Atom matter wave interferometry and the measurement of phase shifts

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The newly emerging field of atom matter wave interferometry using beams of slowly moving laser-cooled atoms is discussed in relation to the measurement of phase shifts caused by accelerations and rotations and the measurement of quantum mechanical phase shifts such as the geometric phase and the Aharonov–Casher phase shift. Comparisons are made with neutron and optical interferometry.

IT is a great honour to be able to contribute to this special issue dedicated to S. Pancharatnam. I first became aware of Panch's works in 1972, some three years after his untimely death, when I arrived at the University of Reading to work with George Series. George had just finished preparing three of Panch's articles[1–3], on alignment in magnetic resonance and on light shifts in atoms, which had been found amongst Panch's papers at the Clarendon Laboratory in Oxford, and I was fortunate to have had preprints passed on as essential reading. But it wasn't for another 20 years, during a visit to Melbourne by Michael Berry in 1992, that I became familiar with Panch's earlier work, in the 1950s, on the generalized theory of interference of polarized light[4]. As has been pointed out[5,6], the additional phase factor that Pancharatnam had discovered was an example of what has since become known as the geometric phase, or Berry's phase[7,8], which describes the topological phase acquired by a quantum mechanical system when it is transported adiabatically around a closed circuit in some parameter space such as an external field.

To test the theory of the geometric phase, Berry[7] proposed an experiment in which a beam of monoenergetic particles in a particular non-zero spin state is coherently split between two arms of an interferometer, one arm of which passes along a constant magnetic field B and the other along a magnetic field with the same magnitude B but with its direction slowly varying around a circuit subtending a solid angle Ω at the origin. The beams are then recombined and fringes resulting from the difference in phase between the de Broglie waves in the two arms of the interferometer are recorded as a function of the solid angle Ω. A similar experiment has now been performed for the case of fermions using neutron matter–wave interferometry[9].

During the past three years, a new type of matter wave interferometry has emerged that promises to permit measurements of quantum mechanical phase shifts such as the geometric phase[7–9], the Aharonov–Casher phase shift[10, 11], and the scalar Aharonov–Bohm phase shift[12,13] with very much higher sensitivity and precision than can be attained by neutron interferometry. This interferometry uses beams of slowly moving laser-cooled atoms[14–17] having velocities of just a few tens of cm s^{-1}, and corresponding to de Broglie wavelengths $\lambda_{dB} = h/p$ of the order of about 10–100 nm. Matter–wave interferometers based on beams of laser-cooled atoms are also potentially highly sensitive sensors of accelerations, rotations and fields such as gravitational fields. Possible applications include the development of a sensitive accelerometer or gravimeter, the development of an atomic gyroscope for measurement of rotations, and various fundamental physics experiments such as tests of the principle of equivalence, tests of general relativity, and tests of quantum mechanics.

Potential sensitivity of an atom interferometer

The treatment below is based on that given in references 18 and 19. We consider a simple idealized Mach–Zehnder interferometer in which the de Broglie waves of a beam of slowly moving monoenergetic atoms are coherently split between two spatially separated arms and then recombined prior to detection, as illustrated in Figure 1. The atoms are assumed to follow simple straight line trajectories.

Effect of accelerations (including gravitational accelerations)

When the interferometer is subjected to an acceleration g in the $-y$ direction, atoms moving in the top arm (ABC) of the interferometer lose kinetic energy between A and B, so that the wave number for atoms moving along BC is reduced, relative to those moving along AD, by an amount

