atom scattering. The basic physics processes are very similar, except that the momentum transfer is much much larger in the case of the atoms and many of the ‘collisions’ lead to the atoms being scattered out of the detected beam. Consequently the loss of contrast in atom collisions is not so bad, but the overall intensity goes down significantly. In addition the atom-atom scattering is a probabilistic process, whereas the photon scattering can be made deterministic (see Chapman et al. (1995)). Additional theory work on collisional decoherence with massive particles can be found in (Fiete and Heller, 2003; Hornberger and Sipe, 2003; Hornberger et al., 2004; Kleckner and Ron, 2001; Vacchini, 2004).

Closely related to these atom scattering decoherence experiments are the studies of stochastic or deterministic absorption and its effect on coherence in neutron interferometers (Namiki et al., 1992; Rauch and Summhammer, 1992; Summhammer et al., 1987, 1988).
4. Realization of Feynman’s gedanken experiment

Scattering a single photon from an atom in superposition of two locations, is one of the icons of decoherence experiments. It is directly related to Feynman’s gedanken experiment discussed above. To realize such an experiment, Chapman et al. (1995b) scattered single photons from atoms within a two-path Mach-Zehnder atom interferometer (Fig. 36). Exactly one photon was scattered by adjusting a tightly focused laser beam so that each traversing atom made exactly half a Rabi cycle, exiting the laser beam in the excited state. To achieve this the transit time of the atoms through the excitation laser ($T_{\text{trans}} \sim 5$ ns) was much shorter then the lifetime of the excited state ($\tau \sim 16$ ns). Translating the laser beam along the interferometer caused excitations at different locations corresponding to different spatial separations of the interfering atom waves.

The experimental results are displayed in Fig. 37. The contrast (which is a direct measure of coherence) decreases smoothly towards zero as the distance between the two paths grows to $d = \lambda/2$. At this point, the separation between paths is equal to the Heisenberg microscope resolution. The observed contrast recurrences at $d > \lambda/2$ have their mathematical origin in the Fourier transform of the dipole pattern for spontaneous photon scattering (Geotsch and Graham, 1996; Holland et al., 1996b; Steuernagel and Paul, 1995; Tan and Walls, 1993). Feynman, who might be surprised at their existence, would be reassured to note that they occur where the prominent diffraction rings of a perfect light microscope would lead to path ambiguity.

The specific arrangement of the experiment allowed separation of the effects of the (classical) momentum transfer and the entanglement between the atom at two locations and scattered photon and the related phase shift. As seen in Fig. 37, the average shift of the pattern at the 3rd grating, and its random variation from the recoil of the emitted photons is much larger then the period of the interference pattern at the 3rd grating ($\sim 30 \mu m$ vs. 200 nm). This demonstrates that the momentum recoil by itself can not explain the loss of contrast (as it can in the diffraction experiments), but the path separation at the point of scattering and the phase shift imprinted by the entanglement in the scattering process must also be taken into account.

The classical recoil shift also allowed a second “recoherence” experiment by allowing the experimenters to infer the momentum of the scattered photon by measuring the atomic recoil. Interference contrast could be regained (Fig. 38) by selecting atoms within a reduced range of momentum transfer. The modern interpretation is that coherence lost to the environment because of entanglement can be regained by learning about the environment. Feynman might say: By restricting the momentum, the microscope could not use the full $4 \pi$ acceptance but only a much smaller numerical aperture. Consequently the maximum obtainable resolution would be degraded, no ‘which path’ information obtained, and the interference contrast thereby regained. This experiment demonstrated the importance of correlations between the recoil momentum and the phase of interference fringes.

These experiments nicely illustrate how the interaction with an environment causes decoherence through entanglement with the states of the environment. If an atom in the two-path interferometer, with the paths separated
FIG. 38 Relative contrast and phase shift of the interferometer as a function of $d$ for the cases in which atoms are correlated with photons scattered into a limited range of directions. The solid curves are calculated using the known collimator geometry, beam velocity, and momentum recoil distribution and are compared with the uncorrelated case (dashed curves). The upper inset shows atomic beam profiles at the third grating when the laser is off (thin line) and when the laser is on (thick line). The arrows indicate the third grating positions for cases I and II. The lower inset shows the acceptance of the detector for each case, compared to the original distribution (dotted line). (Chapman et al. 1995).

by $d$, scatters a photon the quantum state evolves into:

$$|\psi\rangle_i = \left(|x\rangle + |x+d\rangle \right) \otimes |e_0\rangle \xrightarrow{interaction} |x\rangle \otimes |e_x\rangle + |x+d\rangle \otimes |e_{x+d}\rangle,$$

(27)

where $|e_0\rangle$ is the initial wave function of the environment (photon) and $|e_x\rangle$ is the post-interaction wave function of the environment (photon) given an atom at position $x$.

If the environment is now observed to be in state $|e_x\rangle$, the (unnormalized) state of the atom becomes:

$$|\psi_x\rangle = |x\rangle + \beta(d)|x+d\rangle,$$

(28)

where

$$\beta(d) = \langle e_x|e_{x+d}\rangle.$$

(29)

If the two environment states are nearly identical then $|\beta(d)| \approx 1$; very little which-way information is available in the measured state of the environment, and the atom is left in nearly the original superposition. If $|\beta(d)| \ll 1$, significant which-way information about the atom has been left in the environment, and the atom is highly likely, with probability $(1 + |\beta(d)|^2)^{-1}$, to be found in state $|x\rangle$.

Whereas Equation [25] gives the atomic state conditioned on an observation of the environment, we often want to find the final quantum state of the atom when the environment is not observed. This requires averaging over all possible environment states, obtained by taking the trace of the atom+environment density matrix over environment degrees of freedom. Applied to the atom interferometer, this procedure results in a reduction of contrast by a factor $|\beta(d)|$ for every photon scattered, and can be directly applied to describe the results of the Feynman gedanken experiment (Chapman et al. 1995).

Focusing on the which-way information carried away by the scattered photons is not the only way decoherence may be understood. An alternative, but completely equivalent picture involves the phase shift between the two components of the atomic wave function. We switch to this viewpoint by using the translation operator for photon momentum states ($\hat{T}(\vec{x}) = e^{i\vec{k} \cdot \vec{x}}$) to identify that the environment states are related by

$$\langle k_f|e_{x+d}\rangle = \langle k_f|e^{i(\vec{k}_f - \vec{k}_i) \cdot \vec{d}}|e_x\rangle$$

(30)

where the momentum of the absorbed photon $\vec{k}_i$ was assumed to be precisely defined by the incident laser beam. Thus, if one were to measure the momentum of the scattered photon (to be $\vec{k}_f$) the atom would then be found in a superposition state with known phase shift between the two components of

$$\Delta \phi = (\vec{k}_f - \vec{k}_i) \cdot \vec{d}.$$

(31)

Interference fringe patterns for atoms with different recoil momentum kicks will then be slightly out of phase and the ensemble average - the measured interference pattern - will have a reduced contrast. This point of view is useful to calculate

$$\beta(d) = \langle e_x|e_{x+d}\rangle = \int d\vec{k}_f e^{i(\vec{k}_f - \vec{k}_i) \cdot \vec{d}} \langle k_f|e_x\rangle^2.$$

(32)

This is a scaled Fourier transform of the probability distribution $P(\Delta k)$.

We have discussed two views (which-way and dephasing) of the decoherence that accrues when an atom in an interferometer scatters photons. They correspond to two different ways to describe the scattered photon. (position basis vs. momentum basis). In these two cases, an observer in the environment can determine either which path the atom took, or else the phase shift of its fringe pattern. The key point is that when the experimenter is completely ignorant of the state of the scattered photons, whether an apparatus has been set up to measure
them or not, the “which-path” and phase diffusion pictures are equally valid ([Stern et al., 1990]). Both predict decoherence, i.e. loss of contrast.

Building upon the simple framework of the single-photon which-way experiment, we can easily derive the effect of continuous atom-light interaction involving many scattered photons. If successive scattering events are independent, the total decoherence function includes one factor of $\beta$ for each scattered photon (with probability $P_n$ of scattering $n$ photons). If the separation does not change ($d=$constant) one obtains a very simple relation:

$$\beta_{\text{total}}(d) = \sum_{n=0}^{\infty} P_n \beta(d)^n. \quad (33)$$

Even at small separations each successive photon scattering found in $|e_x\rangle$ ($|e_{x+d}\rangle$), will reduce by a small factor the probability that the atom is in state $|x+d\rangle$ ($|x\rangle$) until only one component of the superposition has any remaining amplitude; that is, until “complete” which-path information has been obtained.

This was nicely demonstrated in the experiment by [Kokorowski et al., 2001] studying scattering multiple photons from each atom inside the interferometer at a location where the separation is small compared to the light wavelength. The contrast vanishes as information about which path each atom took in the interferometer gradually becomes available in the photon field as a result of multiple scattering events. These experiments are also discussed in [Pritchard et al., 1998, 2001; Schmiedmayer et al., 1997] and extended to include two separated environments inside the interferometer by [Cronin et al., 2003].

Multiple photon scattering results in a Brownian motion of the phase of the atomic superposition and can be analyzed as phase diffusion. It leads again to an exponential decay of contrast as a function of time (i.e. the average number of scattered photons $\bar{n}$). Taking the specifics of the photon scattering process one finds, in perfect agreement with the experiment, a Gaussian loss of contrast as a function of the path separation $d$.

$$\frac{C}{C_0} = \langle e^{i\phi} \rangle = e^{-\bar{n} \sigma_k^2} \quad (34)$$

where, $\sigma_k$ is the RMS spread in momentum per scattered photon.

Contrast loss due to scattering multiple photons makes contact with more formal theories that describe the dynamics of open quantum systems. A modified Heisenberg equation of motion for the density matrix has been derived for various environments by [Caldeira and Leggett, 1983; Dekker, 1981; Gallis and Fleming, 1990; Gallis, 1993; Hornberger et al., 2004; Joos and Zeh, 1985; Omnes, 1997; Tegmark, 1993]. For example, an environment that causes the probability of scattering waves with wavelength $\lambda_{\text{eff}}$ in an infinitesimal time interval $dt$ to be $\Delta dt$ (where $\Lambda =$ Flux $\times$ cross section), makes the master equation

$$\frac{\partial \rho(x, x')}{\partial t} = -\frac{i}{\hbar} [H, \rho(x, x')] - \frac{\Lambda(x-x')^2}{\lambda_{\text{eff}}^2} \rho(x, x') \quad (35)$$

where the final term on the right causes a damping of the off-diagonal elements of $\rho$ with a rate expressed by

$$\rho(x, x'; t) \approx \rho(x, x'; 0) e^{-\frac{(x-x')^2}{2\lambda_{\text{eff}}^2}}. \quad (36)$$

Here $(x - x')$ denotes the separation of the superposition states in a general coordinate basis, and the diffusion constant $\Delta = \Lambda/\lambda_{\text{eff}}^2$ is also referred to as the localization rate ([Joos and Zeh, 1985]), or the decoherence rate (Tegmark, 1993). Values of decoherence rates are tabulated in ([Holland et al., 1996]; Joos and Zeh, 1985; Tegmark, 1993) for various systems and scattering environments. Comparing equations (34) and (36) allows one to discuss the localization rate caused by photon scattering for atoms in an interferometer.

5. Realization of Einstein’s recoiling slit experiment

To implement Bohr’s original design of Einstein’s recoiling slit Gedanken experiment, one needs a very light beam splitter, which shows quantum properties and will allow an experimenter to distinguish the two possible paths taken. In a Ramsey experiment, one would need to be able to distinguish the photons in the microwave or optical field used to change the state in the first interaction region. As discussed above, classical fields can not do the job. But if the splitting in the first interaction region is induced by a vacuum field, or a single photon field (more generally a field with a definite photon number) then measuring the field will determine if a transition has happened, and consequently infer the path the atom took.

In their seminal experiment [Bertet et al., 2001] implemented a Ramsey interferometer with Rydberg atoms where the first interaction zone is a high-Q cavity which allows the superposition between the $|e\rangle$ and $|g\rangle$ states to be created by the interaction with the vacuum field inside the cavity. This is the ultimate light beam splitter. After passing the interaction region, the atom-cavity system is in an entangled state described in the $|\text{atom}\rangle|\text{cavity}\rangle$ basis:

$$|e\rangle|0\rangle \rightarrow \frac{1}{\sqrt{2}} \left[ |e^\Phi e\rangle|0\rangle + |g\rangle|1\rangle \right], \quad (37)$$

where $\Phi$ is a phase difference between the two states after the interaction.

With this interaction the information about the state of the atom is left in the cavity field, and no interference contrast is observed when completing the Ramsey interferometer with a classical microwave pulse and state selective detection.
The interaction region creates the entangled state with the theoretical variation of the modulus of the beam-splitter final-states scalar product. (Bertet et al., 2001).

The cavity can also be filled with a very small coherent state $|\alpha\rangle$ with a mean photon number of a few ($\bar{n} = |\alpha|^2$). The interaction region creates the entangled state:

$$|\alpha\rangle|\alpha\rangle \rightarrow \frac{1}{\sqrt{2}}[|e\rangle \langle e|\alpha\rangle + |g\rangle \langle g|\alpha\rangle], \quad (38)$$

with

$$|\alpha_e\rangle = \sqrt{2} \sum_n C_n \cos(\Omega \sqrt{n + 1} t_o) |n\rangle \quad (39)$$

$$|\alpha_g\rangle = \sqrt{2} \sum_n C_n \cos(\Omega \sqrt{n + 1} t_o) |n + 1\rangle \quad (40)$$

where $t_o$ is an effective atom-cavity interaction time adjusted to give an equal superposition between $|g\rangle$ and $|e\rangle$.

The results of such an experiment are shown in Figure 39. When employing the lightest beam splitter, that is the vacuum state with $n=0$, the contrast in the Ramsey interferometer remains, and full contrast was observed. This is a beautiful illustration of an unconditional quantum-eraser experiment.

In a second part of their experiment (Bertet et al., 2001) employed the same field twice. Once as first interaction region, and again as second interaction region. In this case even for the vacuum field as a beam splitter no interference contrast is regained.

As our understanding of quantum mechanics deepens, and in particular, as we attempt to exploit quantum mechanics to create more sensitive quantum interferometers, quantum computers, or perfectly secure communication channels based on quantum entanglement, we encounter decoherence as a fundamental limit (Unruh, 1995). Progress relies therefore upon understanding and correcting for decoherence effects. Already our increased understanding of what decoherence means and how to control it has led to the development of quantum error correction codes (Calderbank and Shor, 1996, Shor, 1995, Steane, 1996) and quantum mechanical systems in which certain degrees of freedom are intrinsically decoherence-free (Lidar et al., 1998).

