

Atom optics: Old ideas, current technology, and new results

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Abstract. Atom optics is the coherent manipulation of the atomic matter waves originally postulated by the developers of quantum mechanics. These pioneers also proposed the use of stimulated light forces to manipulate particles. These ideas have been combined with current technology to produce the field of atom optics. This, in turn, has shed new light on old quantum problems like the which way problem and the origins of quantum decoherence. Bose Einstein condensates combine naturally with atom optics to produce new results such as the coherent amplification of matter waves. This review of atom optics traces these connections.

Keywords: quantum physics, atom optics, de Broglie, matter wave interferometer, atom laser, decoherence

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1 Introduction

As its title suggests, this paper concerns the interrelationship of three themes: the fundamental physical principles that underly atom optics, the current technologies which make atom optics a reality, and the scientific results that have recently been obtained using atom optics. In this introduction we first turn briefly to the technology of atom optics, adopting the engineering viewpoint that atom optics is basically the development and perfection of techniques and devices which can manipulate the atom waves coherently [1].

The earliest demonstration of atom optics involving coherent atom waves was the diffraction of atoms from crystal surfaces by Estermann and Stern in 1930 [2]. The observed diffraction pattern (Fig. 1) and its velocity dependence constitute the first demonstration that atoms (or any other heavy particle) propagate as waves. Unfortunately, surface diffraction has not yet been used to make atom wave devices, in part because of the difficulty of aligning sequential crystals with the required tolerance. Therefore this pioneering demonstration cannot be regarded as the foundation of atom optics. Matter wave interferometry with electrons [3–5] and neutrons [6, 7] was demonstrated several decades before related work on atom optics. We shall now address the causes of this - indeed with some humility, in view of the simplicity of atom sources relative to neutron reactors!

From our engineering perspective, matter wave optics consists of lenses, mirrors, beam-splitters, and other components of an optics toolkit. The fact that electron and neutron matter waves can both be transmitted through solid material, and electrons reflected or refracted by static electromagnetic fields, has enabled optical elements to be created for them. For atoms, however, finding suitable materials for lenses or mirrors is a daunting task, as with rare exceptions (e.g. cold H on liquid He [8]) atoms stick to surfaces rather than bouncing from or passing through them. This was the major obstacle which delayed the blossoming of atom optics until the mid 1980's.

This obstacle has now been overcome, but only with difficulty. Electromagnetic fields (whose spatial configuration is severely constrained by Maxwell's equations) can change the potential energy of neutral atoms, but provide only a weak and highly dispersive index of refraction based on the atoms' polarizability or magnetic moment (since their charge is zero). These effects are tremendously enhanced if the electromagnetic fields oscillate near a resonant transition frequency of the atom. Additionally, resonant photons can impart momentum to atoms by spontaneous scattering, although this generally destroys the atoms' spatial coherence. Alternatively, thin sheets of matter with patterned holes can be used as elements of absorptive atom optics, such as diffraction gratings, zone plates, and holograms. Thus, current day technologies including the tunable laser and nanofabrication techniques have been required for the development of useful atom optics. This explains the belated development of atom optics relative to electron and neutron optics: unlike atoms, both electrons and neutrons can pass through matter, allowing construction of transmission optical elements, and in addition, electric and magnetic fields exert much larger forces on charged particles compared to neutral atoms.

The primary objective of matter wave optics is to manipulate matter waves coherently, preserving their phase. However, incoherent manipulations bring new possibilities, for example increasing the brightness of an atom source, and are therefore an important part of atom optics. The flood of recent incoherent atom optics including atom slowers and atom traps, and their application to create Bose Einstein condensates, sets atom optics apart from earlier matter wave optics with electrons and neutrons. In turn, these sources of slow atoms simplify coherent manipulation of atoms and create new scientific possibilities. These applications, and their intellectual history, form the basis of this paper.

2 Optics for atoms

The pioneers of quantum mechanics suggested two basic types of near-resonant light forces on atoms that have recently been incorporated into atom optics. In 1917 Einstein considered an atom in a blackbody cavity in a paper best known for inventing the concept of stimulated emission and showing its relationship to spontaneous radiative decay and absorption [9]. Although less well known, Einstein says "The most important result seems to me, however, to be the one about the momentum transferred to the molecule in spontaneous or induced radiation processes." In this paper, twelve (!) years after he invented the concept of the photon with quantized energy $E = h\nu$, Einstein asserts that photons transfer momentum $p = \hbar k$ in induced processes, and

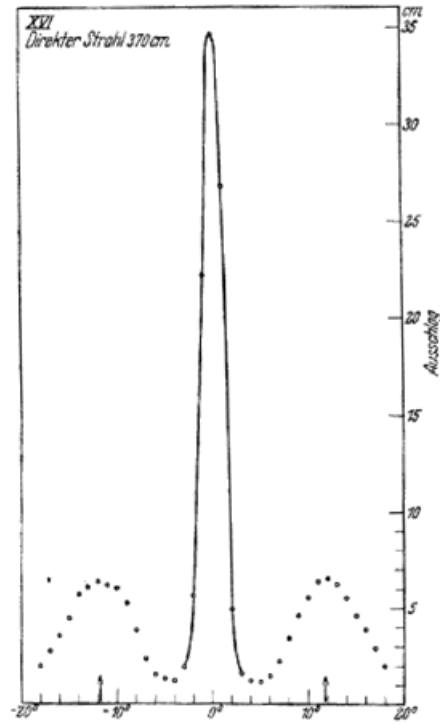


Fig. 1 Eastermann and Stern's diffraction data from 1930. A helium beam was scattered from a LiF crystal which was rotated through a range of angles. The scattered atom flux shows clear diffraction peaks beside the specularly reflected central peak.

makes the bolder assertion that the momentum $\hbar k$ has a direction even in spontaneous decay. (A classical dipole spontaneously radiates energy symmetrically with no net momentum transfer.) This leads to the result that atoms are heated by the recoil of the spontaneously emitted photons. This process that is shown to counteract the slowing due to their motion in the (red-biased) spectrum of the cavity so as to maintain their Maxwell-Boltzmann velocity distribution. Clearly this paper should be considered the first light-cooling paper!

Radiation forces which involve spontaneous decay have the disadvantage that they destroy the spatial coherence of the atom wave since the scattered photon can be used to localize the position of the atom. However, these scattered photons have a great redeeming asset: they can carry away entropy from the atoms, leaving them more densely packed in phase space (i.e., cooler). Optical pumping is the clearest example of this: a collection of atoms initially in several internal states can all be pumped into one of these states. This idea can also be applied in phase space [10] or in momentum space [11, 12]. We shall not elaborate on these possibilities further since they lie at the heart of laser cooling which is discussed in several other papers in this issue.