$$\Delta k = (mv/\hbar)\,[1 - (1 - 2gH/v^2)^{1/2}], \tag{1}$$

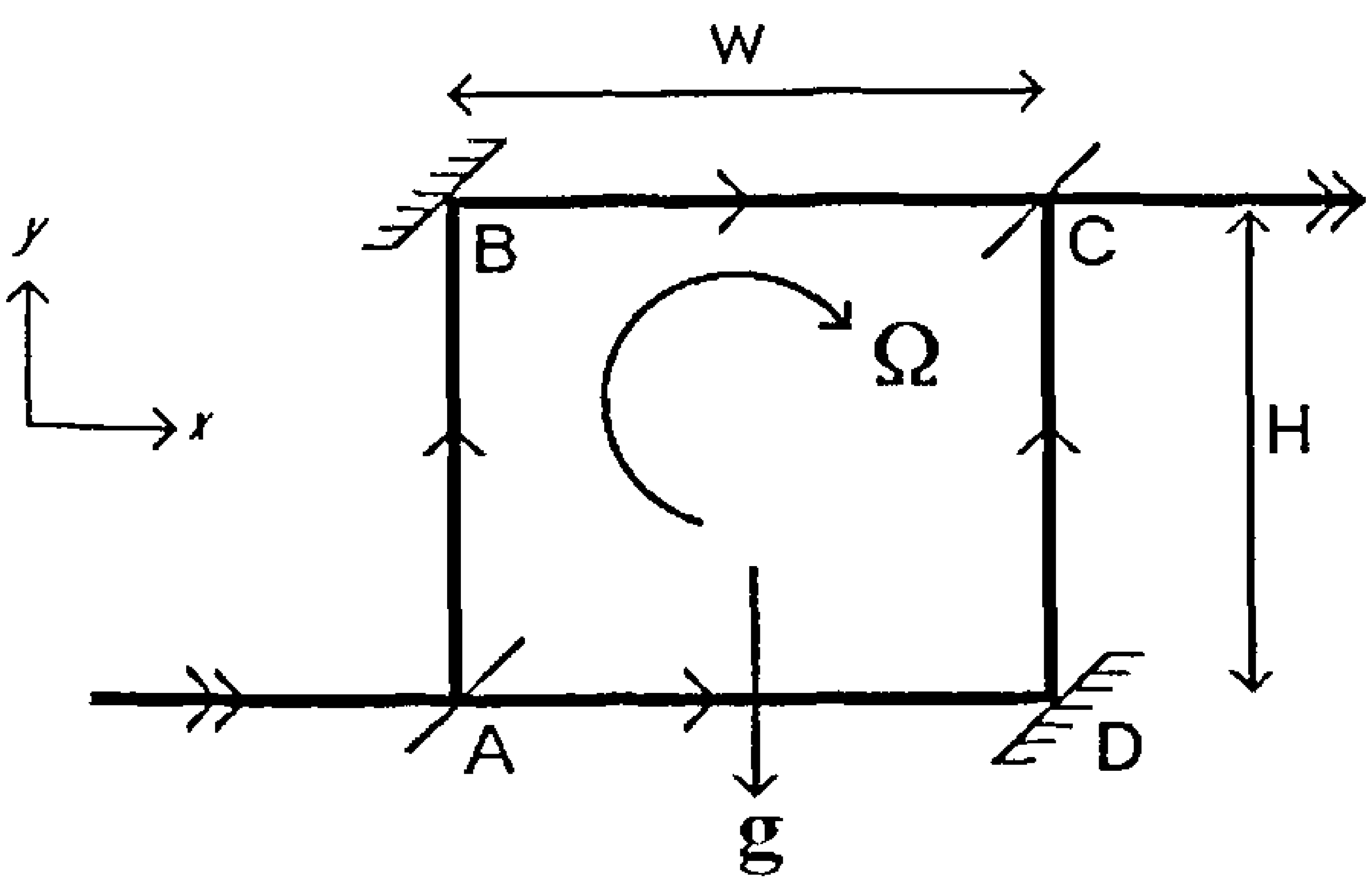

Figure 1. Idealized Mach-Zehnder interferometer.