C. Origins of phase shifts

Phase shifts for interference fringes (see Section II. B. Equation 16) can be induced by photon scattering as discussed in the previous section (Eq 31), or by a variety of other causes such as 1. different potential energy for atoms in each path of the interferometer, 2. transverse or longitudinal forces on atoms, 3. inertial displacements such as rotating or accelerating the interferometer platform, and 4. geometric and topological phase shifts such as the Aharonov-Bohm, Aharonov-Casher, and Berry phase. In the following section we discuss the interrelationship between these types of phase shifts.

1. Dynamical phase shifts

Feynman’s path-integral formulation (Feynman and Hibbs, 1965, Storey and Cohen-Tannoudji, 1994) relates the wave function at $(x, t)$ to the wave function at $(x_0, t_0)$ by

$$\psi(x, t) = e^{-\frac{i}{\hbar} S_{\Gamma}} \psi(x_0, t_0) \quad (41)$$

where the classical action $S_{\Gamma}$ is defined in terms of the Lagrangian

$$S_{\Gamma} = \int_{\Gamma} L[\dot{x}, x] \, dt \quad (42)$$

and $L[\dot{x}, x]$ is the Lagrangian and $\Gamma$ is the classical path from $(x_0, t_0)$ to $(x, t)$. For potentials that are only a function of position, the wave function acquires a phase shift due to a potential $U(x)$ of

$$\phi_{\text{int}} = \int \left[ \sqrt{\frac{2m}{\hbar^2}} [E - U(x)] - \sqrt{\frac{2m}{\hbar^2}} E \right] \, dx. \quad (43)$$

This is analogous to light optics where the wave vector $k = n(x) k_0$ depends locally on the index of refraction, and the phase shift due to the index is

$$\phi = \int (k - k_0) \, dx. \quad (44)$$

To first order in $U/E$ the interaction phase shift (43) is

$$\phi_{\text{int}} \approx -\frac{1}{\hbar v} \int_{\Gamma} U(x) \, dl \quad (45)$$
where \( v \) is the particle’s velocity.

This brings up the question, ‘when does one measure a quantity described by classical physics like a deflection, and when does one measure a quantity only observable in an interference experiment?’. For example, applying a classical force, \( \vec{F} \), to change a particle’s motion is identical to applying a phase gradient to the matter wave. This is because force can be viewed as arising from a potential gradient \( \vec{F}(\vec{r}) = -\nabla U(\vec{r}) \), and in the same potential \( U(\vec{r}) \) a propagating matter wave will get a position-dependent phase shift which is exactly the one needed to account for the deflection. If there are two paths through the interferometer, then the fringe phase shift will be given by

\[
\Delta \phi_{\text{int}} = \phi_{\text{int1}} - \phi_{\text{int2}}.
\]

Thus, in a classical apparatus (as in a moiré deflectometer) or in an interferometer, forces cause a fringe shift that is identical to the classical deflection, which can be observed as an envelope shift (Oberthaler 	extit{et al.} 1996b; Zeilinger, 1980).

On the other hand, there are many cases where the fringe shift is different from the envelope shift. A basic example is a constant potential applied to one arm of an interferometer with separated beams. In this case there is no classical deflection, because neither atom (component) acquires a transverse phase gradient. Still, there is a different interaction phase \( \phi_{\text{int}} \) for one path through the interferometer because of the potential. For example, one interferometer path may traverse a capacitor such that the gradient in potential energy is along the atomic path.

In this case longitudinal phase gradients can be caused as atoms enter and exit the interaction region. For example, an attractive potential causes a classical force that first accelerates then decelerates the atom (component); If the potential is confined to one path through the interferometer then the affected atom component gets displaced ahead of the unperturbed atom component. Furthermore, if the longitudinal displacement between wave function components exceeds their coherence length, then contrast is lost. We prefer to call this ‘inhomogeneous broadening’ (as opposed to decoherence) because the phase shift is correlated (entangled) with the atom’s own longitudinal velocity.

Another interesting case arises when one applies a time-dependent potential to one arm of the interferometer so the atom never sees a gradient in space. An example is the scalar Aharonov Bohm effect. Then there will be no change in the classical motion and the envelope of the atomic probability distribution will remain stationary as high-contrast fringes (there is no velocity dispersion) shift underneath. A similar situation arises when purely topological phases are involved. In these cases the full quantum mechanical properties of an interferometer are in evidence.

2. Aharonov-Bohm and Aharonov-Casher effects

We call a phase shift \( \Delta \phi_{\text{int}} \) topological if it neither depends on the incident \( k \)-vector (velocity) of the interfering particle nor on the shape of the particle’s path through the interferometer. Topological phases are characteristic of all gauge theories, and are related to a singularity enclosed by the interferometer paths.

The most widely known topological phase was described by Aharonov and Bohm (1959) for a charged particle passing on either side of a solenoid. A related effect was described by Aharonov and Casher (1984) for a magnetic dipole encircling a line of charge. To realize a general framework for the discussion of the quantum interaction between sources and fields we consider Fig. [40] If an electric charge \( q_e \) circulates around a magnetic dipole \( d_m \) (or vice versa) then a quantum phase arises (Aharonov and Casher, 1984). Particular configurations of sources can give a variety of contributions. For example, a cylinder filled with aligned magnetic dipoles is equivalent to a solenoid, and creates a homogeneous magnetic field inside the cylinder but zero magnetic field outside. When an electric charge travels around the cylinder it acquires a phase due to the Aharonov-Bohm effect. On the other hand, if a cylinder is filled with electric charges, then a magnetic dipole circulating around it will obtain a quantum phase due to the Aharonov-Casher effect. This can be generalized to the case of a magnetic dipole moving in the presence of a gradient of electric field.

Employing electromagnetic (EM) duality it is possible to obtain a series of similar phenomena. While the charge dual is the magnetic monopole, \( q_m \), which has never been observed, the dual of the dipoles are well defined. The interactions between an electric dipole, \( d_e \), and a monopole (or a monopole-like field) have been extensively studied in the literature (Casella, 1990; Dowling 	extit{et al.} 1999; He and McKellar, 1993; Spavieri, 1999, 2006; Wilkens, 1994). This can also be equivalently viewed as the interactions of an electric dipole, \( d_e \), with an inhomogeneous magnetic field. It should be understood that this categorization, instructive as it may be, is not unique nor exhaustive, e.g. quadrupole interactions have not been considered.

The Aharonov-Bohm phase shift is

\[
\Delta \phi_{AB} = \frac{q_e}{\hbar} \oint A \cdot ds
\]

where \( A \) is the vector potential that represents the fields. The Aharonov-Casher effect causes a phase shift

\[
\Delta \phi_{AC} = \frac{1}{\hbar c^2} \oint d_m \times E \cdot dr
\]

where \( d_m \) is the magnetic dipole.

The Aharonov-Casher effect was observed with neutron interferometers (Cimmino 	extit{et al.}, 1989) using the original geometry proposed by Aharonov and Casher (1984), and the phase shift was 2.19 mrad. With TIF
molecules the Aharonov-Casher effect has been observed using a geometry where components of each molecule with different spin states occupy the same center of mass location (Sangster et al., 1993, 1995). This alternative geometry for the Aharonov-Casher effect, in which the magnetic dipoles are placed in a superposition of spin orientations (but not a superposition of center of mass positions) was described by Casella (1990). The two different geometries are summarized in Figure 11. With molecules possessing a nuclear magnetic moment the phase shift was only 3 mrad. Still, this was sufficient to verify the predicted linear dependence on the electric field and independence of particle velocity. Atomic sized magnetic moments were used by Gorlitz et al. (1995) to demonstrate a much larger Aharonov-Casher phase shift of 300 mrad using Rb atoms. An A-C phase of 150 mrad was observed by Yanagimachi et al. (2002) using Ca atoms, and related measurements are found in Zeiske et al. (1994, 1995).

The AC phase is a restricted topological phase because although the phase is independent of the speed $|v|$ and the size of the interferometer loop, the phase does depend on whether $d_m$ is perpendicular to both $v$ and $E$. Debate over the topological nature of the AC effect has stimulated several discussions, among them Aharonov et al. (1988), Boyer (1987), Han and Koh (1992), Lee (2001), Zeilinger et al. (1991). The similarity between the AC and AB effects has also been discussed in detail by Hagen (1996), Oh et al. (1994). One controversy arose over the question of whether or not a sufficiently large AC phase can lead to decoherence. This position was suggested by Boyer (1987) since the AC effect can be explained in terms of a classical force due to a motion-induced magnetic field in the rest frame of the magnetic dipole. However, as was shown in Zeilinger et al. (1991), since the classical force depends on velocity a wave packet envelope does not get shifted; i.e. $\partial \phi_{AC}/\partial k_{AB} = 0$. The AC effect and AB effect both shift the phase of the wave function, but do not displace the wave packet envelope (a common mis-impression, e.g. see Figs 15-7 and 15-8 of the Feynman et al. (1965) Lectures in Physics Vol II).

The scalar Aharonov-Bohm effect (SAB) for neutral particles is a topological phase that can arise from pulsed magnetic fields interacting with an atomic magnetic dipole. This has been observed by Aoki et al. (2003), Muller et al. (1993), Shinohara et al. (2002) with atoms, and by Allman et al. (1992), Badurek et al. (1993) with neutrons. It is similar in spirit to the interaction discussed in the original paper (Aharonov and Bohm, 1959) for electrons interacting with the scalar electrostatic potential.

The electromagnetic dual of the AC effect, in which an electric dipole moment moves near a line of magnetic monopoles (an idealized picture of an experiment) was investigated theoretically by Wilkens (1994). The phase shift for polarizable particles moving in both electric and magnetic fields has been also discussed by Anandan (1989, 2000), Audretsch and Skarzinsky (1998), Shevchenko (1995). Furthermore, in the case that permanent electric dipole moments are used, the electromagnetic dual to the AC effect can be used to settle any controversy regarding how the topological nature of the AC effect depends on the dipole moment being intrinsic and therefore having quantum fluctuations (Lee, 2001).

3. Berry phase

Phase effects resulting from parallel transport associated with adiabatic evolution (Berry phase) can also be topological. Berry (1984) showed that a quantum system in an eigen-state that is slowly transported round a circuit by varying parameters $R$ in its Hamiltonian $H(R)$ will acquire a geometrical phase factor in addition to the
The Berry phase can be studied with many systems in physics. It has been observed with light in a coiled optical fiber (Chiao and Wu, 1986), neutron interferometers (Bitter and Dubbers, 1987), nuclear magnetic resonance experiments (Suter et al., 1987), nuclear quadrupole resonance experiments (Tervo, 1987), and also mesoscopic electronic systems (Yau et al., 2002). Phase shifts due to non-adiabatic circuits (Aharonov and Anandan, 1987), incomplete circuits (Samuel and Bhandari, 1988), particles in mixed states (Sjoqvist et al., 2000), and particles moving relativistically have also been studied theoretically. For an overview on geometric phases see (Anandan et al., 1997, Wilczek and Shapere, 1989).

An observation of a Berry phase in atoms in an interferometer for the polarization states (internal states) is described in (Commins, 1991). The first observation of a Berry phase in an external state atom interferometer was accomplished by (Miniatura et al., 1992) with a Stern Gerlach longitudinal interferometer. However in this experiment the Berry phase was somewhat obscured because the dynamics were not adiabatic. A Berry phase up to $2\pi$ radians due to an atomic state interacting with a laser field was observed by (Webb et al., 1999). This verified the spin dependence of the Berry phase, and realized an "achromatic phase plate for atomic interferometry" as suggested by (Olshanii, 1994, Reich et al., 1993). A Berry phase shift for partial cycles using a time domain atom interferometer was measured by (Yasuhara et al., 2005) (see Fig. 42).

4. Inertial displacements

Atom interferometers are impressively sensitive to acceleration and rotation because the long transit times allow gravity and fictitious forces due to rotation and acceleration to build up significant displacements of the interference pattern, which directly influence the measured phase (introduced in Section III Equation 15). These are discussed fully in Section V on precision measurements.

D. Extended Coherence and BEC’s

Bose Einstein Condensates of atomic gases are very bright sources for atom optics and atom interferometers. Additionally in a gas cooled below $T_c$, a significant fraction of the atoms are in the condensate, which occupies the lowest translational state of the trap. Typical BEC’s offer a million atoms confined in a cigar shaped sample 100 microns long and 10 microns across, with coherence lengths of the same size, and relative velocities around 0.1 mm/sec. A BEC with its coherence properties (and brightness) constitutes a source analogous to a laser, whereas the traditional thermal atom sources are analogous to thermal sources such as candles or light bulbs in optics.

This ideal source is hindered by the fact that atoms interact which leads to a mean field interactions (chemical potential). A typical condensate would have density $10^{14}$/cm$^3$ with associated mean field energy of $\sim 1$ kHz$(\times h)$, much larger then the ground state energy of the trap. If the trap is turned off, and the BEC released, this mean field energy dominates the expansion and the condensate atoms will separate with several mm/sec relative velocity regardless of how small the RMS velocity was inside the trap. Nevertheless the resulting momentum spread is still an order of magnitude smaller than the recoil velocity from a resonant photon. It is therefore easy to separate the momentum states differing by a photon momentum in atom interferometers based on BEC’s as discussed in section III. (e.g. see Fig. 22).

Atom interferometers now offer a powerful tool to study the properties of a Bose Einstein Condensate.

1. Atom Lasers

Early theoretical studies (Bagnato et al., 1987; Moerdijk and Verhaar, 1994; Stoof, 1991) showed that making a BEC in a trap is easier than making it in free space because the critical density had to be reached only at the bottom of the trap. They showed that the perturbation of the transition temperature and critical number density due to the s-wave scattering of the atoms was less than 1%, encouraging the then-prevalent view...
that the condensate is well described as a blob of very cold atoms. This suggested making a laser like beam of ultra cold atoms simply by extracting the atoms from the condensate - such a beam would have an incredibly low temperature, be almost monochromatic, and have an unprecedented brightness (albeit over a very small cross sectional area with limited total flux).

Early realizations of atom lasers coupled atoms out from a condensate with radio frequency (rf) pulses, rf chirps, Raman pulses, or weak cw rf radiation [Bloch et al., 1999; Hagley et al., 1999; Mewes et al., 1997]. For discussions also see [Holland et al., 1996a; Kleppner, 1997]. The out-coupled atoms have energy given by the out-coupling process plus the mean field energy they gain when emerging from the condensate. In addition, they are accelerated by gravity and any additional potential gradient. The out-coupling frequency can be adjusted as the condensate number changes, to account for the changing chemical potential. Moreover, the number of atoms extractable from the condensate is not limited because the condensate can be recharged (Chikkatur et al., 2002) to produce a continuous atom laser beam. Although a continuous atom laser is yet to be demonstrated.