A way for light to interact with particles *without* destroying their coherence was

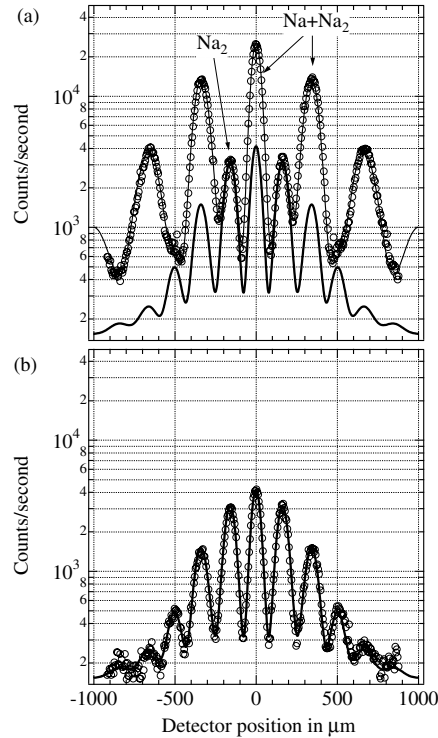


Fig. 2 Diffraction pattern from a combined beam of both atoms and molecules after passing through a nanofabricated transmission grating (top). After removing the atoms from the beam (using resonant light forces), only the molecular diffraction remains visible (bottom).

suggested by Kapitza and Dirac in 1933. They proposed the use of stimulated scattering, in which a photon scatters from one traveling light wave into a second, by two induced processes: absorption followed by stimulated emission. This process imparts momentum equal to the difference of the two photon momenta. For atom opticians, this is a much more useful process than spontaneous scattering because the amount and direction of the momentum transfer can be accurately controlled. Most importantly, coherence of the atom's wave function is maintained by this process if the light beams are coherent (e.g. spatially extended beams from lasers).

As theorists, Kapitza and Dirac can be forgiven for suggesting that this process might be observed for photons scattering from electrons - in which case the relevant process is stimulated Compton scattering. This process has a tiny cross section, equal to the classical electron radius squared, $\sigma_{\text{Compton}} = (8\pi/3)(e^2/mc^2)^2 \approx 6 \times 10^{-25} \text{cm}^2$ and can only be observed using extremely high laser intensities [13–15]. If the electrons are replaced by atoms, however, the scattering cross section for resonant light $\sigma_{\text{atom}} = (1/2\pi)\lambda_{\text{photon}}^2 \approx 4 \times 10^{-10} \text{cm}^2$ is 15 orders of magnitude larger. With atoms,

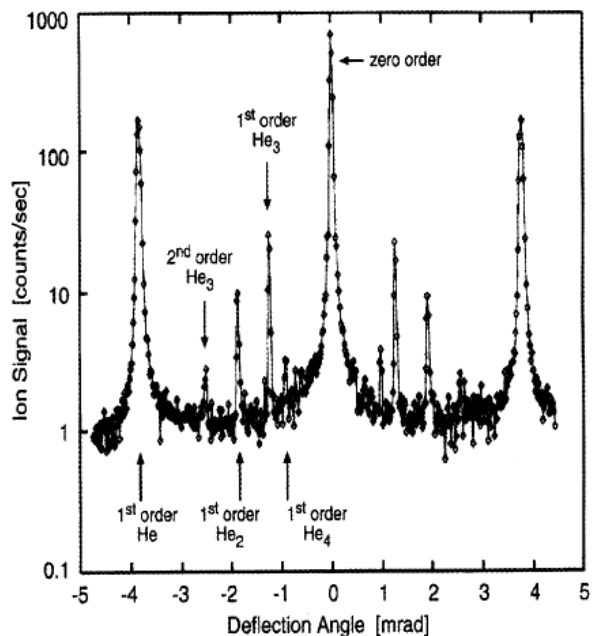


Fig. 3 Helium dimers and trimers were detected using molecular beam diffraction to separate molecules by their de Broglie wavelength, or diffraction angle.

stimulated scattering has emerged as the chief tool of coherent atom manipulation. The use of near-resonant light, required to get significant momentum transfer with cw lasers, makes the resulting atom optical elements specific to the atomic species and even to the atom's internal state.

The development of nanotechnology offers an alternative way to fabricate coherent atom optical elements. Nanofabricated atom optical elements differ from those based on light forces in a number of ways: they are amplitude structures (with corresponding loss of transmission intensity), they are species-independent, their scale size can be several times smaller than attainable with light, and they can be arbitrarily patterned. These features are demonstrated in Fig. 2, where a beam of Na_2 molecules and Na atoms is diffracted and separated by a nanofabricated diffraction grating. The flexibility of nano-lithography has allowed fabrication not only of diffraction gratings [16], but also of spherical and cylindrical zone plates [17], as well as a combination of lens and hologram that generated a focused atom image with 10^4 resolution elements [18,19]. One stunning application laid to rest a long standing argument concerning whether a stable bound state of the $^4\text{He}_2$ dimer exists. For this a diffraction grating was used to separate and resolve $^4\text{He}_2$ and larger clusters, $^4\text{He}_n$ [20] (Fig. 3). Subsequently a nano-sieve was used to estimate the size of the $^4\text{He}_2$ dimers to be $62 \pm 10 \text{ \AA}$ [21].

3 Bragg scattering

In 1912, Max von Laue suggested that the then newly discovered X-rays could be diffracted by crystals because X-ray wavelengths were similar to the atomic spacing in crystals. Friedrich, Knipping and Laue were able to experimentally observe “Laue” spots in X-ray diffraction of crystals [22] (see Fig. 4). Laue was honored for this discovery with the Nobel Prize in 1914. W.L. Bragg explained [23] that for strong reflection from the crystal, incident waves scattered from each successive crystal layer must add coherently (i.e. interfere constructively). This requires that X-rays of wavelength λ_x approach the crystal planes (of spacing d), at an angle θ_B (measured with respect to the crystal planes) given by

$$N_B \lambda_x = 2d \sin \theta_B, \quad (1)$$

where N_B is an integer. This simple relation explains the data in Fig. 4. Equation 1 is known as Bragg’s Law and N_B denotes the Bragg diffraction order. W.L. Bragg and his father W.H. Bragg went on to perform a series of experiments to measure crystal structures using X-ray diffraction [24]. The work earned them the Nobel Prize in 1915. It is interesting to note that this work also brought together the previously disparate fields of crystallography and X-ray physics and helped establish that X-rays are a form of electromagnetic radiation.