where m is the mass of the atoms, v is their initial velocity, and H is the height of the interferometer. For $mgH \ll 1/2mv^2$, which is a necessary condition for straight line trajectories, equation (1) reduces to $\Delta k \approx (m/\hbar v)(gH)$. The phase difference between the two arms of the interferometer with enclosed area $A = HW$ is then

$$\Delta\Phi_{accel} = \Delta k\, W$$
$$\approx (m/\hbar v)(gA) = 2\pi gA/\lambda_{dB}v^2). \qquad (2)$$

Thus, for a caesium atom interferometer in which $v = 10\ \mathrm{cm\ s^{-1}}$ and $A = 1\ \mathrm{cm^2}$, an acceleration of only $5 \times 10^{-9}\ \mathrm{cm\ s^{-2}}$, or 5×10^{-12} of the Earth's gravitational acceleration, is required to yield a phase shift of, for example, 0.1 mrad.

Effect of rotations (Sagnac effect)

When the interferometer is rotated with angular frequency Ω normal to the xy plane (Figure 1), the atoms in each of the two arms of the interferometer experience a path difference $\Delta s = WH\Omega/v$. The phase difference between the two arms of the interferometer is then

$$\Delta\Phi_{rot} = k\, 2\Delta s$$
$$= (2m/\hbar)\Omega A = 4\pi\Omega A/(\lambda_{dB}v). \qquad (3)$$

Thus for a caesium atom interferometer in which $v = 10\ \mathrm{cm\ s^{-1}}$ and $A = 1\ \mathrm{cm^2}$, a rotation of only $3 \times 10^{-10}\ \mathrm{rad\ s^{-1}}$ is required to yield a phase shift of 0.1 mrad.

Precision

To date, densities of laser-cooled atoms of up to about $10^{12}\ \mathrm{cm^{-3}}$ have been generated in atom traps[20]. This is somewhat greater than the maximum density useable in atom interferometers because of limits imposed by atom–atom interactions, and it is probably also somewhat greater than the maximum density attainable in a narrow collimated monochromatic beam of slowly moving atoms. If we assume a maximum density of 10^{10} atoms $\mathrm{cm^{-3}}$ moving at $10\ \mathrm{cm\ s^{-1}}$ in a cross sectional area of $1\ \mathrm{mm^2}$, the beam current ($10^9\ \mathrm{s^{-1}}$) is sufficient to permit the measurement of phase shifts of about 0.1 mrad during an integration time of 1 s.

Comparison with neutron and optical interferometers

Neutron interferometers

The phase shift for rotations scales as m (from equation (3)), and so for a caesium atom interferometer, the phase shift is potentially about 10^2 times larger than that of a neutron interferometer. The phase shift for accelerations, including gravitational accelerations, scales as m/v (from equation (2)), and in this case the phase shift for an atom interferometer with caesium atoms moving at $10\ \mathrm{cm\ s^{-1}}$ is potentially about 10^6 times larger than that of a neutron interferometer with thermal neutrons moving at about $10^5\ \mathrm{cm\ s^{-1}}$.

The maximum beam currents available from laser-cooled atom sources ($\approx 10^9\ \mathrm{s^{-1}}$) are up to 10^6–10^9 times higher than those used in neutron interferometers, and this offers the prospect of a 10^3–10^4 gain in precision for a given integration time.

The magnetic moment of an atom is about $\mu_B/\mu_N = 1836$ times that of a neutron, which implies that phase shifts of milliradians observed, for example, in an Aharonov–Casher experiment by neutron interferometry[11] translate into phase shifts of radians in atom interferometry.

Atoms may be either fermions (e.g. ^{7}Li) or bosons (e.g. ^{6}Li) and their internal structure enables them to be labelled and modified by electromagnetic fields.

Finally, sources of laser-cooled atoms are very much more compact and more readily available than neutron sources, which require a nuclear reactor.