In principle, the output from this type of atom laser can have a greater coherence length than the condensate simply because it has the coherence time of the condensate and is traveling. Using a stable BEC as a phase reference could enable feedback to perfectly compensate the changes in chemical potential. So far, however, coherence lengths of atom lasers have not exceeded the size of the condensate.

Phase coherent matter wave amplification, in direct analogy to laser gain, has been demonstrated [Inouye et al., 1998; Kozuma et al., 1998] and discussed early on by [Bordé, 1995; Holland et al., 1996a; Janicke and Wilkens, 1996].

2. Studies of BEC wavefunctions

In the simplest picture of a BEC, all atoms in the condensate occupy the quantum ground state of the trap. This wave function is modified by the mean field interaction of the atoms. As more atoms accumulate in the condensate, their mutual interaction modifies the condensate wave function. For repulsive interactions the condensate wave function broadens at the expense of increased potential energy from the trap in order to minimize the mean field energy. Each atom in the condensate is coherent across the whole condensate and a double slit experiment in either space or time should show interference fringes.

More sophisticated treatments of atoms cooled below the BEC transition temperature show that they can exist in states called quasi-condensates that have short range coherence, but not long range coherence over the whole condensate. Whether BEC’s have long range coherence was studied in interference experiments on BEC’s, which we now discuss.

Bragg diffraction offers high momentum selectivity. As discussed in Section II.C.3, the spread in velocity of atoms that can be diffracted (σ_v) is determined by the inverse duration of interaction with the grating, and can be deduced from the time-energy uncertainty principle, σ_v = 2/(τG). Near-resonant moving standing waves therefore probe a specific velocity class, creating a high-resolution tool for studying BEC velocity distribution. By increasing the interaction time to nearly 1 ms, (Stenger et al., 1999) at MIT achieved a velocity selectivity of 0.1 mm/sec, which allowed to study the momentum distribution inside the trap and in a released condensate Fig. 43 demonstrating the mean field acceleration. The coherence length was equal to the transverse dimension of the condensate (see Fig. 43 inset).

A similar conclusion was reached independently by Kozuma et al. (1999b) at NIST using an atom interferometry technique in which KD out-coupled atom pulses were applied at two closely spaced times. Each ejected pulse mirrors the condensate itself, so when the front of the second overlapped the back of the first the interference observed was indicative of coherence between two spatially separated places in the condensate. The decay of the fringe envelope was as expected for a fully coherent condensate.

Experiments studying the coherence of atom laser beams were carried out by [Bloch et al., 2000] in T. Hänsch’s lab in Munich. Two atom laser beams coupled out from different locations of the trap were overlapped to interfere. By changing the separation of the out coupling locations, and observing the contrast of the interference between the two out coupled beams they probed the co-
The coherence properties of the condensate wave function on length scales approaching 1 micron (Figure 44). Measurement of the temporal coherence of an atom laser has also been used to give an upper limit for temporal phase fluctuations corresponding to $\sim 700$ Hz in the Bose-Einstein condensate (Kohl et al., 2001). In a related experiment, Anderson and Kasevich (1998) observed interference of atoms from an array of BEC's trapped in an optical lattice. The interference between the BEC's at different gravitational potential leads to a pulsed atom laser beam. Since many sources contribute, the pulses are much shorter than the separation between them, reminiscent of a mode-locked pulsed laser.

3. Many particle coherence in BEC's

The above experiments can all be viewed as looking at single particle coherence. BEC's have an even more dramatic coherence than the extended condensate wave function just discussed. The atoms in the condensate are in one macroscopic state with an order parameter, the phase. Consequently the phase of one condensate atom is the phase of all. Therefore, a condensate also exhibits coherence properties resulting from the interference of different (but indistinguishable) atoms. This gives it coherence properties like a laser: if the phase is determined by measuring some of the atoms, other atoms will have the same phase.

Measuring the phase of condensate atoms requires a coherent and stable reference. Such a reference can be provided by another condensate, or by other atoms from the same condensate. This is in marked contrast to traditional atom interference discussed up to now, where interference is only that of each atom with itself. The BEC experiments using Bragg scattering discussed above demonstrate only the spatial coherence of individual atoms in a BEC. We now turn to experiments that show the coherence of different atoms in a BEC.

The existence of a macroscopic wave functions with an order parameter means that atoms from different sources can interfere. If an atom from one interferes with an atom from the other, subsequent atom pairs will interfere with the same relative phase and fringes will be built up which reflect the relative phase. This is similar to interference between two independent lasers (Castin and Dalibard, 1997; Kaltenbaek et al., 2006; Paul, 1986; Pfleegor and Mandel, 1967), which also generated controversy prior to its observation.

The first experiment demonstrating this striking behavior was by Andrews et al. (1997) in the Ketterle group at MIT. To demonstrate that two independent BEC's can interfere, two independent condensates were produced in a double-trap potential created by dividing a magnetic trap in half with a focused blue-detuned laser beam. After two BEC’s were created from separate thermal clouds, the traps were switched off. The atom clouds expanded ballistically and overlapped.

The atomic density in the overlap region was observed directly with absorption imaging, and revealed a high contrast interference pattern extending over a large region of space (Fig. 45). The interference pattern consisted of straight lines with a spacing of about 15 $\mu$m. This experiment provided direct evidence for first-order coherence and a macroscopic wave function with long
FIG. 46 Comparison of independent and coherently split BEC’s. (a) For the coherent splitting a BEC is produced in the single well, which is then deformed to a double well. A narrow phase distribution is observed for many repetitions of an interference experiment between these two matter waves, showing that there is a deterministic phase evolution during the splitting. (b) To produce two independent BEC’s, the double well is formed while the atomic sample is thermal. Condensation is then achieved by evaporative cooling in the dressed state potential. The observed relative phase between the two BEC’s is completely random, as expected for two independent matter waves (Hofferberth et al., 2006).

range order in the BEC, and caused some to puzzle over why wave packets expanding radially outwards from two small condensates would produce straight fringes.

In a related atom chip experiment (Hofferberth et al., 2006) compared the interference of a coherently split BEC with the interference of two independently created BEC’s in identical traps (Fig. 46). The coherently split BEC shows a well-defined phase, i.e. the same phase for the fringes each time the experiment is run. In comparison, the independently formed BEC’s show high contrast interference patterns but with a completely random phase.

These results are even more surprising than the interference of independent lasers. Theories describing laser sources predict something close to coherent states (for lasers operated well above threshold), which means that each laser beam may be thought of as having a well defined (if unknown) phase. One cannot, however, assert that the phase of a BEC exists prior to its observation. This is because a BEC at T=0 can easily contain a known number of atoms (however many were put in the trap), in which case number-phase uncertainty prevents the phase from being specified. So the existence of a well defined relative phase, and hence fringes in the overlap region seems puzzling.

The resolution to this puzzle is that the phase of the fringes (i.e. the relative phase of the condensates) emerges only as individual atoms are detected in the overlap region (Castin and Dalibard, 1997). Since these atoms cannot be attributed to a particular one of the interfering condensates, an uncertainty develops in the relative number of atoms in the condensates, and in accord with the relative number-phase uncertainty principle, they can have a definite relative phase (even though the total number of atoms in both condensates plus those detected is known). Given that neither the phase of either condensate nor their relative phase existed initially, it should not be surprising that the fringes in each realization of the experiment are observed in a different place. After averaging over many realizations of this experiment, the fringe contrast vanishes because the relative phase of each realization is random.

Even when many independent condensates interfere, spontaneous fringes appear. Hadzibabic et al. (2004) observed high-contrast matter wave interference between 30 Bose-Einstein condensates produced in a large-period one-dimensional optical lattice. Interference was studied by releasing the condensates and allowing them to overlap. High contrast fringes were observed even for independent condensates with uncorrelated phases as shown in Figure 47. This can be explained the same way as the high-contrast speckles formed by laser light reflecting off a diffuser. However, as in the work with two independent condensates, averaging over many realizations of the experiment causes fringe contrast to vanish because the phase is random from shot to shot.
4. Coupling two BEC’s with light

Saba et al. (2005) have demonstrated a way to make an interferometer using two BEC’s that are never in direct contact and which are separately trapped at all times. The key is to use stimulated light scattering to continuously sample the relative phase of the two spatially separated BEC’s. In fact this sampling creates a relative phase between the two condensates which in the beginning had no initial phase relation.

The basis of the measurement is the beating of two atom lasers out coupled from the two condensates by imparting a momentum $\hbar q$. If the relative phase of the condensates is fixed, the total number of out coupled atoms oscillates sinusoidally with periodicity $\hbar/d$ as $\hbar q$ is scanned ($d$ is the separation of the condensates). The experimental tool used to impart a precise momentum to atoms is Bragg scattering. Two counter-propagating laser beams with wave vectors $k_1, k_2$ hit the atoms so that, by absorbing a photon from one beam and re-emitting it into the other one, the atoms acquire recoil momentum $\hbar q = \hbar(k_2 - k_1)$ (provided that the energy difference between photons matches the atom recoil energy).

For each atom out-coupled, a photon is transferred from one beam to the counter-propagating one. Therefore, all information contained in the stream of out-coupled atoms is also present in the light scattered from one beam to the other. Relative phase data were gathered in real time by monitoring the intensity of the weaker of the Bragg laser beams, instead of terminating the experiment to measure the out-coupled atoms using absorption imaging.

Since the relative phase of the condensates can be measured after scattering only a small fraction of the atoms out of the condensates, this technique gives a relatively nondestructive measurement of the relative phase. This technique therefore allows one to prepare an initial relative phase (by an initial measurement) of the separated condensates, then to read it out continuously, and thereby to monitor the phase evolution. This way one can realize interferometry between two trapped Bose-Einstein condensates without ever splitting or recombining the wavefunction. The condensates can’t be too far apart, however, as the relative atom number uncertainty cannot arise until the atoms out-coupled from the first condensate have time to reach the second atom laser beam and create a downstream atom laser whose atoms could have arisen from either condensate. (In fact, when the atom laser beams interfere destructively, the Bragg beams operating on the second condensate effectively capture atoms from the first atom laser beam and insert them in the second condensate!) The necessity for this process to have occurred dictates the temporal delay of the buildup of the light fringes in part A of Fig. 48, it takes about 250 $\mu$sec for atoms to make this trip.

This atom interferometer, featuring interference between always-separated ensembles of interacting atoms is several significant steps away from the prototypical interferometer in which uncorrelated non-interacting individual atoms traverse one at a time. In fact it resembles a gedankenexperiment involving two high Q L-C circuits resonant with the ac power source in the lab. Suppose these are both plugged in to different power outlets for a while, then disconnected. If some time later these are attached to the reference and signal ports of a phase detector, it will read a definite phase. Moreover, this phase will be reproducible shot to shot. If one of the L-C circuits is somehow perturbed, then the phase shift will be systematically modified. Does this situation, involving classical L-C circuits constitute an interferometer, or just classical fields interfering??

In fact it is almost perfectly analogous to the experiment just described, with the roles of matter and E&M waves reversed. The L-C resonant circuits are classical containers containing coherent states of low frequency photons; the light traps are classical containers containing coherent states of atoms. In either case phase shifts
can be caused by interactions with the container (squeezing one of the L-C circuit components or light traps), or by interactions with the quantized medium within (e.g. by non-linear circuit elements added to the L-C circuit or by a magnetic field that interacts with the BEC). The initial coherence is induced by the exchange of photons with the coherent source provided by the power generation station in one case, and by the mutual exchange of atoms in the other. There is a significant interaction among the atoms in the BEC, whereas the Kerr effect for L-C circuits is small, but this is not fundamental. Neither the L-C circuits nor the light wells are interfering, both function as classical containers for \textit{waves} that are phased together. The waves undergo differential interactions, and interfere later to produce a measurable phase shift. Ideally this is solely a measure of the interaction, but in practice small differences between the two containers cause detrimental phase shifts.

E. Studies with and of BEC’s

Up to now we have reviewed experiments and theories pertaining to the coherence of BECs. Now we shift perspective and consider them as interesting condensed objects in their own right. Some of the earliest work that showed this was the study of the frequencies of the shape oscillations of the condensate. In this section we review experiments that were made using the techniques and ideas of atom optics and interferometry and that allow one to address other properties of BECs. In order, we will review the coupling of two BECs to mimic the physics of Josephson junctions, their intrinsic decoherence, and two experiments that probe their structure.

1. Josephson oscillations

As shown by Smerzi \textit{et al.} (1997), two trapped BEC’s that are weakly coupled (i.e. by tunneling through the barrier) are represented by a generalization of the equations that apply to a Josephson junction. The analog is that the sine of the phase difference causes a current flow between the traps that changes the number difference (and hence the potential difference that drives the phase change). Given two trapped BEC’s, by adjusting the tunneling rate (i.e. the coupling strength between the two BEC’s), Josephson oscillations between two weakly linked Bose Einstein condensates can be studied.

The experiments of Albiez \textit{et al.} (2005) demonstrate both the nonlinear generalization of tunneling oscillations in Josephson junctions for small population imbalance \(z\), and non linear macroscopic quantum self-trapping for large population imbalance. The distinction between the two regimes is very apparent in the phase-plane portrait of the dynamical variables \(z\) and \(\Phi\) as shown in Figure 49. The successful experimental realization of weakly coupled Bose-Einstein condensates adds a new tool to both condensed matter physics and to quantum optics with interacting matter waves. In particular, we have to realize that the beamsplitting (and also the recombination if done at high density) of two BECs must be discussed in terms of the Josephson effect, or possibly its generalization.

A detailed study of the phase noise in the interference patterns, allowed Gati \textit{et al.} (2006a,b) to measure the temperature of the tunnel coupled BEC’s. Further examples of tunneling were investigated with BEC’s trapped in optical lattices by Anderson and Kasevich (1998); Orzel \textit{et al.} (2001) in M. Kasevich’s Lab and by Cataliotti \textit{et al.} (2001, 2003) in Florence.

2. Spontaneous decoherence and number squeezing

BECs have an intrinsic decoherence due to fluctuations in the number of atoms they contain. If a BEC is prepared in a number (Fock) state, its phase is indeterminate. If its phase is determined, for example by placing the BEC in a coherent state, then it must be in a superposition of states with different atom number. (For example, a coherent state is a (coherent) superposition of states with different number, with rms variation \(\sqrt{N}\).)

Since the mean field energy of a trapped BEC increases with \(N \sim N^{2/5}\) in a harmonic trap), this means the different components have different energy, evolve at a different rate, and get out of phase. The time for this to happen is typically 25 to 50 ms, severely limiting the accuracy of BEC interferometers.