Just as electromagnetic waves can scatter from a regularly arranged atomic potential, atom waves can scatter from the regular structure of a standing wave of near resonant light. Bragg scattering of a supersonic beam of sodium atoms from a wide standing light wave was first observed at MIT in 1988 [25]. The angle between the atomic beam and the light grating was tuned to the appropriate Bragg angle and population transfer (Fig. 5) in both first and second order Bragg scattering was observed. The experiment required sub-recoil momentum spread of the atomic beam in the transverse direction to resolve the different momentum states in the far field. Pendellösung, an oscillation in population transfer as a function of standing wave intensity, was also observed. (Note that it is not possible to change the intensity of the scattering centers in a crystal!) This oscillation can be understood as Rabi-flopping between two momentum states which are coupled by a two photon process, the Rabi frequency of which is proportional to the standing wave intensity.

The velocity distribution in a sodium Bose-Einstein Condensate (BEC) is approximately 1mm/sec, about 1/30 of the recoil velocity, suggesting that Bragg scattering should be easy to observe with a BEC. To Bragg diffract atoms initially in a stationary BEC, it is easier to move the light crystal than to accelerate the condensate. This is done by frequency shifting one of the traveling waves so that the resultant standing wave formed by its interference with the unshifted traveling wave moves with the proper velocity ($N_B \hbar k / m$) relative to the stationary atoms to impart the necessary momentum. The Bragg scattered atoms will then have momentum $2N_B \hbar k$ in the laboratory frame. The resonance condition thus becomes a condition on relative detuning between the two laser beams forming the diffraction grating

$$\delta_{N_B} = N_B (2\hbar k^2 / m) \quad (2)$$

for N_B th order Bragg diffraction.

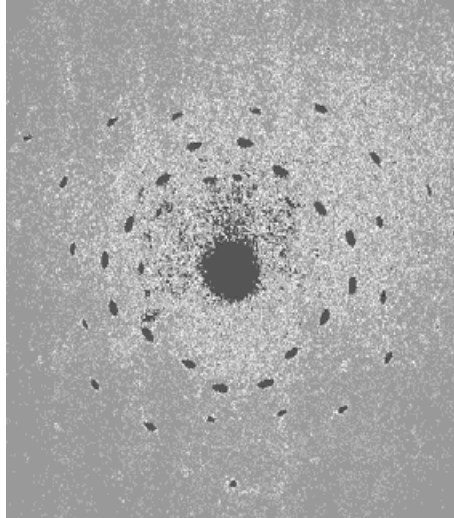


Fig. 4 Photograph of diffracted X-rays (Laue spots) from a crystal of cubical Zinc blende. W.L. Bragg explained this observation by postulating the now celebrated Bragg Law. Each spot corresponds to a solution of Equation 1. The central large spot is the undiffracted X-ray beam. The X-ray source used is broadband, but directional. This causes the Bragg relation to be satisfied for several crystal planes, each acting as a reflecting surface for a particular wavelength and its submultiples. Thus multiple spots can be seen, each corresponding to a distinct crystal plane. Figure from Ref. [23]

The first demonstration of Bragg scattering in BECs was at NIST, Gaithersburg in 1999 [26] by Phillips and co-workers. They used Bragg scattering mainly as a tool to manipulate the momentum of the BEC (with up to $N_B = 6$). At MIT the interaction time was lengthened, increasing the frequency specificity and creating a new type of spectroscopy (Bragg Spectroscopy) of the condensate that was used to observe the momentum distribution of a BEC in a magnetic trap [27]. The width of the Bragg resonance curve (Fig. 6) was primarily due to a Doppler-broadening of 2 kHz which yielded the condensate's momentum distribution. This distribution was at the Heisenberg uncertainty limit imposed by the finite size of the condensate, establishing for the first time that the coherence length of the condensate was equal to its size. In addition, the narrow Bragg resonance was shifted by the repulsive interactions within the condensate, resulting in a spectroscopic measurement of the mean-field energy.

4 Kapitza-Dirac scattering

Diffraction of neutral atoms from a standing wave of near resonant light with a short interaction time (generally much shorter than the inverse recoil frequency) has come to be called Kapitza-Dirac scattering, in honor of their pioneering suggestion [13]. The atomic motion during the interaction time is small compared to the characteristic

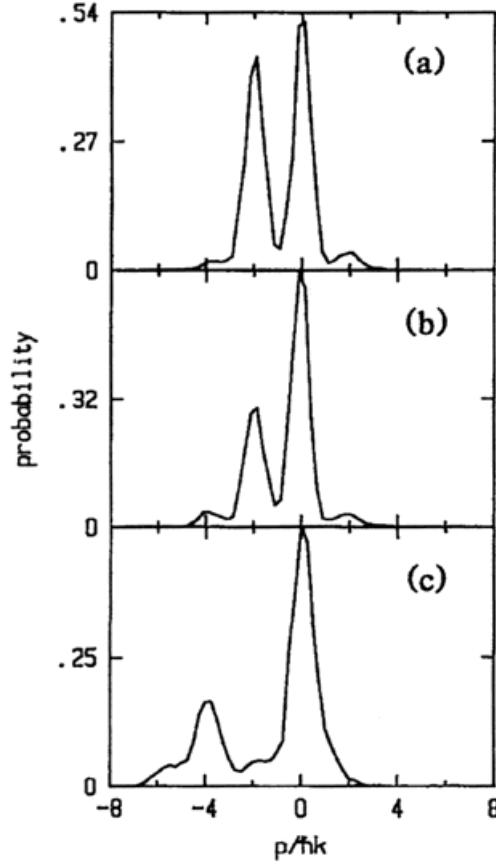


Fig. 5 Bragg scattering of an atomic beam from an optical standing wave. First-order Bragg scattering at (a) lower power, (b) higher power of laser beams (pendellösung has set in, increasing the amplitude of the undeflected peak). (c) Second order Bragg scattering.

dimensions of the interaction potential. Approximating the standing wave potential at a minimum as parabolic, an oscillation frequency, ω_{osc} , can be estimated which also limits the interaction time τ from above. Thus Kapitza-Dirac scattering is limited to short interaction times τ_{KD}

$$\tau_{KD} \ll \frac{1}{\omega_{rec}}, \frac{1}{\omega_{osc}}. \quad (3)$$

This is equivalent to the eikonal (thin-lens) approximation for scattering (optics). The idea is that the phase of the incident particle changes along each classical trajectory, but not the amplitude. Furthermore there may be momentum transfer perpendicular to the trajectory, but the trajectory is not significantly displaced (until after the interaction is over).