Optical interferometers

The mass of a caesium atom is about 5×10^{10} times larger than the effective mass of a photon ($m_\gamma = \hbar\omega/c^2$), which suggests that for identical configurations, a caesium atom interferometer should be about 5×10^{10} times more sensitive to rotations than an optical interferometer. As discussed by Scully and Dowling[21], the photons in a typical laser ring gyroscope make about 10^4 round trips, compared to only one round trip for atoms in an atom interferometer, and the photon current

($\approx 10^{16}$ s^{-1} for a 3 mW red laser) is about 10^7 times higher than the maximum current circulating in an atom interferometer. These factors enhance the effective sensitivity of a laser ring gyroscope by more than a factor of 10^7, so that on the whole an atom interferometer would appear to be capable of measuring rotations about 10^3 times smaller than for a laser ring gyroscope.

A comparison of atom and optical interferometers is somewhat less clear for the measurement of accelerations. For identical configurations, the phase shift scales as m/v, which suggests that a caesium atom interferometer may be potentially about 10^{20} times more sensitive to accelerations than an optical interferometer, or 10^{13} times more sensitive after allowing for the higher beam currents and larger number of round trips in optical interferometers. However, measurement of the frequency shift of the light itself is a very insensitive way of measuring accelerations. Current state-of-the-art methods, based on a falling corner cube in one arm of a Michelson optical interferometer[22], can measure gravitational accelerations with an absolute accuracy approaching a few parts in 10^9. Our estimates (see subsection 'Effect of accelerations') suggest that the precision of an atom interferometer for an integration time of 1 second may be up to about 10^3 times greater than this.

Current status of atom interferometers

The first atom interferometers employed beams of thermal atoms, for which the de Broglie wavelengths are very short (0.01–0.1 nm). Carnal and Mlynek[23], in 1991, performed a Young double-slit experiment using a thermal beam of metastable helium atoms. At about the same time, Keith *et al.*[24] at MIT reported the operation of a Mach–Zehnder atom interferometer based on a supersonic beam of sodium atoms and three nanofabricated (400 nm-period) transmission diffraction gratings as beam splitter, mirror, and spatial filter (Figure 2). With rigidly mounted gratings separated by 0.6 m, partial separation of the two interferometer arms was achieved, and high visibility fringes were observed. The spatial separation of the arms has recently been improved[25] by using 200 nm-period gratings, which