Even if a BEC interferometer starts with a definite number of atoms in the central well, the \(\sqrt{N}\) projection noise at the beam splitter, translates into fluctuations of the chemical potential which results in fluctuations in the accumulated phase of the interferometer and conse-

![Image](49)(color online) Josephson oscillations. (a) Small population imbalance causes Josephson oscillations, and large population imbalance causes self-trapping. (b) Quantum phase-plane portrait for the bosonic Josephson junction. In the regime of Josephson oscillations the experimental data are represented with filled circles and in the self-trapping regime with open circles. The shaded region, which indicates the Josephson regime, and the solid lines are obtained by solving the coupled differential with the specific experimental parameters. Figure from \textit{Albiez et al.} (2005)
quently in a rapid dephasing of the split BEC. The phase diffusion rate can then be estimated by:

\[ R_\phi = \frac{1}{\hbar} \frac{d\mu}{dN} \Delta N, \tag{49} \]

where \( N \) is the number of Atoms in the BEC, \( \mu \) its chemical potential. With the chemical potential \( \mu \) larger then the trapping frequency \( \omega \) (\( \mu > \hbar \omega \)) for trapped atoms after typically a few transverse trapping times the phase is random and the coherence is lost. This phase diffusion caused by the interactions between the atoms puts stringent limits on the persistence of coherence in a BEC interferometer.

This interaction-induced dephasing can be reduced in different ways:

- Reduce the effect of interactions by tuning the scattering length with a Feshbach resonance. This may permit setting the scattering length to zero. This requires precise control over the magnetic field, and may limit the number of atoms used in the experiments since the mean field repulsion is proportional to the scattering length and hence the ground state condensate will no longer be spread out.

- If the method of light scattering described above to measure the phase evolution of the two condensates is applied to two initially number-squeezed condensates (e.g. if a large condensate were separated adiabatically), it will add differential number uncertainty only in proportion to how well the phase is determined.

- If the splitting is performed adiabatically, the repulsive interaction itself will tend to equalize the chemical potentials of the splitting condensates. Thus the relative atom number distribution will be reduced if the splitting is performed slowly. This will reduce the relative phase diffusion rate of the initial condensates at the cost of an increased uncertainty in the initial phase, but this can be increased to the measurement noise level without penalty. For interferometers using large condensates this can lead to significant increases in their sensitivity and applicability.

In fact, dramatic observations of number squeezing have already been made. Squeezing between atoms trapped in arrays of traps was observed by Orzel et al. (2001). Recently Jo et al. (2007) observed a dramatically reduced phase diffusion in a trapped BEC split with an RF splitter on an atom chip.

3. Structure studies of BEC

According to theory, a BEC possesses collective modes (e.g. sound waves) due to the interactions of the atoms.

In a quantum many-particle description, it’s dispersion relation has the Bogoliubov form

\[ \nu = \sqrt{n^2 + 2n \omega \mu \hbar}, \tag{50} \]

where \( \mu = 4a \hbar^2 a/m \) is the chemical potential, with \( a \) and \( m \) denoting the scattering length and the mass, respectively, \( n \) is the density of the condensate, and \( \hbar n = q^2/2m \) is the free particle dispersion relation. (Ozeri et al., 2003; Stamper-Kurn et al., 2001).

In a typical Rb or Na condensate, \( \mu/\hbar \) is about a kHz, corresponding to speeds of \( \sim \)cm/sec or less. The Bragg Spectroscopy discussed previously generates atoms with several times this speed, which therefore have nearly their free-particle dispersion relation (the mean field energy term being negligible). However, by reducing the angle of the Bragg beams from 180 to much smaller angles, the transferred momentum was correspondingly reduced, and many fewer atoms are liberated from the condensate (i.e. the static structure factor is no longer unity), and the frequency shift relative to a free particle follows Eq. Studies of BEC structure are in (Katz et al., 2004; Steinhauer et al., 2002), and theory for these measurements is discussed by Blakie and Ballagh (2000; Carusotto et al., 2000).

Physics which goes deeper into the properties of degenerate quantum gases and their coherence properties is outside the purview of this review, so we refer the reader to a series of excellent reviews in the literature which summarize the status of this still very fast moving field (Cornell and Wieman, 2002; Dalfovo et al., 1999; Kasevich, 2002; Ketterle, 2002).

4. Dynamics of coherence in 1-D systems

Interference allows to study the dynamics of (de)coherence in degenerate Bose gases. This is especially interesting in the one-dimensional (1D) regime where long-range order is prevented by the ubiquitous phase-fluctuations.
In their experiments Hofferberth et al. (2007a) coherently split a 1d quasi-condensate, characterized by both the temperature $T$ and chemical potential $\mu$ fulfilling $k_B T, \mu < h\nu_\perp$, along the transverse direction which initializes the system in a mutually phase coherent state, and phase fluctuation patterns of the two individual 1d systems being identical. This highly non-equilibrium state relaxes to equilibrium over time and the evolution of (de) coherence is revealed in local phase shifts leading to increased waviness of the interference pattern (Figure 50).

If the two parts of the system are completely separated, the equilibrium state consists of two uncorrelated quasi-condensates and Hofferberth et al. (2007a) observe a randomization of the relative phase $\theta(z,t)$ as expressed in the coherence factor $\Psi(t) = \frac{1}{2} \int dz e^{i\theta(z,t)}$. Most interestingly $\Psi(t)$ decays sub exponential $\Psi(t) \propto e^{-(t/t_0)^{2/3}}$ as predicted by Burkov et al. (2007) based on a Luttinger liquid approach (Haldane, 1981). Qualitatively similar behavior was recently observed at MIT (Jo et al., 2007) for elongated condensates with $\mu \sim 2h\nu_\perp$ and $T \sim 5h\nu_\perp$.

For finite tunnel coupling between the two systems, Hofferberth et al. (2007a) observe that the final equilibrium state shows a non-random phase distribution (Figure 50 (bottom)). The phase randomization is counterbalanced by the coherent particle exchange between the two fractions, equivalent to injection locking of two matter wave lasers. The final width of the observed phase spread depends on the strength of the tunnel coupling (Gati et al., 2006).}

5. Measuring noise by interference

In many-body systems quantum noise can reveal the non-local correlations of underlying many-body states Altman et al. (2004). Recently it has been suggested that the statistics of the shot to shot fluctuations in fringe contrast probe higher order correlation functions Gritsev et al. (2006), Polkovnikov et al. (2006).

This rational was used by Hofferberth et al. (2007b) in an experiment investigating the statistical properties of interference experiments performed with pairs of independently created one-dimensional atomic condensates Hofferberth et al. (2006). The shot-to-shot variations of interference can then be directly related to the full distribution functions of noise in the system Polkovnikov et al. (2006). Probing different system sizes they observe the crossover from quantum noise to thermal noise, reflected in a characteristic change in the distribution functions from Gumbel-type to Poissonian.

The results are in excellent agreement with the predictions of Gritsev et al. (2006) based on the Luttinger liquid formalism (Haldane, 1981).

These experiments demonstrate the power of quantum noise analysis in interference patterns as a probe of correlated systems, and the power of simple ultra cold atom systems to exhibit and illustrate fundamental quantum processes relevant in many areas of physics.

6. Momentum of a photon in a medium

The momentum of a photon propagating in a medium is a topic fraught with controversy. When an electromagnetic wave enters a medium with index of refraction $n$, its wavelength is reduced, and its wavenumber is increased, by $n$. Thus it seems evident that a single photon in this medium would have momentum $p = nh\nu_{\text{vac}}$, a conclusion reached by Minkowski (1908), Minkowski (1910) using classical physics. On the other hand, if the photon is considered as a particle, it seems very strange that it should increase its momentum when entering a medium in which its speed is reduced! Such a viewpoint is supported by Abrahams (1909) who found $p = \hbar k_{\text{vac}}/n$. Resolving these two viewpoints has been cited as one of the challenges of theoretical physics (Peierls, 1991).

When a photon propagating in an atomic gas is absorbed by one of the atoms in the BEC, what is the momentum of the atom after the absorption? This question seems less subject to uncertainty since it can be settled by a measurement; it is also important in precision experiments to measure $h/n$ that will be discussed in the next Section. For a dilute atomic gas, a third opinion seems justified: a BEC has only a few atoms per cubic wave-
The variation near the resonance, consistent with that predicted from the resonance. The results showed marked structure of the resonance. The dashed line shows expected result for free atoms, solid line corrects for chemical potential assuming \( p = \hbar k_{\text{vac}} \). Solid line with error shading shows expectation if \( p = n\hbar k_{\text{vac}} \).

\[
\phi = \frac{(q_p + q_e) Z \mathcal{E} \Delta x L}{v \hbar} \approx 10^{-4} \text{rad}
\]

where we have assumed \( Z = 55 \) is atomic number, \( \mathcal{E} = 10 \text{kV/mm} \) is the applied field, \( \Delta x = 100 \mu\text{m} \) is the separation of the paths in the interferometer, \( L \) is the length of the interaction region, and \( v = 100 \text{ m/s} \) is the atomic velocity. [Champenois et al. 2001b] and [Dehuille et al. 2001] studied this. The main difficulty will come from the electric polarizability of atoms which will cause large phase-shifts due to field gradients. But because these phase-shifts are quadratic in the applied electric field while the proposed effect is linear, these stray phase-shifts should mainly limit sensitivity.

V. PRECISION MEASUREMENTS

Since their demonstration in 1991, atom interferometers have become precision measurements tools. The advantages of small de Broglie wavelengths, long propagation times, and the narrow frequency response of atoms are responsible for atom interferometers already having made an impact on many fields of fundamental science and engineering. In the present section, we discuss measurements of acceleration, platform rotation, the Molar Planck constant \((N_A \times \hbar)\) and the fine structure constant \( (\alpha) \). Although some of the measurements of atomic and molecular properties are precision measurements by the standards of those fields, they will all be discussed in Section VI.

A. Gravimeters, Gyroscopes, Gradiometers

Inertial sensors based on atom interferometers already perform comparably to the best available sensors based on any technology. At their current levels of resolution summarized in Table II several interesting applications are within reach. In fact, development has begun for commercial sensors and commercial applications using atom interferometers. To explore the precision, resolution, accuracy, response factor, bandwidth, dynamic range, and stability achievable with atom interferometers we begin by looking at the different designs used for gravimeters, gyroscopes, and gravity gradiometers.

Thermal atom beams for rotation, freely falling atoms for acceleration, and two clouds of falling atoms with a common laser beam for the gradiometer have given the best results to date. This is in part because rotation sensors have a response factor (i.e. phase shift per rotation rate) that increases linearly in proportion to the atom’s time of flight; but accelerometers have a response factor that increases quadratically with time of flight. Part of the tradeoff is that fast atom beams offer more atoms...
TABLE II Inertial sensing resolutions demonstrated with atom interferometers.

| Sensor                        | Resolution                                      |
|-------------------------------|-------------------------------------------------|
| Gravimeter<sup>a</sup>        | $2 \times 10^{-8} \ (g) / \sqrt{\text{Hz}}$    |
| Gravity gradiometer<sup>b</sup>| $4 \times 10^{-9} \ (g/m) / \sqrt{\text{Hz}}$   |
| Gyroscope<sup>c</sup>         | $6 \times 10^{-10} \ (\text{rad/sec}) / \sqrt{\text{Hz}}$ |

<sup>a</sup>(Peters et al. 2001)<br><sup>b</sup>(McGuirk et al. 2002)<br><sup>c</sup>(Gustavson et al. 2006)

per second than cold atom sources. Larger interferometers will improve sensitivity and slow atom interferometers can make compact sensors. In each case, to judge the overall performance one must also look at systematic errors.

Displacements from an inertial reference frame with a constant acceleration $\vec{g}$ and a constant rotation $\vec{\Omega}$ causes a phase shift for a 3-grating interferometer

$$\phi = (\vec{G} \cdot \vec{g}) \tau^2 + 2\vec{G} \cdot (\vec{\Omega} \times \vec{v}) \tau^2.$$  \hspace{1cm} (52)

where $\vec{G}$ is the reciprocal lattice-vector of the gratings, and $\tau$ is the time of flight for atoms with velocity $\vec{v}$ to travel between gratings [Anandan 1981; Bongs et al. 2003; Dresden and Yang 1979; Dubetsky and Kasevich 2006; Malykin 2000]. Referring to our previous section on the origin of phase shifts, this phase is equivalent to the envelope shift, a classical property. Equation 52 can be derived from the grating phase (introduced in Section III Equation 15)

$$\phi = \vec{G} \cdot [\vec{x}_1(t_1) - 2\vec{x}_2(t_2) + \vec{x}_3(t_3)]$$  \hspace{1cm} (53)

where $x_i$ is the transverse position of the $i$th grating (with respect to an inertial frame) at time $t_i$ (when the atoms interact with the grating).

Rotation about the center grating in a space-domain interferometer causes a phase shift

$$\phi_{\text{atom}} = 2\Omega G L \tau = 4\pi \Omega \frac{m c}{\hbar} A$$  \hspace{1cm} (54)

where $L$ is the separation between gratings, $\tau$ is the time of flight between gratings, and $A$ is the area enclosed by the interferometer paths. For an optical interferometer

$$\phi_{\text{light}} = 2\Omega G L^2 \frac{1}{c} = 4\pi \Omega \frac{1}{\lambda_{ph} c} A.$$  \hspace{1cm} (55)

The ratio of phase shifts for a given rotation rate ($\Omega$), assuming equivalent interferometer areas ($A$), is

$$\frac{\phi_{\text{atom}}}{\phi_{\text{light}}} = \frac{mc^2}{\hbar \omega} = \frac{\lambda_{ph} c}{\lambda_{dB} v} \approx 10^{10}. $$  \hspace{1cm} (56)

This famous ratio shows that atom interferometers have a huge Sagnac response factor compared to optical interferometers.

However, to really gain this large increase in resolution (at the expense of bandwidth $v/c$), both the enclosed area and the count rate of the two types of interferometers must be equal. But a fiber optic ring gyro can easily have an enclosed area of $A = 10^3 \text{ m}^2$ and still have a much better bandwidth compared with the largest atom interferometers that have $A = 10^{-4} \text{ m}^2$. So the response factor is only a few orders larger for today’s atom interferometers. Furthermore, while the count rate for an optical Watt of power is on the order of $10^{15} \text{ photons per second}$, typical atom interferometers offer only $10^7 \text{ atoms per second}$.

For acceleration, one can see from Eq. 52 that,

$$\frac{\phi_{\text{atom}}}{\phi_{\text{light}}} = \left( \frac{c}{v} \right)^2$$

if identical gratings are used for light and atom interferometers.