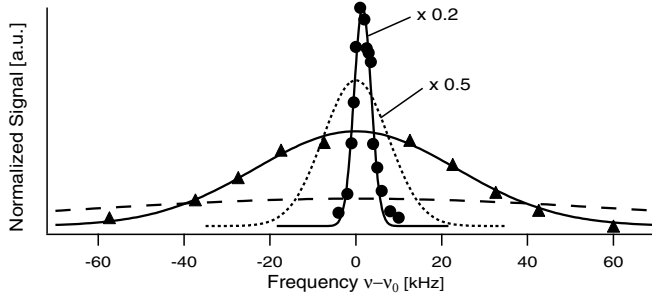


Fig. 6 Bragg resonances for a trapped condensate (solid circles) and 3 ms after release (triangles). Plotted is atom number (normalized to the total number) versus frequency detuning of the laser beams from $\nu_0 = 2\omega_{rec}/\pi$, the Bragg resonance frequency for isolated cold atoms. For comparison, the momentum distributions of the ground state of the trapping potential (dotted curve) and of a $1\mu\text{K}$ cold, thermal cloud (dashed curve) are indicated. The heights of the curves for the trapped condensate and the ground state momentum distribution are scaled down as indicated in the figure.

The Eikonal approximation allows Kapitza-Dirac scattering to be described as simply a phase modulation of the atomic wave-function due to the AC Stark shift potential of the standing wave. The standing wave imprints a sinusoidal phase variation which develops, in the far field, into a Bessel function distribution of intensities in the various diffracted orders [28, 29].

Kapitza-Dirac diffraction of atoms was first observed at MIT in 1986 [28]. Diffraction of a well-collimated supersonic atomic beam was observed after passage through the tightly focussed waist of a near-resonant standing wave. Significant diffraction into momentum states $|g, \pm 10\hbar k\rangle$ was observed with a thermal atomic beam [28] (see Fig. 7). Even higher diffracted orders should be observable in the future using laser beams directed at small Bose-Einstein Condensates for somewhat longer times.

For larger interaction times, $\tau > \tau_{osc}$, the atomic system undergoes a periodic refocussing in both momentum and position space due to oscillations in the wells of the periodic potential. This regime has been observed in a BEC by the Phillips group [29].

5 Atom interferometry

In the 19th century, Fizeau (1853), Michelson (1881), Rayleigh (1881), and Fabry and Perot (Fabry 1899) exploited the interference properties of light waves to create the light interferometer which has since resulted in many beautiful experiments and precise measurements. We do not know of suggestions by de Broglie and Schroedinger to make matter wave interferometers, but using technologies invented since the start of the Second World War, their basic ideas have led to the construction of interferometers for neutrons, electrons, and atoms. These new interferometers are proving to be valuable

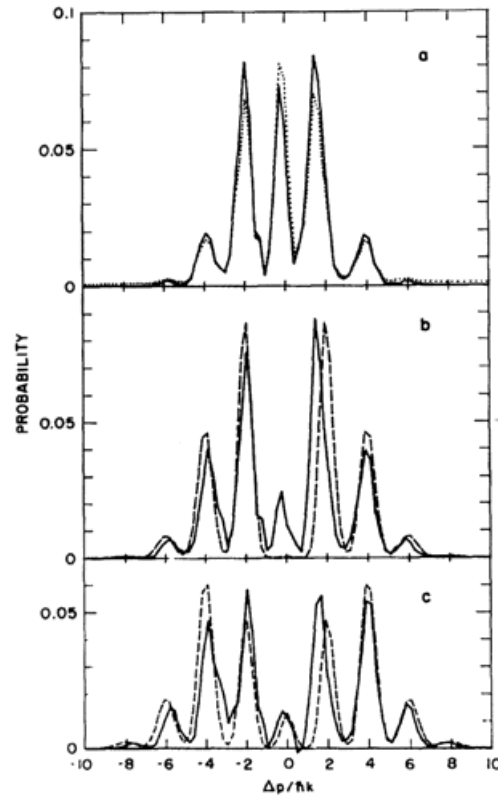


Fig. 7 Kapitza-Dirac diffraction of an atomic beam from a standing wave light grating. (a),(b),(c) are arranged in ascending order of standing wave intensity. From (a) to (b), the standing wave detuning from resonance is decreased. From (b) to (c), the standing wave intensity is increased. The solid lines are data and the dashed lines in (b) and (c) are the corresponding theoretical predictions. The dashed line in (a) is raw (uncorrected) data. Figure from Ref. [28].

tools for probing fundamental physics, for studying quantum mechanical phenomena, and for making inertial measurements. For an overview of matter wave interferometry see [30–32].

The scientific value of interferometry with atoms and molecules has long been recognized. In fact, the concept of an atom interferometer was patented in 1973 [33] and it has been extensively discussed since [34–37]. Atom interferometry offers great richness stemming from the varied internal structure of atoms, the wide range of properties possessed by different atoms (e.g., mass, magnetic moment, absorption frequencies, and polarizability), and the great variety of interactions between atoms and their environment (e.g. static E-M fields, radiation, and other atoms).

Light interferometers are generally based either on achromatic beam-splitters such as half-silvered mirrors or on other semi-transparent membranes whose structure is

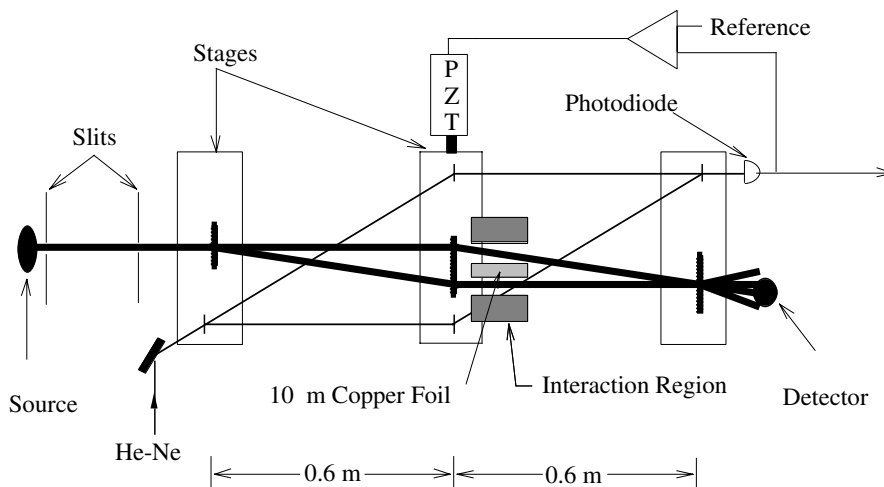


Fig. 8 A schematic, not to scale, of the MIT atom interferometer (thick lines are atom beams). The 0th and 1st order beams from the first grating strike the middle grating where they are diffracted into the 1st and -1st orders. These orders form an interference pattern in the plane of the third grating, which acts as a mask to sample this pattern. The detector, located beyond the third grating, records the flux transmitted through the third grating. The 10 cm long interaction region with the 10 μm thick copper foil between the two arms of the interferometer is positioned behind the 2nd grating. An optical interferometer (thin lines are laser beams) measures the relative position of the 200 nm period atom gratings (which are indicated by vertical dashed lines).

small compared to the wavelength of the wave they are splitting. Lacking structures that satisfy either of these requirements for atoms, diffraction gratings have been pressed into service as beam-splitters for atom waves. This means that atom interferometers are constrained to designs which somehow compensate for the dependence of diffraction angle on the wavelength of the individual atoms. In spite of this challenge, a surprising variety of atom and molecule interferometers have been built since 1991. A majority have used the three-grating configuration in which the first grating splits the incident beam, the second reverses the differential momenta given by the first, and the third recombines the two beams at the location where they overlap [38]. Both material and light gratings have been developed and used in the Raman-Nath, Bragg, and adiabatic regimes to obtain interference fringes in either position or internal state space.