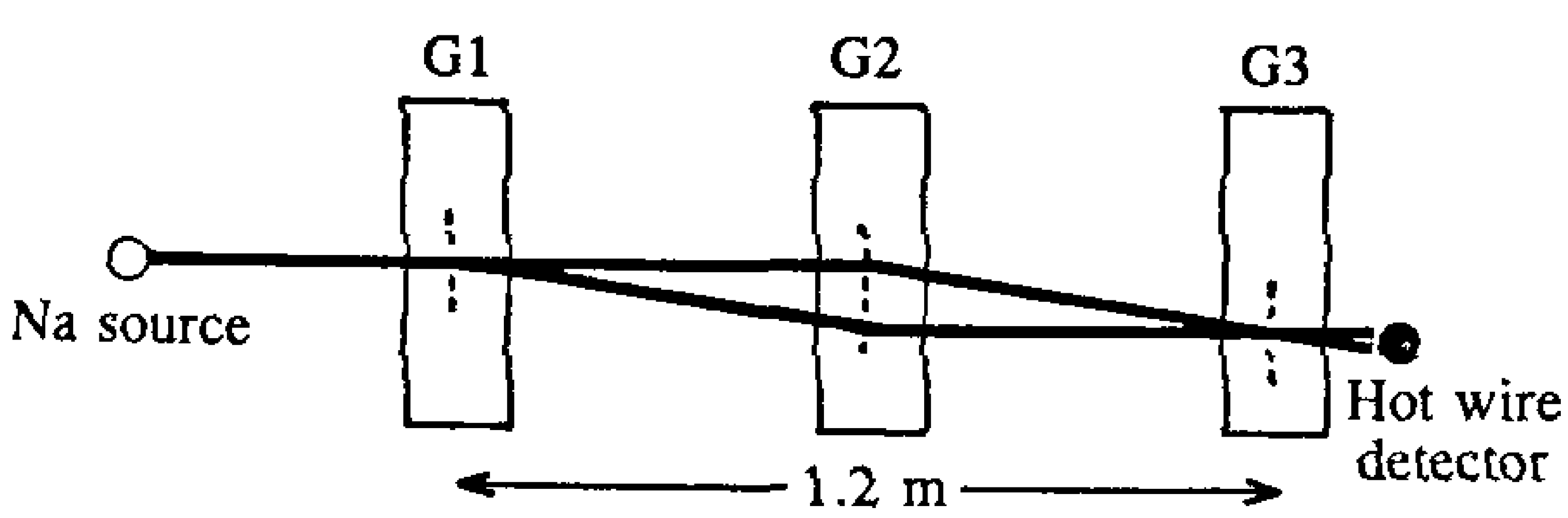

Figure 2. Schematic diagram of the MIT atom interferometer[24,25]. G1, G2 and G3 are nanofabricated transmission diffraction gratings. The sodium atoms in the two arms of the interferometer are separated by 25–50 μm.

permitted a uniform electric field to be applied to one of the arms and precision measurements to be made of the polarizability of the ground state of sodium. Clauser and Li[26] have recently constructed an atom interferometer based on a sequence of three microfabricated transmission gratings and two co-propagating beams of potassium atoms. The first beam is a dc thermal beam which produces shadow Moiré fringes and the second is an a.c. modulated beam of velocity-selected cooler atoms with longer de Broglie wavelengths which produces Talbot-von-Lau interference fringes at the fifth and sixth spatial harmonics of the shadow Moiré fringes.

Following a proposal by Bordé[27], Riehle *et al.*[28] have constructed an atom interferometer in which four transverse travelling laser fields interact with a thermal beam of calcium atoms in a Ramsey separated oscillatory fields arrangement. The photon recoil momentum $\hbar k$ associated with the absorption or stimulated emission of photons in the four interaction zones coherently splits the wavepacket into superpositions of momentum states such as $|g, 0\rangle \rightarrow |g, 0\rangle + |e, \hbar k\rangle$ and $|e, 0\rangle \rightarrow |e, \hbar k\rangle + |g, 0\rangle$. Thus the four laser interaction zones play the role of coherent beam splitter, mirrors and beam recombiner. The atomic deflection of a thermal calcium beam after a photon absorption or stimulated emission process leads to angular separations of about 20 μrad. An inherent characteristic of this type of interferometer is that the atoms in the two arms are labelled by different internal states, $|g\rangle$ and $|e\rangle$, and so the two paths of the interferometer do not have to be spatially separated in order to observe interference fringes. This interferometer has been used[28] to measure the Sagnac effect produced by rotation of the interferometer and very recently[29] to measure the Aharonov–Casher phase shift. The ratio of experimental to theoretical Aharonov–Casher phase shift is 0.98 ± 0.03, which is to be compared with 1.39 ± 0.22 by neutron interferometry[11].

Robert *et al.*[30] have constructed an atom interferometer based on the longitudinal Stern-Gerlach effect. A thermal beam of metastable 2s hydrogen atoms is spin-polarized by a transverse magnetic field B_P, then passed through a nonuniform longitudinal magnetic field $B_{\|}(z)$, having two zones of opposite field gradient, and finally through a transverse quenching field B_Q which selects one of the spin states. The rapid passage from the transverse B_P fringe field to the longitudinal $B_{\|}(z)$ fringe field induces transitions between the two spin states and prepares the atoms in linear superposition states. In the first field-gradient zone of $B_{\|}(z)$ the wave packets associated with the two spin states are accelerated or retarded depending on the orientation of their magnetic moments, leading to a spatial separation, and in the second (opposite) field-gradient zone the velocity change is reversed. Due to different phase shifts of the