The presence of velocity $v$ in the Eq. 52 has two important consequences. For a space-domain interferometer, the acceleration phase depends on $v^2$ while the rotation phase depends on $\tau$. Therefore, slow atoms are particularly advantageous for sensing acceleration, but fast atoms (beams) offer competitive sensitivity for gyroscopes. That is why the best gravimeters use cold atoms, and the best gyroscopes use thermal atomic beams. From the vector notation in Eq. 52 one can see that reversing the atom velocity switches the sign for the rotation phase but not the acceleration phase. This provides a method to distinguish $\Omega_z$ from $g_y$ or $g_z$. Kasevich used counter-propagating atom beams for this reason [Gustavson et al. 200].

Instrument resolution is given by the response factor times the precision with which the phase shift can be measured. Since the noise-limited phase precision increases with the square root of time (as discussed in Section III Eq. 19), it is customary to report the resolution per root Hertz. Instrument bandwidth is limited in part by the desired resolution and also simply by the atom’s time of flight. Dynamic range can be limited by dispersion. For example, if there is a velocity spread in a space domain interferometer, then the resulting spread in inertial phase decreases the contrast, as discussed in Sections III and IV. For a Gaussian distribution in phase with an RMS $\sigma_\phi$, the contrast is reduced by the factor $C/C_0 = \langle e^{i\phi} \rangle = e^{-\frac{1}{2} \sigma_\phi^2}$.

Measurements of gravitational acceleration in the engineering literature are often reported in units of $\mu\text{Gal}$ (1 $\mu\text{Gal} = 10^{-8} \text{ m/s}^2$) or the more common unit of $g$ ($g \approx 9.8 \text{ m/s}^2$). Many applications in geophysics are currently served with sensors that have $5 \times 10^{-9} \text{ g (5\mu Gal)}$ precision after averaging for 15 minutes (Allis et al. 2000). The light pulse (Raman) interferometer in [Peters et al. 2001] (described in chapter III) attains this precision in less than one minute. Measurements with this apparatus that show time-variations in local $g$ due (mostly) to tides are shown in Figure 53. Some
TABLE III List of geophysical sources of change in \( g \). [Allis et al. 2000; Peters et al. 2001; Sasagawa et al. 2003]

| Gravitation Source                                      | Magnitude |
|--------------------------------------------------------|-----------|
| Tides at Stanford, CA                                  | \( 2 \times 10^{-7} \) g |
| 1000 kg 1.5 meters away                                | \( 3 \times 10^{-9} \) g |
| Loaded truck 30 m away                                 | \( 2 \times 10^{-9} \) g |
| Elevation variation of 1 cm                            | \( 3 \times 10^{-9} \) g |
| Ground water fluctuation of 1 m                        | \( 5 \times 10^{-9} \) g |
| \( 10^8 \) kg of oil displacing salt at 1 km           | \( 5 \times 10^{-7} \) g |

TABLE IV Rotation rates due to various causes.

| Cause                        | Rotation Rate (rad/s) |
|------------------------------|-----------------------|
| Earth’s rotation             | \( \Omega_e = 7.2 \times 10^{-6} \) |
| Tidal drag in 1 yr.          | \( \delta\Omega = 10^{-13} \) |
| Lense-Thirring               | \( \Omega_{LT} = 10^{-14} \) |
| Geodetic Effect              | \( \Omega_{GD} = 10^{-12} \) |

variations in \( g \) due to sources of geophysical interest are shown in Table III.

Gravity gradients in the engineering literature are often measured in units of \( E = 10^{-9} \text{s}^{-2} \approx 10^{-10} \text{g/m} \) or simply \( g/\text{m} \). By measuring the differential gravitational acceleration in two atom interferometers located one meter apart from each other, Snadden et al. (1998) measured the Earth’s gravity gradient \( \nabla g = 3 \times 10^{-9} \text{g/m} \) with an uncertainty of 5% and Fixler et al. (2007) measured the change in gravity gradient caused by a 540 kg source mass of Pb \( (\nabla g = 8 \times 10^{-9} \text{g/m}) \) with an uncertainty of 0.3%. Related measurements are also described in Foster et al. 2002, Kasevich et al. 2002, McGuirk et al. 2007. Second order phase shifts due earth gravity and gravity-gradients and centrifugal and Coriolis forces due to Earth rotation have been identified by Bertoldi et al. 2006, Bongs et al. 2006, Dubetsky and Kasevich 2006.

**Historical background:** The first measurements of \( g \) with a matter-wave interferometer was done with neutrons by Colella et al. (1975). An early proposal for atom interferometer measurements of \( g \) by Clauser (1988) was followed by several demonstrations with rapidly improving resolution and accuracy. Kasevich and Chu 1992, Peters et al. 1999, 2001, 1997, Young 1997, Schmiedmayer et al. 1997, Young et al. 1997. An atom beam sensor for little \( g \) based on the classical moire-effect was also constructed with three material gratings by Oberthaler et al. (1996).

In 1913, Sagnac (1913a,b) made his famous light-interferometric measurement of platform rotation. Michelson (1922) measured the rotation rate of the earth, \( \Omega_e \), with a large optical interferometer. The Sagnac effect with neutron and electron interferometers has also been demonstrated (Hasselbach and Nicklaus, 1993, Werner et al. 1979). Atom interferometer gyroscopes were proposed early on by Clauser (1988). An atom interferometer Sagnac gyroscope was first built by Riehle et al. (1991), and huge improvements in sensitivity were demonstrated by Gustavson et al. 1997, 2000, Lenef et al. 1997.

**B. Newton’s constant**

Newton’s constant \( G \) is the least accurately known fundamental constant. The 2005 CODATA value of \( G \) has a precision of \( 1.4 \times 10^{-4} \) (Mohr and Taylor, 2005), although several individual experiments have recently claimed precision better than this (Gundlach and Merkowitz, 2000, Quinn et al., 2001). Atom interferometry is a relatively new method to measure \( G \), and may soon provide comparable precision to the CODATA value.

The Kasevich group determined \( G \) with a precision of \( 3 \times 10^{-3} \) (Fixler et al. 2007), and the Tino group reported a value for \( G \) with a precision of \( 1 \times 10^{-2} \) (Bertoldi et al. 2006). Both of these groups use two atom interferometer gravimeters and a movable source mass of order 500 Kg. The Tino group plans to extend their precision to the \( 10^{-4} \) level. Methods to measure \( G \) with atom interferometry are also discussed in Fattori et al. 2003, Kasevich et al. 2002, McGuirk et al.
C. Tests of Relativity

In accord with Einstein’s principle of equivalence, atomic mass \( m \) does not enter into Equation 52. However, theories that go beyond Einstein’s general relativity motivate the search for composition-dependent gravitational forces. The principle of equivalence has been tested accurately enough to state \( \Delta g/g = 1.2 \pm 1.7 \times 10^{-7} \) for the two different Rb isotopes \( \text{Fray et al.} \ 2004 \) and there are plans based on current technology to increase the precision of this test to \( \Delta g/g \sim 10^{-15} \) (300 times better than current limits from any method) \( \text{Dimopoulos et al.} \ 2007 \).

Searches for a breakdown of the \( 1/r^2 \) law are another test of general relativity, in this case motivated by string theories and the possibility of compact dimensions. Experiments to detect non-Newtonian gravitational potentials with multiple atom interferometers located at different distances from the earth’s center have been discussed in \( \text{Dimopoulos et al.} \ 2003, \text{Mathevet et al.} \ 2002 \). Experiments to search for a breakdown of the \( 1/r^2 \) law at micrometer length scales using atom interferometry were discussed in \( \text{Dimopoulos and Geraci} \ 2003, \text{Ferrari et al.} \ 2008 \).

The gravitational scalar A-B effect would be an interesting test at the intersection of quantum mechanics and gravity. If a 5 cm radius lead sphere has a small hole in the center, Cs atoms placed there have a frequency shift of about 7 Hz. Thus atoms at the top of their trajectory could easily experience a phase shift \( \sim 10 \) radians, enabling a quantum measurement of the gravitational potential. If the lead is assembled around the atoms in one interferometer arm, or if the lead is moved into position quickly compared to the atoms’ transit time, the effects of the gravitational field (force) can largely be eliminated, making this a sensitive measure of gravitational potential.

Atom interferometer rotation sensors in low earth orbit should be able to measure the geodetic effect and possibly the Lense-Thirring rotation. According to Special Relativity, freely-falling gyroscopes orbiting in the vicinity of the Earth will experience the geodetic effect caused by the motion of the gyroscope in the gravitational field of the earth \( \text{Jentsch et al.} \ 2004, \text{Schiff} \ 1964 \). For low earth orbit, the rotation rate induced by the geodetic effect is \( 10^{-12} \) rad/sec, and is independent of the earth’s rotation rate.

The Lense-Thirring rotation \( \text{Thirring} \ 1918 \) is a General Relativity effect that causes a gyroscope to rotate relative to the fixed stars due to a massive rotating body being nearby. It is also called the gravito-magnetic effect. In low earth orbit (700 km altitude), this can be as large as \( 10^{-14} \) rad/sec and depends on the orientation of the earth’s spin. Measurements of both the geodetic effect and the Lense-Thirring effect is the objective of future space bourne atom interferometer missions \( \text{Jentsch et al.} \ 2004 \).

D. Interferometers in orbit

In addition to ultra-precise atomic clocks to improve the atomic clocks already aloft for the GPS system, physics experiments that could benefit from being in space include measurements of the gravitational redshift, tests of Einstein’s equivalence principle, mapping the Lense-Thirring effect close by the Earth, and measurements of \( h/m \).

NASA works on these goals with the ‘Laser Cooled Atom Physics’ (LCAP) and ultra-precise primary atomic reference clocks in space (PARCS) programs planned for the international space station \( \text{Lee and Israelsson} \ 2001 \). The European Space Agency’s ‘HYPER-precision atom interferometry in space’ project is described in several articles in General Relativity and Gravitation, Vol. 36, No. 10, (2004) starting with \( \text{Jentsch et al.} \ 2004 \) (see Figure 54).

![Figure 54 (color online) The Mission Scenario: HYPER, which follows a nearly polar circular orbit, will measure with two atomic gyroscopes the two characteristic components of the Lense-Thirring rotation as a function of latitudinal position \( \theta \). Figure and caption reproduced from \( \text{Jentsch et al.} \ 2004 \).](Image 354x371 to 524x478)

E. Fine structure constant and \( h/M \)

One of the highest precision atom interferometry experiments is the measurement of \( h/m_{\text{atom}} \) This leads to a measurement of the Molar Planck Constant, \( N_A \times h = M_{\text{atom}}/m_{\text{atom}} \times h \times 1000 \) where \( M_{\text{atom}} \) is the atomic weight of the atom in grams and the factor of 1000 comes in converting the atomic mass into kilograms. This was done at Stanford by \( \text{Weiss et al.} \ 1994, 1993, \text{Wicht et al.} \ 2002 \), and more recently in Paris by Biraben and coworkers \( \text{Battesti et al.} \ 2004, \text{Clade et al.} \ 2006 \). Both groups achieved a precision of \( \sim 14 \) parts per billion by measuring the velocity change of an atom due to the photon recoil (from emission or absorption). As we shall discuss, these measurements lead to a value for the fine structure constant at \( \sim 7 \) ppb when combined with other measurements.
The underlying physics, first exploited using neutrons by Kruger et al. (1993), is based on the de Broglie wavelength,

$$\lambda_{DB} = \frac{h}{mv}. \quad (58)$$

Obviously a simultaneous measurement of both $\lambda_{DB}$ and $v$ gives $h/m$, where $m$ is the mass of the neutron of the particular atom used in the experiment. In the interferometer experiment of Chu, the measured quantity is essentially the frequency with which an atom with the recoil velocity (from absorbing a photon of wavevector $k$)

$$v_{rec} = \frac{\hbar k}{m_{Cs}} \quad (59)$$

crosses the fringes in a standing wave,

$$\omega = 2\pi v_{rec}/\lambda_{DB} \sim \hbar k^2/m_{Cs} \quad (60)$$

where we have replaced $\lambda_{DB}$ with the wavelength of the light causing the recoil. In the Biraben experiment, the Doppler shift associated with this recoil is measured:

$$\omega_D = kv_{rec} \sim \hbar k^2/m_{Rb}. \quad (61)$$

These frequencies are both equal to the recoil frequency (typically 10 kHz) derived earlier from consideration of the energy of recoil.

In the actual experiments, the measured frequency is several times the recoil frequency. Measuring the small recoil frequency to ppb accuracy is impossible given a maximum free fall time for the atoms of a fraction of a second. Hence both experiments increase the measured velocity by contriving to add recoil velocities from the absorption of many photons. In the Chu experiments these are added in using up to 60 Raman pulses or adiabatic (STIRAP) transfers; in the Biraben experiment by accelerating an optical lattice into which the atoms are embedded. Although the initial and final lattice speeds are not quantized, the atoms accelerated in them always absorb an integral number of lattice momenta (sum of momenta in the two laser beams forming the moving lattice) - up to 900 photon momenta in (Clade et al, 2006).

Both of these experiments are essentially measurements of velocity, using the combined techniques of atom optics (to add velocity) and atom interferometry to detect it. This is indicated by the fact that the signal increases linearly with the extra velocity. An interferometer configuration that uses contrast interferometry to measure the recoil energy has been proposed and demonstrated (Gupta et al, 2002). It shows the quadratic dependence of phase shift on photon number (velocity) expected for an energy measurement, and therefore requires that less additional momentum be added to achieve the same precision.

An important consequence of the $h/m$ measurement is to provide a very high accuracy route to the determination of the fine structure constant, $\alpha$. This is based on the relationship

$$\alpha^2 = \left(\frac{e^2}{\hbar c}\right) = \frac{2R_\infty}{h} \quad (62)$$

Combining atom interferometer results with independent measurements of the optical frequency ($\omega = ck$) (Gerginov et al, 2006) and the mass ratios $m_{Cs}/m_p$ (Bradley et al, 1999; Riehle et al, 1996), and $m_p/m_e$ (Mohr and Taylor, 2003), and the Rydberg $R_\infty$ (Mohr and Taylor, 2003), gives a value of the fine structure constant.