Figure 8 shows a three-grating atom interferometer for a supersonic Na beam which features sufficient separation between interfering paths to accommodate an interposed metal foil [39], allowing different fields or media to act on the atom waves on either side of the barrier. Thermal or supersonic beam interferometers have since been made for Ar*, Ca, Cs, He*, K, Mg, Ne*, Rb, and Na₂ and I₂ molecules, interferometers starting with trapped atoms have been made for Cs, Ca, He*, Mg, and Rb, and interferometers

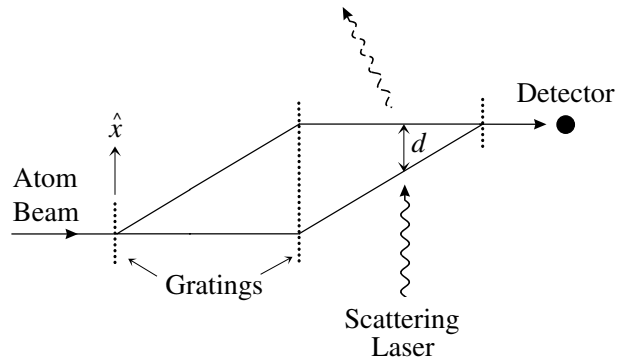


Fig. 9 Realization of the Feynman light microscope gedanken experiment in an atom interferometer. Photons are scattered from a two-path atom interferometer where the paths are separated by a distance d . In Ref [43] the photons were scattered from the symmetrical location near the first grating.

using Bose-Einstein condensates have been demonstrated with Na and Rb.

Recently, the MIT atom interferometer was used to explore wave-particle duality, perhaps the most counter-intuitive aspect of quantum mechanics. This old quantum conundrum was discussed at the 1927 Solvay Congress [40] in the famous Einstein-Bohr debate concerning the two-path interferometer: could one know which path the particle took and still observe the interference of the waves? According to Feynman, this experiment “has in it the heart of quantum mechanics. In reality it contains the only mystery.” [41]. In 1960, Feynman proposed a gedanken experiment now known as the “Feynman light microscope” in which a perfect light microscope (i.e., a Heisenberg microscope) is used to determine “which-way” information in a two-slit experiment with electrons by analyzing a single scattered photon. In Feynman’s analysis of this experiment, loss of visibility of the interference pattern occurs when the light wavelength is shorter than the separation between the two slits, allowing which-path information to be obtained from a single scattered photon.

To realize the experiment Feynman proposed, single photons were scattered from atoms within a two-path atom interferometer at different locations corresponding to different spatial separations of the interfering atom waves (Fig. 9). If the scattered photons had been collected with a microscope, they could have been used to localize the atom with a maximum resolution limited to roughly half the wavelength of the photon. From the principle of complementarity, which forbids simultaneous observation of wave and particle behavior, we conclude that the atomic interference (a manifestly wave-like behavior) must be destroyed when the separation of the interfering paths, d , exceeds the wavelength of the probe (i.e. when it is possible to identify which path the atom traversed). Note that this is true whether or not one actually looks with the microscope—the ability in principle to identify the atom’s path is enough to destroy the interference pattern.

The experimental results are displayed in Fig. 10. As Feynman predicted, the

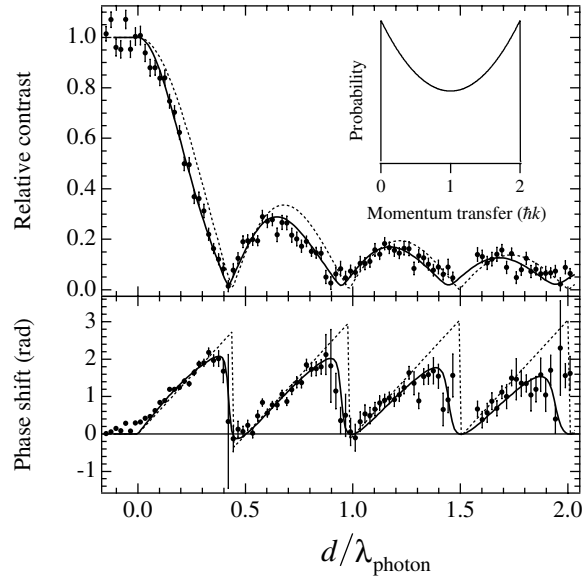


Fig. 10 Relative contrast and phase shift of the atom interference pattern as a function of the separation of the interfering arms at the point of scattering. The inset shows the angular distribution of spontaneously emitted photons projected onto the axis. The dashed curve corresponds to purely single photon scattering, and the solid curve is a best fit that includes contributions from atoms that scattered 0 photons (4%) and 2 photons (14%). From Ref. [43].

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 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 [42], but Feynman would be reassured to note that they occur where the prominent diffraction rings of a perfect light microscope would lead to path ambiguity.

The realization of Feynman’s gedanken experiment demonstrates that, depending on whether which-path information is available, matter sometimes behaves as particles and other times as waves. But Feynman says, “It really behaves like neither.” He continues:

Because atomic behavior is so unlike ordinary experience, it is very difficult to get used to and it appears peculiar and mysterious to everyone both to the novice and to the experienced physicist. Even the experts do not understand it the way they would like to, and it is perfectly reasonable that they should not, because all of direct, human experience and of human intuition applies to large objects.

6 Quantum decoherence

This acknowledgement that the classical and quantum worlds bear little resemblance to each other raises another profound question: if quantum mechanics is the correct underlying theory of the classical world, why are its hallmark features of interference and nonlocality not manifest in that world? This question is central to the field of quantum decoherence. Decoherence is now understood as the dynamical processes coupling a quantum system to an outside environment which tend to reduce coherent quantum superpositions into incoherent mixtures. The amount of decoherence typically depends exponentially on the number of environmental degrees of freedom involved. Thus, macroscopic objects lose their quantum coherence almost instantaneously compared to microscopic objects, simply because they scatter light or gas particles at a far greater rate than do microscopic objects.