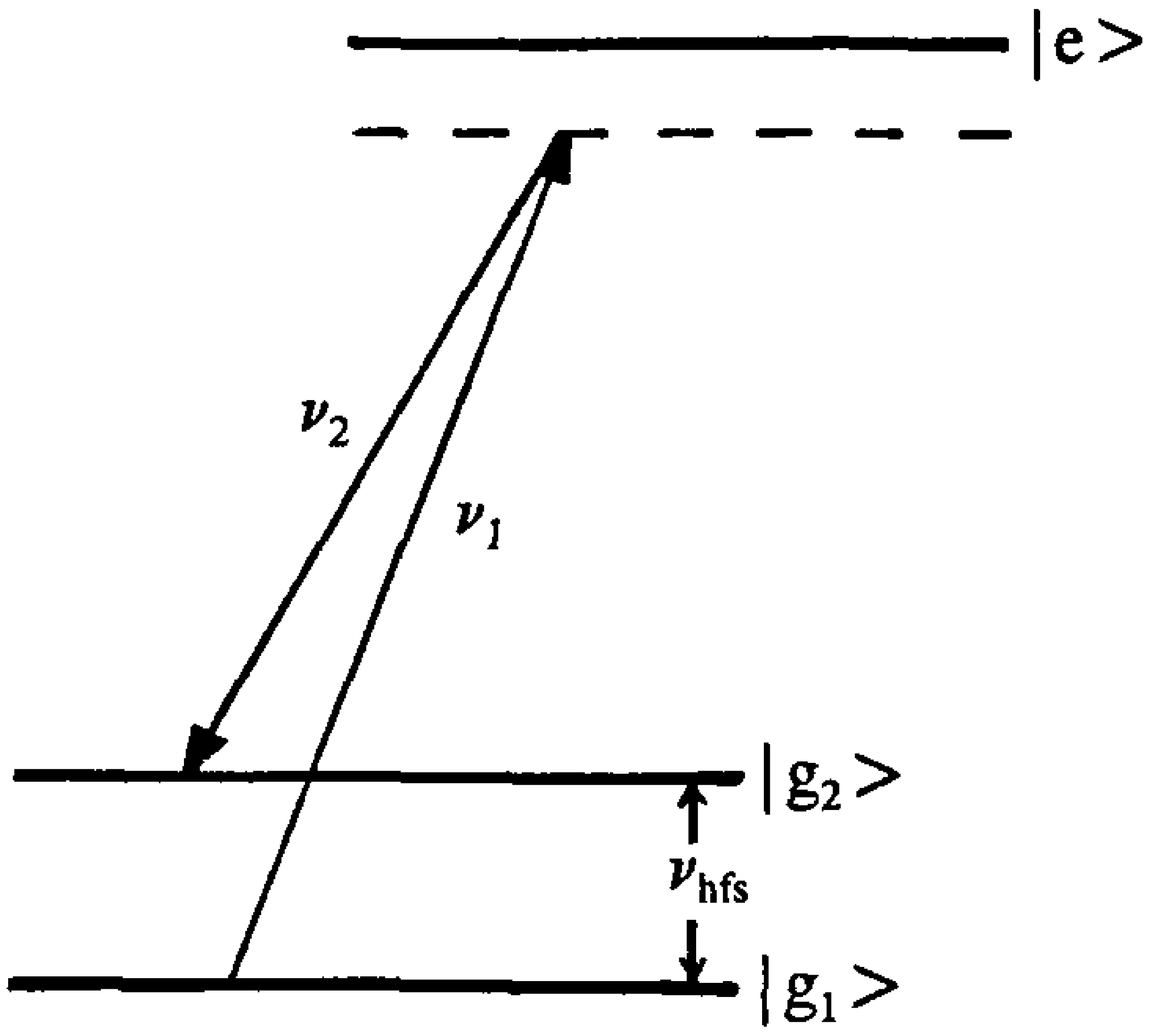

Figure 3. Stimulated two-photon Raman transition between two ground-state hyperfine levels, $|g_1\rangle$ and $|g_2\rangle$. The two laser frequencies ν_1 and ν_2 are detuned to the red wings of the atomic resonances.

two wave packets, their recombination during passage from $B_{||}(z)$ to B_Q leads to phase-dependent populations of the two spin states. This interferometer has recently[31] been successfully applied to observe an analogue of the scalar Aharonov–Bohm effect[12].