![FIG. 55 Determinations of the fine structure constant, $\alpha$, by several methods. The value from $h/m$(Cs) is from atom interferometry (Wicht et al, 2002) and the $h/m$(Rb) value is determined with Bloch oscillations (Clade et al, 2006). References are given in (Mohr and Taylor, 2005) for the values obtained from measuring the muonium hyperfine splitting ($\Delta\nu_{Mu}$), or measuring the von Klitzing constant with the quantum Hall effect ($R_K$), or measuring recoil velocity of neutrons Bragg-reflecting from silicon crystals ($h/m$), or measuring gyromagnetic ratios ($\gamma_{p,\mu} - \gamma_0$), or measuring electron and positron anomalies ($a_e \equiv g_e/2 - 1$). Figure adapted from (Mohr and Taylor, 2005).](image-url)

The determination of $\alpha$ from $h/m_{Cs}$ has a precision of 7 ppb (Wicht et al, 2002), and from Rb of 6.7 ppb (Clade et al, 2006). Thus this route already offers the second most accurate value of $\alpha$ (after the measurement of $g_2$ for the electron), and therefore allows the most precise comparison across different subfields of physics, as shown in Figure 55. It essentially offers a comparison of QED with such things as the de Broglie wavelength relationship and calculations of atomic structure in hydrogen. Such cross-field comparisons are extraordinarily important for the unity and global understanding of physics, and provide one of the few routes to discover underlying errors in an isolated subfield. It is interesting to note that several of the values appearing in figure 55 have been substantially re-evaluated between 1998 and 2002, which proves that the fine structure constant is not so well known (it is known mostly due to the electron spin anomaly).

No precision experiment is easy, and the $h/m$ measurements discussed here experience difficulties from vibration that changes the velocity of the reference light waves...
(the scheme in [Gupta et al., 2002] demonstrated vibrational insensitivity), stray field gradients, etc. Other sources of noise and systematic error in these experiments include the index of refraction for light due to the atomic ensemble (Campbell et al., 2003; Wicht et al., 2002), atomic errors at the 0.2ppb level. We know of no other experiments where there are two or more measurements of both the Rydberg and electron mass ratios that are consistent.

Stark shifts for the atomic energy levels due to the laser fields (Wicht et al., 2002, 2003), beam mis-alignment and wavefront curvature (Gibble, 2006; Wicht et al., 2002), and mean field shifts for the atomic energy states due to interaction with nearby atoms (Gupta et al., 2002; Le Coq et al., 2006).

Still, the accuracy of these atom interferometric methods for measuring $\hbar/m$ is increasing due to the rapid overall progress in atom interferometry with cold atoms and because sources of error are being understood and overcome. It is certain that the accuracy of $\hbar/m$ will soon be improved in both Rb and Cs, which employ significantly different atom optics methods. This might mean that the real limit of confidence in this route to $\alpha$ would be in the measurements of the atomic masses of Rb and Cs for which there is only one high precision measurement (Bradley et al., 1999), and that had unexplained systematic errors at the 0.2ppb level. We know of no other experiments planned that could check these heavy masses, whereas there are two or more measurements of both the Rydberg and electron mass ratios that are consistent.

Here is more detail on the Chu group experiment, described in (Weiss et al., 1994, 1993; Wicht et al., 2002). To determine $\hbar/m$ they measure the relative frequency of the final $\pi/2$ pulses in two different atom interferometers (Figure 56). The frequency difference between the resonances of the two interferometers depends only on conservation of energy and conservation of momentum. As an example of the recoil shift, consider a simplified experiment (Weiss et al., 1994) where an atom (with mass $m$) in state $|a\rangle$ with zero velocity in the laboratory frame first absorbs a photon from a leftward propagating laser beam with frequency $\omega$. The atom recoils by $\hbar k/m$ and the process has a resonance condition

$$\omega - \omega_{ab} = \frac{\hbar k^2}{2m}$$  

(63)

where $\hbar \omega_{ab}$ is the energy difference between atomic states $|b\rangle$ and $|a\rangle$ at rest. The atom can then be de-excited by a rightward propagating beam with frequency $\omega'$. It receives another velocity kick $\hbar k'/m$ in the same direction and the new resonance condition is

$$\omega' - \omega_{ab} = -\frac{\hbar k k'}{m} - \frac{\hbar k'^2}{2m}.$$  

(64)

The two resonances are shifted relative to each other by

$$\Delta \omega = \omega - \omega' = \hbar(k + k')^2/2m.$$  

(65)

Furthermore, the resonance condition for an atom in $|b\rangle$ moving with velocity $(N-1)v_{rec}$ towards a laser beam is

$$\omega' - \omega_{ab} \approx \frac{\hbar k'^2}{2m} \left[ ((N-1)^2 - (N)^2) \right]$$  

(66)

so that

$$\Delta \omega \approx \frac{N \hbar k^2}{m}$$  

(67)

where $N$ is the total number of photon recoil momenta imparted to the atom and the approximation comes from the fact that $k' \approx k$. This shows why $\Delta \omega$ depends linearly on $N$.

FIG. 56 (a) A double interferometer where the two interfering pairs have their velocities shifted with respect to each other by four photon recoils. Solid lines indicate atoms in internal state $a$, and dashed lines represent internal state $b$. (b) Sets of Ramsey fringes displaced by $2\pi \Delta \omega$ (due to 8 $\pi$ pulses in the middle of the interferometers). Only the frequency of the final two $\pi/2$ pulses is scanned. Figure from [Weiss et al., 1994].

VI. ATOMIC PHYSICS APPLICATIONS

A major motivation for atom interference experiments is to learn more about atoms and molecules themselves.

Atoms in a separated beam interferometer experience a phase shift if a uniform but different potential is applied to each arm. Thus interferometers offer exquisite sensitivity to the potentials (not just forces). This sensitivity has been used to measure the index of refraction due to other atoms and energy shifts due to electric and magnetic fields. We emphasize that de Broglie wave phase shift measurements bring spectroscopic precision to experiments where usually classical methods like beam deflection or velocity measurement were applied, as discussed in Sections I - IV.

In another application, the nanogratings used as a de Broglie wave gratings can function as a very gentle spectrometer that diffracts different molecular species in a molecular beam to different angles.

The nanostructures themselves also produce potentials due to atom-surface interactions that have been measured with interferometric techniques. For gratings with 50-nm wide slots, each transmitted atom must pass within 25 nm of a grating bar; hence the measured intensities are affected by the non-retarded vdW potential. With larger gratings, on the other hand, the Casimir-Polder potential has been probed.
A. Discovery of He\textsubscript{2} molecules

One stunning application of coherent atom optics laid to rest a long standing argument concerning whether a stable bound state of the 4\textsuperscript{He} dimers exists. (The attribution of He\textsubscript{2}\textsuperscript{+} to He\textsubscript{2} dimers formed in cryogenic expansion by [Luo et al., 1993] primarily reopened an old debate). For this a diffraction grating was used to separate and resolve 4\textsuperscript{He} dimers from a helium beam (Figure 57) (Schollkopf and Toennies, 1996). Subsequently a grating was used as a nano-sieve to measure the size of the 4\textsuperscript{He} dimers. They have a size of \( r = 6.2 \pm 1.0 \) nm which corresponds to a binding energy of \( E/k_B = 1 \) mK (Grisenti et al., 2000a; Luo et al., 1996). Diffraction has also been used to study the formation of more massive clusters [Bruhl et al., 2004], and searches using this technique are underway for an Efimov-type trimer. (Bruhl et al., 2004; Hegerfeldt and Stoll, 2005; Stoll and Kohler, 2005). For this a diffraction grating was used to separate and resolve 4\textsuperscript{He} dimers from a helium beam (Figure 57) (Schollkopf and Toennies, 1996). Subsequently a grating was used as a nano-sieve to measure the size of the 4\textsuperscript{He} dimers. They have a size of \( r = 6.2 \pm 1.0 \) nm which corresponds to a binding energy of \( E/k_B = 1 \) mK (Grisenti et al., 2000a; Luo et al., 1996). Diffraction has also been used to study the formation of more massive clusters [Bruhl et al., 2004], and searches using this technique are underway for an Efimov-type trimer. (Bruhl et al., 2004; Hegerfeldt and Stoll, 2005; Stoll and Kohler, 2005).

B. Polarizability measurements

1. Ground state dc scalar polarizability

By inserting a metal foil between the two separated arms, as shown in Fig. 58, an electric field can be applied to a single path. The resulting de Broglie wave phase shift was used to measure the static ground-state atomic polarizability of sodium, \( \alpha_{Na} \) with a precision of 0.35\% [Ekstrom et al., 1995]. Similar precision has been demonstrated for \( \alpha_{He} \) (Toennies group) and \( \alpha_{Li} \) (Vigué group) using this method [Miffre et al., 2006].

In this experiment a uniform electric field \( E \) is applied to one of the separated atomic beams, shifting its energy by the Stark potential \( U = -\alpha E^2/2 \). The static scalar ground-state polarizability \( \alpha_{pol} \) is determined from the phase shift, \( \Delta \phi \), of the interference pattern by

\[
\alpha_{pol} = \left( \frac{\Delta \phi}{V^2} \right) \left( \frac{D^2}{L_{eff}} \right) (2\hbar v),
\]

where \( V \) is the voltage applied to one electrode in the interaction region, \( D \) is the distance between the electrode and the septum, \( v \) is the mean velocity of the atomic beam, and \( L_{eff} \) is the effective interaction region length defined as

\[
\left( \frac{V}{D} \right)^2 L_{eff} = \int \xi^2 dz.
\]

For an accurate determination of electric polarizability, the three factors in Equation (68) must each be determined precisely. They are (1) the phase shift as a function of applied voltage, (2) the geometry and fringing fields of the interaction region, and (3) the velocity of the atoms. In [Ekstrom et al., 1995] the uncertainty in each term was less than 0.2\%.

Taking all sources of error into account, and adding statistical and systematic errors in quadrature, the static polarizability of the ground state of sodium was measured to be \( \alpha_{pol} = 24.11 \times 10^{-24} \) cm\(^3\), with a fractional uncertainty of 0.35\%. This measurement was a nearly 30 fold improvement on the best previous direct measurement of the polarizability of sodium [Hall and Zorn, 1974] based on beam deflection.

A similar experiment for He was done with a 3-grating Mach Zehnder interferometer (with nanogratings) by the Toennies group. The phase stability of this interferometer was so good that the fringes could be observed directly as a function of applied electric field, while the gratings were not moved. (Figure 59). The statistical precision in \( \alpha_{He} \) was 0.1\% [Toennies, 2001].

![Fig. 57](image_url) Diffraction of helium atoms and helium molecules through a nano-fabricated grating. These data, reproduced with permission from Wieland Schoellkopf, were obtained at the Max-Planck-Institute in Göttingen.

![Fig. 58](image_url) Measurement of atomic polarizability. (a) Schematic of the interaction region installed behind the second grating. (b) Measured phase shifts vs. applied voltage. The two different signs of the phase shift stem from the voltage being applied on either the left (open circles) or the right (filled circles) side of the interaction region (arm of the interferometer). The fit is to a quadratic and the residuals are shown on the lower graph. Figure from [Schmiedmayer et al., 1997].
Using three Bragg diffraction gratings for Li atoms and a septum electrode, the group of Vigué measured $\alpha_{Li}$ with a precision of 0.66% \cite{Miffre et al., 2006}. Because atom interferometry gives sub-Hertz precision on the energy shift of the atomic ground state, \textit{ratios of polarizabilities} for different species can be very accurately determined with multi-species atom interferometers. Uncertainty in the interaction region geometry would then be less significant because the quantity $(D^2/L_{eff})$ in Eq 65 cancels out in a ratio of, for example, $\alpha_{Rb}/\alpha_{Li}$. The ratio of velocities of the two species would still need to be measured, or taken into account. Thus, improved precision in measurements of $\alpha_{pol}$ may come from using an engineered phase shift to cancel the velocity-dependence of the polarizability phase shift. This is known as dispersion compensation \cite{Roberts et al., 2004}. Velocity multiplexing \cite{Hammond et al., 1995} and magnetic re-phasing \cite{Schmiedmayer et al., 1994} are other approaches for dealing with the experimental spread in velocity. With these improvements it seems feasible to perform polarizability measurements with uncertainties in the $10^{-4}$ range.

This precision offers an excellent test of atomic theory, because theoretical uncertainties in light elements like Li are orders of magnitude smaller than in heavier alkalis. Polarizability $\alpha_{pol}$ of an atomic state can be expressed as a sum over dipole matrix elements:

$$\alpha_{pol} = e^2 \sum_{j \neq i} \frac{\langle i | r | j \rangle \langle j | r | i \rangle}{E_j - E_i} \quad \text{(70)}$$

where $E_j$ is the energy of state $|j\rangle$. Accurate calculation of static dipole polarizabilities for heavy atoms still remains a great challenge because electron correlation and relativistic effects become increasingly important for heavy atoms. Major theoretical efforts so far have included the relativistic Hartree Fock approach, many body perturbation theory, density functional theory, and relativistic coupled-cluster technique. Several calculations of atomic polarizability all show the need for precise experimental measurements \cite{Bonin and Kadarkallen, 1994; Derevianko et al., 1999; Derevianko and Porsev, 2002; Hagen, 2004; Kharchenko et al., 1997; Kronik et al., 2001; Lim et al., 1999; Maroulis, 2001; Rerat et al., 1998; Safronova et al., 1999; Thakkar and Lupinetti, 2007}.

2. Transition dc and ac Stark shifts

When two paths have different internal states, e.g. in an optical Ramsey Bordé interferometer, then a uniform electric field applied to both paths makes phase shifts proportional to the \textit{difference} of polarizability of the two states. (This is similar to what can be measured with laser spectroscopy.) For example, the dc-Stark shift of the magnesium $3s^2(1S_0)-3s3p(3P_1)$ intercombination line was measured by subjecting both arms of an atom interferometer to a constant electric field. The Stark energy perturbation provides two different potentials in the two arms of the interferometer. The resulting relative phase shift (Figure 60) corresponds to a difference of $-(8 \pm 1)$ kHz (kV/cm)$^{-2}$ in the polarizabilities of the $1S_0$ and the $3P_1 (m = 1)$ states. \cite{Rieger et al., 1993}.

![FIG. 59 Measurement of the electric polarizability of He. The gratings are held stationary while the electric field is increased. The measurement uncertainty is statistical only. Figure courtesy of J.P. Toennies and R. Breuhl.](image)

![FIG. 60 Optical Ramsey Bordé interferometer for measuring polarizability differences. (a) Schematic of the atom interferometer with a capacitor. (b) Frequency shift of the interference pattern versus voltage across the capacitor. The fit is a parabola. The inset shows the energy levels as a function of position through the capacitor. \cite{Rieger et al., 1993}](image)

A related approach was used to measure the difference between the polarizabilities of the $3P_1$ state and the $1S_0$ state of Ca to be $\alpha(3P_1)-\alpha(1S_0) = (13 \pm 2) \times 10^{24}$ cm$^3$ \cite{Morinaga et al., 1996}.