The experiment just described already gives a hint of how classical behavior is obtained when a system becomes coupled to an uncontrolled environment. When an atom within the interferometer is isolated from its environment it exhibits interference: a wave-like property. On the other hand, when we scatter photons from the atom we find that it behaves as if it were localized on one or the other trajectory of the interferometer as classical intuition requires.

The origin of this behavior (and of decoherence generally) is quantum entanglement. The wave function of a quantum object that interacts with anything outside of itself becomes entangled with that environment and the two can no longer be considered separate entities, even after the interaction ends. If an atom within a two-path atom interferometer, whose wavefunction is peaked at two positions which we label x and $x + d$, interacts with the environment (e.g., scatters a photon), the atom and environment become entangled:

$$|\psi\rangle_i = \left(|x\rangle + |x + d\rangle \right) \otimes |e_0\rangle \xrightarrow{\text{interaction}} |x\rangle \otimes |e_x\rangle + |x + d\rangle \otimes |e_{x+d}\rangle, \quad (4)$$

where $|e_0\rangle$ is the initial wavefunction of the environment and $|e_x\rangle$ is the post-interaction wavefunction of the environment 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

$$|\psi_e\rangle = |x\rangle + \beta(d)|x + d\rangle, \quad (5)$$

where

$$\beta(d) = \langle e_x | e_{x+d} \rangle \quad (6)$$

is known as the decoherence function.

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 $1 - \beta(d)$) to be found in the final state corresponding to the measured environment state.

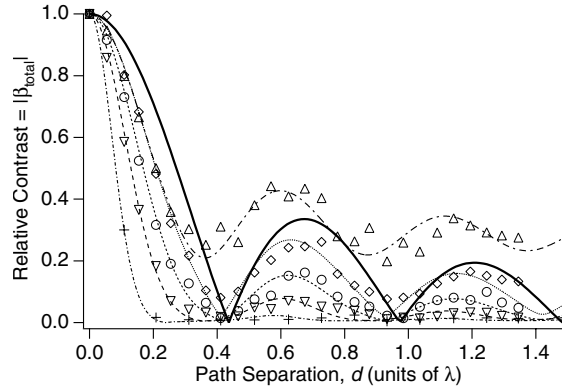


Fig. 11 Loss of contrast after spontaneous photon scattering. The solid line is the single photon decoherence function. The other traces represent data for different numbers of scattered photons. Also displayed are the best fits from which we determine the average number of scattered photons per atom $\bar{n} = 0.9$ (Δ), 1.4 (\diamond), 1.8 (\circ), 2.6 (∇), and 8.2 (+).

Whereas Eq. 5 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 [43].

The decoherence of macroscopic objects generally occurs much more rapidly than microscopic objects simply because there is a greater degree of entanglement with their environment—a large object will scatter more photons than a small one. 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 β for each scattered photon (with probability P_n of scattering n photons):

$$\beta_{\text{total}}(d) = \sum_{n=0}^{\infty} P_n \beta^n(d). \quad (7)$$

In Fig. 11 are the results of an experiment which measures atomic decoherence in the transition from the single to the many-photon regime. For increasing number of scattered photons, the overall amount of decoherence increases, and the contrast revivals present in the single-photon case disappear. If one were to observe the scattered photons, each successive photon 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.

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 photon translation operator $e^{-i\hat{k}_x d}$ to rewrite the right hand side of Eq. (4) (noting that $|e_{x+d}\rangle$ is simply $|e_x\rangle$ translated by d):

$$|\psi\rangle_i \xrightarrow{\text{interaction}} |x\rangle \otimes |e_x\rangle + |x+d\rangle \otimes e^{-i\hat{k}_x d} |e_x\rangle = \int d\mathbf{k} (|x\rangle + e^{-i\hat{k}_x d} |x+d\rangle) \otimes |\mathbf{k}\rangle \langle \mathbf{k} | e_x \rangle \quad (8)$$

This expression for the entangled atom-photon wavefunction makes clear that if one were to measure the momentum of the scattered photon, the atom would then be found in a superposition state with known phase shift between the two components, $\Delta\phi = (k_x - k_0)d$. The direction of the scattered photons is random, so k_x is random, and the phase of each atom's interference fringes will vary. The sum of many such single atom distributions - the measured interference pattern - will therefore have reduced contrast, with details dependent on the particular probability of the photon having final momentum \bar{k} .

We have discussed two views (which-way and dephasing) of the decoherence that accrues when an atom in an interferometer scatters photons. 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 [44]. Both predict decoherence, i.e., loss of contrast.

As our understanding of quantum mechanics evolves, and in particular, as we attempt to exploit quantum mechanics to create quantum computers or perfectly secure communication channels based on quantum entanglement, we encounter decoherence as a fundamental limit. 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 and quantum mechanical systems in which certain degrees of freedom are intrinsically decoherence free.

7 Atom amplification

Einstein's 1917 paper on the A and B coefficients introduces stimulated emission, the basic physics behind the laser: that an excess population in the upper of two atomic energy levels will cause stimulated emission to predominate over absorption, and result in amplification of radiation. Einstein invented the concept of stimulated emission to avoid the unnatural condition of a population inversion, and this perspective made the laser – which exploits a population inversion – difficult to imagine. This, the realization that stimulated emission is coherent, and the need to develop high Q resonators delayed the development of the maser [45] and the optical maser or laser [46, 47].

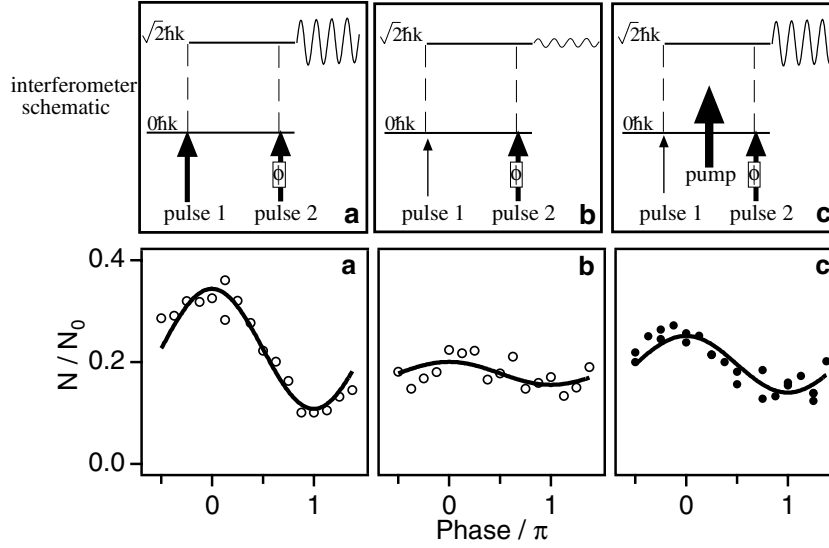


Fig. 12 Interference fringes in the number of transferred atoms as a function of relative phase between the two Bragg pulses (diffraction gratings). (a) Large contrast fringes from two equal strength Bragg pulses. (b) Reduced fringes from a weakened first pulse and a second pulse which has the same strength as in (a). (c) Contrast partially regained by applying an amplification pulse in between the two Bragg pulses. The Bragg coupled and amplified momentum state (lower state in the inverted system) is a 2-photon recoil state with absorbed and emitted momenta angled 90 degrees with respect to each other. Thus the recoil momentum is $\sqrt{2}\hbar k$ where k is the photon momentum.