The first atom interferometer based on beams of slow-moving laser-cooled atoms was reported by Kasevich and Chu[32], who developed a light-pulse interferometer based on stimulated two-photon Raman transitions between two ground-state hyperfine levels, $|g_1\rangle$ and $|g_2\rangle$, in laser-cooled sodium atoms (see Figure 3). An initial $\pi/2$-pulse prepares the atom in a coherent superposition of $|g_1\rangle$ and $|g_2\rangle$ states, and the momentum recoil $2\hbar k$ associated with the two-photon Raman pulse coherently splits the wavepacket. A π-pulse then acts as a mirror to redirect the trajectory of each wave packet, and a final $\pi/2$-pulse recombines the two wavepackets, putting the atom into either the $|g_1\rangle$ or $|g_2\rangle$ state. This interferometer has been used to make precision measurements of the gravitational acceleration of a falling laser-cooled sodium atom with a sensitivity $\Delta g/g$ of 3×10^{-8} (ref. 33) and to make precision measurements of the photon recoil of a caesium atom[34].

Other types of atom interferometers based on beams of slow-moving laser-cooled atoms have been reported by Shimizu *et al.*[35], who performed a Young double-slit experiment by dropping a cloud of laser-cooled metastable neon atoms through a pair of slits, and Sengstock *et al.*[36] who developed a four-beam Bordé atom interferometer[27] based on laser-cooled Mg atoms. The latter group has recently[37] used their interferometer to observe an analogue of the scalar Aharonov–Bohm phase shift[12], and have proposed a scheme[38] to measure the geometric phase based on a two-level atom in a light field with slowly varying intensity and detuning.

Atom optics

An ultimate goal is to develop a Mach–Zehnder atom interferometer having spatially separated beams of ultra-slow atoms and a large enclosed area A (see Figure 1), suitable for the measurement of small phase shifts. The major limitation at present is the optical elements required to coherently split and reflect the beams of slowly moving atoms. Efficient coherent beamsplitters with large angular separations and efficient coherent atomic mirrors are required and considerable effort is currently being invested by a number of groups to develop such elements, using different approaches.

The MIT atom interferometer[24,25], illustrated in Figure 2, uses 200–400 nm nanofabricated transmission gratings as atomic beamsplitters and mirrors, and angular separations of 25–50 µrad have been achieved for beams of sodium atoms moving with velocities of about 1000 m s^{-1}. Very large angular separations should be attainable when similar gratings are used with beams of slowly moving laser-cooled atoms.

In the atom interferometers reported by Riehle *et al.*[28], Sengstock *et al.*[36] and Kasevich and Chu[32], the atomic recoil associated with the exchange of momentum between a photon in the light field and the atom plays the role of atomic beamsplitter or mirror. Schemes based on the exchange of multiple photon momenta $n\hbar k$, such as the optical Stern–Gerlach effect[39], Kapitza–Dirac diffraction by a standing wave light field[40], and magneto-optical schemes based on counter-propagating crossed linearly polarized beams and static axial magnetic fields[41], have been investigated as beamsplitters and offer the prospect of larger angular separations.