The ac Stark shift of the $4s0^1S_o-4s4p^3P_1$ line in $^{40}$Ca was measured with a time-domain Ramsey-Bordé atom interferometer (in a magneto optical trap) for perturbing laser wavelengths between 780 nm and 1064 nm. \cite{Degenhardt et al., 2004}. Ac Stark shifts have also been
where the gas are phase shifted and attenuated by the index

\[ n = 1 + \frac{2\pi N}{k^2} f(k, k) \]

(72)

where \( N \) is the gas density. Atoms propagating through the gas are phase shifted and attenuated by the index

\[ \psi(z) = \psi(0)e^{iNz} = \psi(0)e^{i\Delta \phi(N, z)}e^{-\frac{\pi N}{2}} \]

(73)

The phase shift due to the gas,

\[ \Delta \phi(N, z) = (2\pi N k z/k_{cm}) \text{Re}[f(k_{cm})], \]

(74)

is proportional to the real part of the forward scattering amplitude, while the attenuation is related to the imaginary part. Attenuation is proportional to the total scattering cross section which is related to \( \text{Im}[f] \) by the optical theorem

\[ \sigma_{\text{tot}} = \frac{4\pi}{k_{cm}} \text{Im}[f(k_{cm})]. \]

(75)

Measurements of phase shift as a function of gas density are shown in Figure 61.

The ratio of the real and imaginary parts of the forward scattering amplitude is a natural quantity to measure and compare with theory. This ratio,

\[ \rho(k) = \frac{\Delta \phi(N)}{\ln[A(N)/A(0)]} = \frac{\text{Re}[f(k)]}{\text{Im}[f(k)]}, \]

(76)

where \( A \) is the fringe amplitude, gives orthogonal information to the previously studied total scattering cross section. In addition it is independent of the absolute pressure in the scattering region and therefore much better to measure.

The ratio \( \rho(k) \) shows structure as a function of \( k \) known as glory oscillations\(^\text{13}\) (Figure 62). These were predicted in (Audouard et al. 1995, 1997; Forrey et al. 1997) and observed (Roberts et al., 2002). Measurements of \( \rho(k) \) plotted as a function of Na beam velocity \( v \) for target gases of Ar, Kr, Xe, and \( N_2 \) are shown in Fig. 62.

To compare these measurements with predictions based on various potentials \( V(r) \), the forward scattering amplitude was computed using the standard partial wave treatment and the WKB approximation. Predictions for \( \rho \) must also include an average over the distribution of velocities in the gas sample, and this damps the glory oscillations as discussed in (Champenois et al. 1997, Forrey et al. 1997). Fig. 62 shows calculations of \( \rho(v) \) based on predictions of \( V(r) \) for Na-Ar, Na-Kr and Na-Xe derived from spectroscopic measurements and beam scattering experiments.

The motivation for studying the phase shift in collisions is to add information to long-standing problems such as inversion of the scattering problem to find the interatomic potential \( V(r) \), interpretation of other data that are sensitive to long-range interatomic potentials, and description of collective effects in a weakly interacting gas (Bagnato et al. 1993; Chadan and Sabatier 1989; Cheville et al. 1994; Lett et al. 1994; Moerdijk et al. 1994; Moerdijk and Verhaar 1994; Stock 1991; Stwalley et al. 1994; Walker and Feng 1994). The glory measurements of \( \rho \) are sensitive to the shape of the potential near the minimum, where the transition

\[^{13}\text{Glory oscillations in the absorption cross section were first measured by Roth (1962) for Li and K beams, and related phenomena with light waves have been studied by Bryant and Cox (1964); Cheville et al. (1994); Khare and Nussenzveig (1977, 1978); Nussenzveig (1974).}\]

FIG. 61 (Left) Phase shift \( \Delta \phi \) as a function of gas density \( N \) for different gas samples. (Right) Phase shift vs Fringe amplitude. The fringe amplitude is proportional to \( e^{-N\sigma_{\text{tot}}k^2/2} \). Figure from (Schmiedmayer et al. 1997).

C. Index of refraction due to dilute gases

A physical membrane separating the two paths allows insertion of a gas into one path of the interfering wave, enabling a measurement of the index of refraction for atom waves traveling through a dilute gas caused by the collision-induced phase shift. Measurements are presented in (Kokorowski et al. 1997, Roberts et al. 2002; Schmiedmayer et al. 1995, 1997) and these experiments are discussed in (Audouard et al. 1995, 1997; Blanchard et al. 2003; Champenois et al. 1997; Forrey et al. 1996, 1997; Kharchenko and Dalgarno 2001; Vigue 1995).

Scattering makes a wave function evolve as:

\[ \psi - \infty e^{ikr} + f(k, k') e^{ik'r}, \]

(71)
from the repulsive core to the Van der Waals potential is poorly understood. The measurements of $\rho$ as derived from predicted potentials: Na-Ar (Champenois et al., 1997), Duren and Groger, 1978, Forrev et al., 1979, Tellinghuisen et al., 1979, Tang and Toennies, 1977; Na-Kr (Champenois et al., 1997), Duren et al., 1968; and Na-Xe (Baumann et al., 1992), Duren et al., 1968. Figure from Roberts et al., 2002.

After J.D van der Waals suggested modifications to the equation of state for gases to allow for atom-atom interactions (which he did in 1873), London (1937) calculated the strength of interactions between two polarizable atoms using quantum mechanics, and similar ideas were used to describe atom-surface interactions (Lennard-Jones, 1932). Casimir and Polder (1948) generalized the theory of atom-surface interactions to include the effect of retardation, and Lifshitz (1950) modified this theory to allow for a surfaces with a dielectric permittivity. Since then, hundreds of theoretical works used quantum electrodynamics to predict the interaction potential for real atoms near real surfaces.

The Casimir-Polder potential for an ideal surface (Casimir and Polder, 1948; Sukenik et al., 1993)

$$U(r) = \frac{1}{4\pi \rho r^4} \int_0^\infty \alpha_p(i\omega/\rho) e^{-2\pi} [2x^2 + 2x + 1] dx$$

where $\alpha_p$ is atomic polarizability (evaluated as a function of imaginary frequency), $r$ is the distance to the surface, and $\alpha$ is the fine structure constant. This has well-known limits of the Van der Waals (vdW) regime

$$r \to 0 \quad U(r) = \frac{\hbar}{4\pi \rho} \int_0^\infty \alpha_p(i\omega/\rho) d\omega \equiv C_3 \frac{1}{r^3}$$

and the retarded regime

$$r \to \infty \quad U(r) = \frac{2\hbar c \alpha_p(0)}{32 \pi^3 \epsilon_0 r^4} = -\frac{K_4}{r^4}.$$}

Marinescu et al., 1997 evaluated $U(r)$ for sodium atoms at arbitrary distances from a perfectly conducting half space, using a single electron (Lorenz oscillator) model of the atom. Derevianko et al., 1999 calculated $C_3$ for the alkali atoms using the best available model of frequency-dependent atomic polarizability. It is noteworthy that 18% of the interaction potential between sodium atoms and a perfect mirror is due to excitations of the core electrons. The one-electron (Lorenz) oscillator model yields $C_3 = \hbar \omega_0 \alpha_p(0)/8$ with $\alpha_p(0) = e^2/\omega_0^2 m_e [4 \pi c_0]$ where $\omega_0$ is the resonance frequency and $m_e$ the electron mass. This one-electron model for sodium atoms and a perfectly conducting surface gives $C_3 = 6.3$ meV nm$^3$, while the calculation with many electrons gives $C_3 = 7.6$ meV nm$^3$. The Lifshitz formula

$$C_3 = \frac{\hbar}{4 \pi} \int_0^\infty \alpha_p(i\omega) \left| \frac{e^{i\omega/\rho}}{e^{i\omega/\rho} + 1} \right| d\omega.$$
FIG. 63 Distorted de Broglie waves. Van der Waals interactions with mechanical grating bars cause near-field phase shifts. This view is exaggerated: in beam experiments there are typically $10^4$ wave fronts in the 100 nm thickness of a nanograting slot (Grisenti et al., 1999; Perreault et al., 2005).

FIG. 64 The Phase (a) and modulus (b) of far-field diffraction orders both depend on the vdW coefficient $C_3$ divided by atom velocity [shown in units of meVnm$^3$ / (km/s)]. Figure adapted from (Perreault and Cronin, 2006).

2005; Shimizu, 2001), atoms undergoing quantum reflection (Anderson et al., 1986; Berkhout et al., 1989; Druzhinina and DeKieviet, 2003; Pasquini et al., 2006; Shimizu, 2001; Shimizu and Fujita, 2002a), atoms reflecting from evanescent waves near surfaces (Esteve et al., 2004; Hainal et al., 1999; Kaiser et al., 1996; Westbrook et al., 1998) and atoms trapped near surfaces (Harber et al., 2005; Lin et al., 2004; McGuirk et al., 2004) and atoms in interferometers (Brezger et al., 2002; Kolno et al., 2003; Nairz et al., 2003; Perreault and Cronin, 2005, 2006) have been used to measure atom-surface interaction potentials. For a review of several such experiments see the CAMS proceedings (CAMS, 2005).

1. VdW-modified diffraction

Because of van der Waals interactions with mechanical grating bars, atoms propagating through a nanograting get a phase shift that depends on position within each slot, as shown in Figure 63. An analogous structure in light optics is an array of diverging lenses held between absorbing bars. The index of refraction in the free-space between material grating bars gives nanogratings a complex transmission function that has been studied in (Brezger et al., 2002; Bruhl et al., 2002; Cronin and Perreault, 2004; Grisenti et al., 1999, 2000b; Kolno et al., 2003; Nairz et al., 2003; Perreault and Cronin, 2005, 2006; Perreault et al., 2005; Shimizu, 2001).

Figure 63 is a cartoon of the de Broglie wave phase fronts in the near-field immediately after a nanograting. Far-field diffraction orders are affected by van der Waals interactions too. We can describe the $n$th far-field order by

$$\psi_n = A_n e^{i\phi_n} e^{i\vec{k}_n \cdot \vec{x}}$$

(81)

where the modulus $A_n$ and phase $\phi_n$ for the $n$th order are given by

$$A_n e^{i\phi_n} = \int_{-w/2}^{w/2} \exp\left[i\phi(\xi) + inG\xi\right] d\xi.$$  

(82)

Here $w$ is the size of the windows (or ‘nano-slots’) between grating bars, and $\phi(\xi)$ is the phase-shift sketched in Figure 63 that can be calculated by putting the atom-surface potential $U(r)$ into the expression for a phase shift (Equation 43). Thus the modulus and a phase of each diffraction order depends on the strength of the potential ($C_3$ in the vdW regime) and on atomic velocity as shown in Figure 64. Several experiments have measured the intensity $|A_n|^2$ in diffraction orders to determine $C_3$ for various atom-surface combinations, with some results shown in figures 65 and 66 (Bruhl et al., 2002; Cronin and Perreault, 2004; Grisenti et al., 1999; Perreault et al., 2005).

The diffraction intensities $|A_n|^2$ depend on phase gradients induced by $U(r)$. To detect the diffraction phases, $\phi_n$, an atom interferometer can be used as described in the next Subsection.

2. Interferometer VdW and CP measurements

The complex transmission function of the gratings modifies the location at which the Talbot effect re-
FIG. 66 Measurements of $C_3$ for various atoms and a silicon nitride surface, obtained by studying atom diffraction patterns (Grisenti et al., 1999).

FIG. 67 Dependence of the interference fringe visibility on the mean velocity of the molecular beam. Numerical simulation results are plotted for four models without free parameters: classical or quantum behavior, with or without consideration of the van der Waals (vdW) interaction of the molecules with the second grating. The quantum result including the van der Waals effect is clearly the only adequate theory (Brezger et al., 2002).

In a separated-path interferometer, Perreault and Cronin (2005) inserted an auxiliary interaction grating in one path. This allowed a measurement of the phase shift $\phi_0$ due to Van der Waals interactions (Perreault and Cronin, 2005).

In the Atomic Beam Spin Echo (ABSE) interferometer, discussed in III.D.2, Druzhinina and DeKieviet (2003) observed atoms reflecting from the attractive part of the atom-surface interaction potential. This quantum reflection allowed DeKieviet et al to map the van der Waals potential in an energy range between 1 neV and a sub-meV. Figure 69 shows the measured probability of He atoms quantum reflecting from a quartz surface, as a function of the impinging wavevector. (Later both metallic and semi-conductor samples were used.) Deviation of the experimental data from the high-energy asymptote is attributed to Casimir-Polder retardation. Importantly the spin echo interferometer was used to precisely select the velocity of the detected atoms. In this regard it complements other quantum reflection experiments (Anderson et al., 1986; Berkhout et al., 1989; Pasquini et al., 2006; Shimizu, 2001; Shimizu and Fujita, 2002a) that do not explicitly use atom interferometers (though we note that quantum reflection itself is inherently a wave phenomenon).

VII. OUTLOOK

In the early 1980’s “Mechanical Effects of Light” was the name for the study of light forces on atoms. See, for example, (Chebotayev et al., 1985) and Table VI. At first these forces were used simply to change the momentum of atoms. Then it emerged that, with care in application, light forces could be conservative. When atom diffraction from a standing light wave was demonstrated (Gould et al., 1986), it became appreciated that interactions with classical light fields can transfer momentum in precise quanta and preserve the coherence of atomic de Broglie waves. This led to many papers contrasting “Diffraction and Diffusion” and emphasizing that diffraction of atoms by light was coherent, whereas the occurrence of some spontaneous decay processes led to diffusion which is not coherent (Deng, 2006).
FIG. 69 Experimental ABSE data for the quantum reflection of $^3$He atoms from a disordered single crystal quartz surface. (Druzhinina and DeKieviet, 2003)

Gould et al., 1991; Ryytty et al., 1998; Tanguy et al., 1993; Wilkens et al., 1991). It also led workers in the field to consider other coherent ways to manipulate atoms. The term “optics” started to replace “diffraction” in conversations. Although some felt that “atomic optics” was the preferable phrase (in part to emphasize that atomic physics was the driving force), we felt that “Atom Optics” was more closely analogous to “electron optics” and decided to make it the title of our 1991 review in ICAP12 (Pritchard, 1991). Perhaps nothing shows the growth of this field, and the coalescence around this phrase, more than the fact that there are almost 200,000 Google hits to “Atom Optics” plus over 20,000 for atom interferometers (and even fewer than this for “atomic optics”).

The reviews on Atom Optics that the MIT group wrote in 1990 and 1991 considered Atom Optics as a way to mimic photon optics. Relative to a list of standard optical components, it was pointed out that atom lenses could be made in various ways but that material beamsplitters were impossible, shifting the burden for coherent beamsplitting and recombining to diffractive processes using matter and light gratings. The observation that light and matter diffraction gratings would be the beamsplitters has been borne out by the vast majority of work with atom interferometers over the past 15 years. However, their refinement has been quite remarkable. In addition, a host of new developments in atom optics have greatly lengthened the list of atom optical components and devices – see the Atom Optics Toolkit in Table[4] The art of atom optics is in its golden age because the techniques listed in this toolkit are just beginning to have an impact on scientific questions beyond the specialty of atom optics. As larger and more controlled atom optical systems are constructed, opportunities abound to efficiently and coherently manipulate atoms for scientific gain.