We now turn attention to the atom laser, wondering whether the laser might also have an analog in atom optics, just as the atom optical devices described above are close analogs to the corresponding light optical devices which motivated their development. The obvious obstacle is the difference that photons are not conserved whereas atoms are (at least at easily accessible laboratory energies). This obstacle can be overcome by analogy with photon downconversion. We suggested an AASTE (Atom Amplifier using Stimulated Emission of Atoms) [1] based on the idea that atoms formed by dissociating molecules were “created” from the standpoint of the statistics of the atom population. This idea was developed by Borde [48], but has yet to be applied to the amplification of atoms.

The extraction of a coherent beam of atoms from a BEC has been demonstrated in a number of regimes: pulsed [49], cw [50, 51] and mode locked [52]. These are referred to as atom lasers primarily because the outcoupled atoms have coherence properties characteristic of laser light. It has also been argued that the condensate is produced by stimulated scattering analogous to stimulated emission in a laser [53]. But these atom lasers do not offer the possibility of phase coherent amplification of matter waves.

Recently, phase coherent amplification of an atom wave has been demonstrated

at MIT [54] and U. Tokyo [55]. It is enlightening to discuss the process from the perspective of the two sufficient conditions to make a laser: a population inversion and a gain mechanism strong enough to overcome the losses. Before discussing the mechanism, we note that an overriding theme of atom optics is to generalize the techniques for coherent control of atoms' internal states to their external (center of mass) motional states. Our preceding discussions of optical pumping in momentum space and atom interferometry represent examples of this perspective. In this view a BEC represents a population inversion with respect to every other point in momentum space! Having perceived this inversion, we need only a gain mechanism.

The recently discovered superradiant Rayleigh scattering [56] provides a gain mechanism capable of adding atom population to either a spontaneously generated velocity group or to atoms seeded into this velocity group. Gain results from the scattering of pump light from the atomic density grating formed by the superposition of the BEC and the atoms in the new velocity group. Each scattered photon transfers an additional atom from the BEC into the new velocity group, increasing the amplitude of the density grating. The process has enough gain to transfer a substantial fraction of the BEC to the new velocity group within the coherence time of the grating. This process shares similarities with lasing without inversion and also with CARL [57].

In order to determine whether this process is phase coherent, we first created an interferometer in which atoms in the new velocity group were created by two successive Bragg pulses which acted as diffraction gratings. Varying the phase of the second pulse relative to the first caused fringes in the number of atoms transferred versus relative phase (see Fig. 12). We then attenuated the first pulse and added the pumping light for the Rayleigh amplifier. As expected, the fringe contrast decreased with the attenuation and subsequently increased when amplification was applied, demonstrating phase coherent amplification of an atom wave. The amplification process had no observable phase shift [54].

8 Conclusion and future

This review has shown how the rapid recent development of atom optics, based on current technology, is interwoven with the birth and fundamental questions of quantum mechanics. While basic quantum theory which proposes the existence of coherent matter waves is prerequisite for designing atom optical elements and techniques, experiments with new atom optics have provided atom interferometers and Bose-Einstein condensates which deepen our understanding of decoherence and other nuances of quantum theory. In conclusion we look briefly the other way: toward the future. We have not touched on the successes of atom optics in precise measurement of inertial effects, atomic properties, and fundamental quantities [32]. Yet the levels of accuracy already obtained with such young techniques portend even greater future successes in these important areas. Another area that is on the brink of spectacular development is the confinement of coherent matter waves in atom waveguides and the development of the scientific and technological opportunities that these represent. While we have described the application of nanofabrication techniques to atom optics, it is possible to imagine technology transfer in the other direction. The fundamental problem of

fabricating ever smaller structures might be tremendously advanced by atom optics because the de Broglie wavelength of even cold atoms is much smaller than that of light, permitting them to be focussed to directly deposit much smaller features than possible with photolithography.

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References

- [1] D. E. Pritchard, in *Twelfth International Conference on Atomic Physics*, edited by W. Zorn, Lewis (American Institute of Physics, Michigan, 1990), Vol. 12, pp. 165–174
- [2] I. Estermann and A. Stern, *Z. Physik* **61** (1930) 95
- [3] L. Marton, *Phys. Rev.* **85** (1952) 1057
- [4] J. Marton, L. Simpson and H. Suddeth, *Rev. Sci. Instrum.* **25** (1954) 1099
- [5] M. G. and H. Duker, *Naturwissenschaften* **42** (1955) 41
- [6] H. Maier-Leibnitz and T. Springer, *Z.Phys.* **167** (1962) 368
- [7] H. Rauch, W. Treimer, and U. Bonse, *Phys. Rev. A* **47** (1974) 369
- [8] J. J. Berkhout, O. J. Luiten, I. D. Setija, T. W. Hijmans, T. Mizusaki, and J. T. M. Walraven, *Phys. Rev. Lett.* **63** (1989) 1689
- [9] A. Einstein, *Physikalische Zeitschrift* **18** (1917) 121
- [10] V. S. Bagnato, G. P. Lafyatis, D. E. Pritchard, K. Helmerson and A. Martin, in *Eighth International Conference on Laser Spectroscopy*, edited by W. P. Svanberg and S. (Springer-Verlag, Are, Sweden, 1987)
- [11] A. Aspect, E. Arimondo, R. Kaiser, N. Vansteenkiste, and C. Cohen-Tannoudji, *Phys. Rev. Lett.* **61** (1988) 826
- [12] M. Kasevich and S. Chu, *Physical Review Letters* **69** (1992) 1741
- [13] P. L. Kapitza and P. Dirac, *Cambridge Phil. Soc., Proceedings* **29** (1933) 297
- [14] H. Schwarz, *Z. Phys.* **204** (1967) 276
- [15] H. C. Pfeiffer, *Phys. Lett.* **26A** (1968) 362
- [16] D. Keith, M. Schattenburg, H. Smith, and D. Pritchard, *Phys. Rev. Lett.* **61** (1988) 1580
- [17] R. B. Doak, R. E. Grisenti, S. Rehbein, G. Schmahl, J. P. Toennies, and C. Woll, *Phys. Rev. Lett.* **83** (1999) 4229
- [18] F. Shimizu, *Advances in Atomic Molecular, and Optical Physics, Vol. 42*, Vol. 42 of *Advances in Atomic Molecular and Optical Physics* (Academic Press Inc, San diego, 2000), pp. 73–93
- [19] J. Fujita, T. Kishimoto, M. Morinaga, S. Mitake, and F. Shimizu, *NEC Research and Development* **40** (1999) 401
- [20] W. Schollkopf and J. P. Toennies, *Journal of Chemical Physics* **104** (1996) 1155
- [21] F. Luo, C. F. Giese, and W. R. Gentry, *Journal of Chemical Physics* **104** (1996) 1151
- [22] W. Friedrich, P. Knipping, and M. v. Laue, *Sitzungsberichte der Königlich Bayerischen Akademie der Wissenschaften* **June 1912** (1912)
- [23] W. L. Bragg, *Proceedings of the Cambridge Philosophical Society* **17** (1912) 43
- [24] W. H. Bragg and W. L. Bragg, *X-rays and Crystal Structure* (G. Bell and Sons, Ltd., London, 1915)
- [25] P. J. Martin, B. G. Oldaker, A. H. Miklich, and D. E. Pritchard, *Phys. Rev. Lett.* **60** (1988) 515
- [26] M. Kozuma, L. Deng, E. W. Hagley, J. Wen, R. Lutwak, K. Helmerson, S. L. Rolston, and W. D. Phillips, *Phys. Rev. Lett.* **82** (1999) 871