Another approach[42,43], currently being investigated in several laboratories, is to use an evanescent light field created by total internal reflection of a laser beam at a dielectric–vacuum interface. The evanescent field generates a high intensity light field gradient just above the surface, so that when the light is detuned to the high frequency side of the atomic resonance the incoming atoms are repelled by the dipole force and the evanescent wave then behaves as an atomic mirror. It has been proposed[43] that when the evanescent wave is generated by a pair of counterpropagating laser beams to form a standing wave the evanescent field may also behave as a large-angle reflection grating. A detailed analysis[44] has recently been made using the dressed-atom approach, in which the incoming de Broglie wave is coupled to non-zero diffraction orders via non-adiabatic transitions near avoided crossings between position-dependent quasi-potentials. The analysis shows that the evanescent standing wave behaves as a diffraction grating only for slowly moving atoms and that the population of the lowest even diffraction orders requires the incoming beam to make four avoided crossings, so that the maximum population of the diffraction orders is only $(1/2)^4$, or about 6%. Diffraction intensities of 1.5–3% have recently been observed experimentally for a beam of laser-cooled metastable neon atoms[45].

In all of the light-field optical elements mentioned above, spontaneous emission from light-induced transitions destroys the coherence of the reflection or diffraction process, and needs to be minimized, for example, by operating with large laser-atom detunings and raising the laser intensity to compensate. A particularly promising approach, in which spontaneous emission is suppressed, is based on transferring the momenta and population of laser-cooled atoms between ground-state sublevels by Raman transitions in a slowly evolving light field[46–48]. The atoms evolve in a non-absorbing coherent superposition state that follows the light field, so that spontaneous emission is totally absent. A large-angle coherent beamsplitter may then be formed by slowly alternating two counterpropagating laser beams of opposite circular polarization to allow multiple transfers between the ground-state sublevels.

A type of evanescent-wave element, which does not involve light fields and hence avoids the complication of spontaneous emission, has been proposed by Opat *et al.*[49]. This scheme uses spatially varying periodic magnetic fields laid down on a substrate to manipulate the atoms. For a surface potential with just a single harmonic of periodicity a along x in the xz plane, the magnetic energy density for distances $y > a$ is not periodic in x, but dies away exponentially with distance y from the surface. For a fixed value of y, the magnetic fields simply rotate with constant magnitude as x changes. When slowly moving atoms move adiabatically towards the surface, those which are in a positive Zeeman substate are repelled by the increasing magnetic energy density, and thus the surface behaves as a magnetostatic evanescent-wave mirror. The magnetic field strengths required to reflect slowly moving laser-cooled atoms are of the order of tens of gauss. When a uniform magnetic field is superimposed in the y direction (normal to the surface), the magnetic energy density has an additional term, which is periodic in x and which dies away more slowly with y than the non-periodic mirror term[49]. The surface can then behave as a diffraction grating, and hence a beamsplitter, for slowly moving atoms.

The trajectories of laser-cooled atoms in an atom interferometer will not normally be straight, especially in the presence of the Earth's gravitational field. For example, in order to satisfy the condition $mgH \ll 1/2mv^2$ (see subsection 'effect of accelerations') for $v = 10$ cm s^{-1} and $H = 1$ cm, background accelerations are required to be much less than 5% of the Earth's gravitational acceleration. Thus for an interferometer to accommodate background gravitational (or magnetic) fields and also to have a reasonable dynamic range as a sensor, it is important to be able to compensate for beam curvature. This could be accomplished in principle by applying a magnetic field gradient such that the compensating force on the atoms cancels the deflecting force in the interferometer[19].

Conclusion

The development of matter wave atom interferometers based on spatially separated beams of slowly moving laser-cooled atoms offers the prospect of a highly sensitive sensor for measurement of accelerations, rotations and fields, and also for conducting various fundamental physics experiments such as precision measurements of the Aharonov–Casher phase shift and the geometric phase. The major challenge ahead will be the ability to develop efficient atomic mirrors and large-angle beamsplitters which are suitable for coherently reflecting and splitting beams of slowly moving atoms.

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ACKNOWLEDGEMENTS. We gratefully acknowledge helpful discussions with G. I. Opat on the sensitivity of atom interferometers, and J. Kimble and P. Grangier on the sensitivity of optical interferometers.