Not all predictions in (Pritchard, 1991) were so prescient however; although coherent atom amplifiers were discussed, they were not anticipated. Hence the demonstration of coherent atom amplification (using interferometry to verify its phase coherence) was an unexpected development, as was non-linear atom optics generally. The power of, and interest in, non-linear atom optics should lead to many more advances in atom interferometry such as sub-shot noise measurements of phase shifts, \cite{Jo et al., 2005; Pezze and Smerzi, 2006; Scully and Dowling, 1993; Search and Meystre, 2003}, and coherent oscillations between atomic and molecular BEC’s. Non-linear optics is outside the scope of this paper although techniques of linear atom optics and interferometry are extremely valuable as tools in this field \cite{Anderson and Meystre, 2003; Bongs and Sengstock, 2004; Meystre, 2003; Rolston and Phillips, 2002}. Another unanticipated development is the immense amount of development on atom chips.

As this review shows, experimental and theoretical understanding of atomic and molecular matter waves has come a long way since the first demonstrations of coherent diffraction with laser light and nanogratings in the early 1990’s. In the MIT group’s first paper on diffraction by a light grating, the rms momentum transfer was far below predictions; the second paper reported it was low by a factor of two noting there was “no explanation for this discrepancy”. Recently this effect was used to measure the standing wave intensity of a standing wave (depth of optical lattice) to within 1% \cite{Mun et al., 2007}.

This shows the transformation of pioneering scientific work in atom optics into a high-precision tool for use in cold atom physics. Similarly, our review shows that atom interferometers are now routinely used for scientific endeavors ranging from fundamental investigations of quantum physics to precision metrology. We now briefly project anticipated progress over the main categories used in this review (diffraction, interferometry, fundamental studies, precision measurements, and atomic properties). We also speculate on areas that we expect will become more important: e.g. optics with molecules and ultracold fermions, atom chips and optical lattices, surface science, fundamental studies of gravitation, new ways to control atom-atom interactions, entanglement and multi-particle interferometry, and more formal analogies to condensed matter phenomena that arise from quantum coherence.

We expect coherent atom optics to become an even more flexible, powerful, and precise tool for manipulating atoms and molecules, especially for interferometers, and for applications to other scientific and technical problems. The development of techniques for accelerating (and in the future decelerating) atoms and especially molecules, both in light crystals and by optimizing the temporal envelope of light for higher-order beam splitters will enable coherence to be maintained between wave function components with relative velocities of meters/sec that are determined with 10^-10 accuracy. This will result in interferometers of far greater precision with
| Light Optics                     | Atom Optics                                                                 |
|--------------------------------|----------------------------------------------------------------------------|
| SOURCES                        | thermal (supersonic) beam                                                  |
|                                | coherent                       |
|                                | Bose Einstein condensate       |
| LENSES                         | spherical electrostatic quadrupole or magnetic hexapole                     |
|                                | cylindrical Gaussian optical beams                                        |
|                                | Fresnel nano structure zone plates (cyl. or sph.)                         |
|                                | achromat combination zone plate + E-M lens                                |
|                                | axicon magnetic quadrupole                                                |
| MIRRORS                        | (giant) quantum reflection                                                |
|                                | helium from (bent) crystal surfaces                                       |
|                                | evanescent light waves                                                    |
|                                | periodically poled magnetic domains (on curved surfaces)                   |
| GRATINGS                       | phase standing waves of light: Bragg, or Kapitza-Dirac (pulses)           |
|                                | amplitude nano-structure gratings                                          |
|                                | reflection standing waves of resonant radiation                           |
|                                | crystal surfaces                                                          |
|                                | quantum reflection from (nano-structured) surfaces                        |
|                                | structured evanescent light                                               |
|                                | blazed Bragg scattering                                                   |
|                                | two- and three-color standing waves                                        |
| POLARIZING SPLITTERS           | stimulated Raman transitions                                              |
|                                | optical Ramsey π/2 pulses                                                 |
|                                | Stern-Gerlach magnets                                                    |
|                                | optical Stern-Gerlach effect                                              |
| PHASE PLATES                   | glass E-field                                                             |
|                                | B-field                                                                    |
|                                | dilute gas                                                                 |
|                                | nearby surface                                                             |
| HOLOGRAMS                      | transmission perforated nano-structures (with E and B fields)             |
|                                | reflection nano-structures (with enhanced quantum reflection)              |
| λ SHIFTERS                     | modulators amplitude modulated standing waves                              |
|                                | gravity                                                                    |
|                                | bi-chromatic laser fields                                                 |
|                                | reflection from a receding rotor                                           |
| INTERFEROMETERS                | Young’s experiment micro (or nano) slits                                   |
|                                | Mach-Zehnder space domain using (separated) beams (spin entanglement)      |
|                                | time domain, with pulsed gratings (spin entanglement)                      |
|                                | longitudinal (RF or Stern-Gerlach beam splitters)                         |
|                                | near field Talbot Lau, Lau, and Talbot interferometers                    |
|                                | Michelson atoms confined in a waveguide                                   |
|                                | Fabry-Perot atoms confined in a 3-dimensional trap                        |
| WAVEGUIDES                     | fiber optics permanent magnets                                             |
|                                | optical dipole force                                                      |
|                                | evanescent light in hollow fiber                                          |
| DETECTORS                      | photon counter hot wire (or electron bombardment) ionizer and counter      |
|                                | state selective field ionization, laser ionization, metastable detection  |
|                                | polarization spectroscopy                                                  |
|                                | imaging multichannel plate for ions or (metastable) atoms                 |
|                                | (state selective) fluorescence, absorption, or phase contrast imaging      |
| AMPLIFIERS                     | stimulated emission four-wave mixing with BEC [nonlinear quantum optics]  |
much greater separation of the arms and much greater enclosed area.

These bigger and better interferometers will be applied to fundamental problems in gravity and quantum mechanics. They will allow one to measure the gravitational potential in experiments analogous to the scalar Aharonov-Bohm effect in which the potential has influence in the absence of any gravitational field (such as when one component of the wave function spends time inside a hollow massive cylinder). Placed in orbit around earth, interferometers with large enclosed area will be useful for fundamental gravitational measurements such as tests of parallel vector transport and the Lense-Thirring frame-dragging effect. As a byproduct of developing interferometers with larger separation for heavier particles, more stringent limits will placed on alternative theories of quantum decoherence that involve spontaneous projection. It may also be possible to observe some new sources of decoherence that are hard to shield out [Tegmark, 1993]. These advances in interferometer size will also enable better measurements of inertial effects such as gravitational fields, gravitational gradients, and in gyroscopes. These will have application to inertial navigation, geodesy, and prospecting.

Precision in atom and molecular interference experiments will also be increased by using higher fluxes and longer interaction times. This also implies larger instruments in order to reduce the atom densities, thus reducing the systematic shifts due to atom-atom interactions. However, more imaginative approaches are needed since atom-atom interactions can be a severe problem. For example, they are one of the limiting factors for the Cs atomic fountain clocks, all interferometers using Bose-Einstein condensates, and they modify the index of refraction of near-resonant light passing through even non-degenerate atom samples. There are at least two solutions to the problem:

- If one uses ultracold fermions in a single atomic state, the Pauli exclusion principle switches off the s-wave interaction. Since for neutral atoms at ultracold energies the higher partial waves can be ignored, a fermionic ensemble is nearly interaction free, and therefore ideal for precision measurements. This was nicely demonstrated in the Bloch oscillation experiment by [Pezze et al., 2004].

- The second solution is to put each atom in a separate potential well, for example in an optical lattice. Having only one atom per well vastly reduces the nonlinear interaction. The effects of these additional potential wells can be mitigated by using light that energy shifts the interfering states equally.

Application of atom interferometers to atomic and molecular physics will benefit from advances in precision and should continue to provide definitive measurements with higher precision. A key application will be determination of polarizabilities and stark shifts for atoms and molecules in applied fields. These will serve as benchmark measurements to test and refine atomic theory calculations as discussed in Section V.

Since atoms are very small, techniques for their manipulation on small scales will open up many scientific frontiers and technical possibilities in surface physics, nanophysics, and quantum information. The rapid pace of current developments in atom chips, and the more creative use of focused light beams and light crystals are both leading to techniques for producing, detecting, and coherently manipulating atoms on very small spatial scales, e.g. where tunneling can be carefully studied.

Small interferometers will enable novel applications in surface science. Atom interferometry can be used to (a) measure fundamental atom-surface interactions like the Van der Waals and Casimir potentials or (b) study the temporal and spatial behavior of electro-magnetic fields close to the surface. This will allow new probes of surface structure- both magnetic and electric. The nature of thermally induced time varying fields can be studied, both for its own sake and because such fields induce decoherence. This will lead to engineering advances that reduce deleterious decoherence close to surfaces, advancing quantum information technology that uses ions and atoms close to surfaces as q-bits.

Coherent atom optics generally, and interferometers in particular, will be applicable to a central problem in quantum information science: how to characterize, control and use entanglement and correlations in atomic ensembles. The challenge here will be to prepare the ensembles in complex quantum states with high fidelity, and to develop methods for their characterization - with decoherence reduced as much as possible (or with its effects reduced by error-correction methods). One helpful new interferometric technique will be the development of powerful homodyne and heterodyne methods for detecting atoms, in analogy to quantum optics. This will be greatly aided by the development of detection methods with high quantum efficiency, which are also highly desirable in studying atom-atom correlations, particularly of higher order.

Having a good understanding of the electromagnetic atom-surface interaction, and ways to mitigate near-surface decoherence, the physics community will have a tool to search for fundamental short-range interactions, as predicted in some unified theories. In principle atom interferometry has the potential to improve the present limits on non-Newtonian gravitational potentials at the micrometer length scale by many orders of magnitude [Dimopoulos and Geraci, 2003]. The main challenge here will be to control the systematic effects, mainly coming from the electromagnetic interactions of the atom with the close by surfaces, and the atom-atom interactions as discussed below. Smaller and more compact atom interferometers also have application to inertial sensors for commercial applications.

Atom interference will be one of the central tools in the study of many-atom systems generally and of atoms...
in lattices that model condensed matter Hamiltonians in particular. First, diffraction peaks are the hallmark of atoms in the regime where tunneling dominates in a periodic lattice \cite{Bloch2000}. As more complex lattices are studied, higher order interference will play a role. In their turn, these lattices can have regions where a particular number of atoms are confined in each lattice site; this suggests a way to make a source of atomic number states allowing studies of degenerate atomic systems. Especially interesting in this arena will be the study of phase transitions in mesoscopic ensembles, which are too large to permit full quantum calculations, but too small for the thermodynamic description to be valid. This will give us a new and detailed look at the thermodynamic border. There are many new avenues to explore with dense degenerate quantum gases. In the present review we focused on single particle interference or in the language of quantum optics: to first order coherence. One very fruitful avenue will be extension to multi particle interferometry, which can give more rapidly varying fringes and sub-shot noise statistical precision. Detecting higher order coherences requires measurements of correlations between N atoms. Noise correlation with bosons and fermions \cite{Altman2004,Gritsev2006,Hofferberth2006,Hofferberth2007b,Morsch2006,Polkovnikov2006} are examples of recent developments in this field.

The field of atom and molecular interference is young but has already impacted atomic and quantum physics across a broad frontier. New techniques and the application of previously developed techniques to new scientific problems promises much future scientific gain.

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### TABLE VI Selected books, special journal issues and review articles germane to atom interferometers

#### Books:

- **Atom Interferometry** *(Berman, 1997)*
- **Atom Optics** *(Meystre, 2001)*
- **Laser Cooling and Trapping** *(Metcalf and van der Stratten, 1999)*
- **Neutron Interferometry** *(Rauch and Werner, 2000)*
- **Electron Interferometry** *(Tonomura, 1999; Tonomura et al., 1999)*
- **Molecular Beams** *(Ramsey, 1985)*
- **Atomic and Molecular Beam Methods** *(Scoles, 1988)*
- **Atomic, Molecular, and Optical Physics Handbook** *(Drake, 1996)*
- **Atom and Molecular Beams, State of the Art** *(Campargue, 2000)*
- **Encyclopedia of Modern Optics** *(Robert D. Guenther and Barvel, 2004)*

#### Special Journal Issues

- JOSA-B: Mechanical effects of Light (1985)
- JOSA-B: Mechanical effects of Light (1989)
- JOSA-B: Atom Optics (1992)
- Applied Physics B **54** (1992)
- JOSA-B: Atom Optics (1994)
- Journal de Physique: Optics and Interferometry with Atoms, **4**, (11), (1994)
- SPIE Conference on Atom Optics *(SPIE, 1997)*
- Journal of Modern Optics: Quantum State Preparation and Measurement **44** (1997)
- Comptes Rendus de L’Academie des sciences Dossier on BEC and atom lasers, t.2 serie IV, (2001)
- General Relativity and Gravitation, **36** (10) (2004)
- Insight Review Articles in Nature **416** (2002)
- Applied Physics B: Quantum Mechanics for Space Application **84**, (4), (2006)

#### Selected review articles:

- Atom Optics *(Pritchard, 1991)*
- Atom Interferometry *(Schmiedmayer et al., 1993)*
- The Feynman Path-Integral Approach to Atomic Interferometry - a Tutorial *(Storey and Cohen-Tannoudji, 1994)*
- Atom Optics *(Adams et al., 1994)*
- Atom Interferometry *(Carnal and Mlynek, 1996)*
- de Broglie Optics *(Wilkens, 1996)*
- Precision atom interferometry *(Peters et al., 1997)*
- Matter-wave index of refraction, inertial sensing, and quantum decoherence in an at. interf. *(Hammond et al., 1997)*
- Interferometry with atoms and molecules: a tutorial *(Pritchard et al., 1997)*
- Atomic interferometry *(Baudon et al., 1999)*
- Prospects for atom interferometry *(Godun et al., 2001)*
- Atom optics: Old ideas, current technology, and new results *(Pritchard et al., 2001)*
- Miniaturizing atom optics: from wires to atom chips *(Schmidmayer and Folman, 2001)*
- Coherence with atoms *(Kasevich, 2002)*
- Microscopic atom optics: from wires to an atom chip *(Folman et al., 2002)*
- Atom Interferometry *(Miffre et al., 2006a)*

For nonlinear atom optics see:

- Nonlinear and quantum atom optics *(Rolston and Phillips, 2002)*
- Nonlinear atom optics *(Anderson and Meystre, 2003)*
- Physics with coherent matter waves *(Bongs and Sengstock, 2004)*
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