- [27] J. Stenger, S. Inouye, A. P. Chikkatur, D. M. Stamper-Kurn, D. E. Pritchard, and W. Ketterle, *Phys. Rev. Lett.* **82** (1999) 4569
- [28] P. L. Gould, G. A. Ruff, and D. E. Pritchard, *Phys. Rev. Lett.* **56** (1986) 827
- [29] Y. B. Ovchinnikov, J. H. Muller, M. R. Doery, E. J. D. Vredenburg, K. Helmerson, S. L. Rolston, and W. D. Phillips, *Phys. Rev. Lett.* **83** (1999) 284
- [30] U. Bonse and H. Rauch, *Neutron Interferometry* (Oxford University Press, Oxford, 1979), h. Rauch
- [31] G. Badurek, H. Rauch, and A. Zeilinger, *Physica B* **151**(1988) R9, experiments measuring the refractive index of gases are described in: H. Kaiser *et al.* *Z. Phys. A* **291** (1979) 231
- [32] *Atom Interferometry, Advances in Atomic, Molecular, and Optical Physics*, edited by P. Berman (Academic Press, San Diego, 1997)
- [33] S. Altschuler and L. Franz, Patent Atom Interferometers, 1973
- [34] V. Chebotayev, B. Dubetsky, A. Kasantsev, and V. Yakovlev, *J. Opt. Soc. Am. B* **2** (1985) 1791
- [35] C. J. Borde, *Phys. Lett. A* **140** (1989) 10
- [36] Special Issue on Atom Optics (1992), *Appl. Phys. B* **54**, (1992), a recent review of atom optics and atom interferometry is contained in the special issue
- [37] Special Issue on Atom Optics (1994), *J. Phys. II* **4**, (1994)
- [38] D. W. Keith, C. R. Ekstrom, Q. A. Turchette, and D. E. Pritchard, *Phys. Rev. Lett.* **66** (1991) 2693
- [39] J. Schmiedmayer, M. Chapman, C. Ekstrom, T. Hammond, D. Kokorowski, A. Lenef, R. Rubenstein, E. Smith, and D. Pritchard, in *Atom Interferometry*, Vol. Advances in Atomic and Molecular Physics of *Advances in Atomic, Molecular and Optical Physics*, edited by P. Berman (Academic Press, San Diego, 1997), pp. 2–83
- [40] N. Bohr in *A. Einstein: Philosopher - Scientist* edited by P. A. Schilpp p. 200-241 (Library of Living Philosophers, Evanston, 1949); a detailed analysis is given in: W. Wothers and W. Zurek, *Phys. Rev. D* **19** (1979) 473
- [41] R. Feynman, R. Leighton, and M. Sands, *The Feynman Lectures on Physics* (Addison-Wesley, Reading, MA, 1965)
- [42] S. Tan and D. Walls, *Phys. Rev. A* **47** (1993) 4663
- [43] M. S. Chapman, T. D. Hammond, A. Lenef, J. Schmiedmayer, R. A. Rubenstein, E. Smith, and D. E. Pritchard, *Phys. Rev. Lett.* **75** (1995) 3783
- [44] A. Stern, Y. Aharonov, and Y. Imry, *Phys. Rev. A* **41**(1990) 3436
- [45] J. Gordon, H. Zeiger, and C. Townes, *Phys. Rev.* **99** (1955) 1264
- [46] A. Schawlow and C. Townes, *Phys. Rev.* **112**, (1958)
- [47] T. H. Maiman, *Nature* **187** (1960) 493
- [48] C. J. Borde, *Phys. Lett. A* **204** (1995) 217
- [49] M. O. Mewes, M. R. Andrews, D. M. Kurn, D. S. Durfee, C. G. Townsend, and W. Ketterle, *Phys. Rev. Lett.* **78** (1997) 582
- [50] E. W. Hagley, L. Deng, M. Kozuma, J. Wen, K. Helmerson, S. L. Rolston, and W. D. Phillips, *Science* **283** (1999) 1706
- [51] I. Bloch, T. W. Hansch, and T. Esslinger, *Phys. Rev. Lett.* **82** (1999) 3008
- [52] B. P. Anderson and M. A. Kasevich, *Science* **282** (1998) 1686
- [53] D. Kleppner, *Physics Today* **50** (1997) 11
- [54] S. Inouye, T. Pfau, S. Gupta, A. Chikkatur, A. Gorlitz, D. Pritchard, and W. Ketterle, *Nature* **402** (1999) 641
- [55] M. Kozuma, Y. Suzuki, Y. Torii, T. Sugiura, T. Kuga, E. W. Hagley, and L. Deng, *Science* **286** (1999) 2309
- [56] S. Inouye, A. P. Chikkatur, D. M. Stamper-Kurn, J. Stenger, D. E. Pritchard, and W. Ketterle, *Science* **285** (1999) 571
- [57] R. Bonifacio and L. Desalvo, *Nuclear Instruments and Methods in Physics Research Section A- Accelerators, Spectrometers, Detectors and Associated Equipment* **341** (1994) 360