Focus on modern frontiers of matter wave optics and interferometry

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\textbf{Abstract.} The level of experimental control and the detailed theoretical understanding of matter wave physics have led to a renaissance of experiments testing the very foundations of quantum mechanics and general relativity, as well as to applications in metrology. A variety of interferometric quantum sensors surpasses, or will surpass, the limits of their classical counterparts, for instance in the measurement of frequency and time or forces such as accelerations due to rotation and gravity with applications in basic science, navigation and the search for natural resources. The collection of original articles published in this focus issue of \textit{New Journal of Physics} is intended as a snapshot of the current research pursued by a number of leading teams working on the development of new matter wave physics, devices and techniques. A number of contributions also stress the close relation between the historic roots of quantum mechanics and aspects of modern quantum information science which are relevant for matter wave physics.
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Louis de Broglie’s concept of matter waves is indisputably one of the cornerstones that paved the way for the development of modern quantum physics; the first interference experiments with electrons, neutrons and other light-weight particles confirmed the existence of matter waves very soon after the initial proposal by de Broglie in 1923. It took, however, several decades before the idea could also be routinely applied to more complex particles, such as alkali atoms or molecules. The scientific and technological advances of the last decade have yielded spectacular achievements in the area of matter wave optics. Today, it is a multifaceted, interdisciplinary field that enables scientists to coherently manipulate objects from electrons and neutrons over quantum degenerate atomic ensembles up to large molecules and complex clusters. The level of experimental control and the detailed theoretical understanding of matter wave physics have led to a renaissance of experiments testing the very foundations of quantum mechanics and general relativity, as well as to applications in metrology. A variety of interferometric quantum sensors surpasses or will surpass the limits of their classical counterparts, for instance in the measurement of frequency and time or forces such as accelerations due to rotation and gravity with applications in basic science, navigation and the search for natural resources. The collection of original articles published in this focus issue is intended as a snapshot of the current research pursued by a number of leading teams working on the development of new matter wave physics, devices and techniques. A number of contributions also stress the close relation between the historic roots of quantum mechanics and aspects of modern quantum information science which are relevant for matter wave physics. In what follows, we briefly summarize the content of the contributions.

1. Back to the roots: historic experiments experience a new wave

A pioneering experiment of quantum physics—the transverse splitting of spins—is revisited here in an article by McGregor et al [1]. In contrast to the original experiment by Stern and Gerlach, which was performed with silver atoms, the challenge is now to extend this idea to free electrons. While it has already been explicitly shown by Bohr and Pauli that a simple Stern–Gerlach configuration will not work, the team around Herman Batelaan shows how matter
interferometry can be used as the functional equivalent to the original idea. The suggested solution involves quantum trajectories as imposed by magnetic phase gratings, magnetic phase interferometry or grating bi-prism interferometers. The proposal shows the way toward new experiments and improved spin polarizers.

While the original Stern–Gerlach experiment demonstrated the quantization of spin and a fundamental discreteness in the quantum motion of matter, the demonstration of Poisson’s spot, as a bright dot in the shadow behind a dark obstacle, clearly supports the continuous and delocalized wave nature of things. First demonstrated for light more than 200 years ago, it has recently been implemented with small molecules, such as deuterium, with the question to what extent this fundamental phenomenon might be observed in experiments with fullerenes or even larger objects. Reisinger et al [2] argue that quantum diffraction should indeed lead to an enhancement of the matter wave intensity on the axis behind a circular obstacle. They also point, however, to the fact that van der Waals or Casimir–Polder forces may mimic the effect of quantum deflection and steer molecules on the axis. The interpretation of Poisson spot data therefore requires a detailed numerical analysis and may also provide insight into subtle matter–surface interactions.

Mechanical diffraction gratings have been known for more than 200 years. Relying on interference of electromagnetic waves, they have been the main workhorses of optical spectroscopy throughout the entire last century. The 21st century may harbor new life for this historic instrument in a novel context. Zhao et al [3] explore the diffraction of helium atoms at mechanical reflection gratings under grazing incidence. The arrangement with blazed grooves nearly parallel to the plane of incidence allows them to study conical diffraction and emerging beam resonances. They refer to diffraction conditions where the diffracted and the specularly reflected beams are vigorously modulated and another beam emerges parallel to the surface plane.

2. Phase front effects in matter waves

Phase front effects of matter waves allow one to gain insight into the quantum properties of particles using phase space tomography. Paz et al [4] point to the fact that the Schrödinger equation includes a phase anomaly near the waist of a converging matter wave, analogous to the Gouy phase of Gaussian light beams; they propose measuring this using Ramsey interferometry with Rydberg atoms. They discuss how the spatial mode of an atomic matter wave function may be seen as implementing a higher-order element of quantum information, a q-dit, since the Gouy phase is crucial for rotating the quantum state.

In another paper, Chewedenczuk et al [5] study the measurement of atomic positions to estimate the relative phase between two Bose–Einstein condensates (BECs). They consider different arrangements and argue that a phase estimation, based on the position measurement of all atoms contributing to the resulting interference pattern, can provide sub shot-noise sensitivity.

Three contributions in this issue focus on methods for reconstructing quantum phases, and do this by recurring to phase space representations of the matter wave, such as the Wigner function. Quantum phases play a role in the filtered back-projection algorithm for reconstructing the Wigner function that is associated with a system of high angular momentum in Stern–Gerlach type experiments. Schmied et al [6] reconstruct the phase-space information from data of a spin-squeezed state of a BEC of about 1250 atoms and demonstrate that measurements along the quantization axes lying in a single plane are sufficient for performing
a tomographic reconstruction. The idea of quantum state tomography is also applied by Lee et al to show how the Wigner function of the motional quantum state of complex molecules will become accessible through a careful evaluation of near-field (Talbot) matter-wave diffraction data [7].

3. Near-field diffraction of matter waves

Near-field diffraction can be particularly attractive for demonstrating the de Broglie coherence of massive quantum systems. Mark et al start from two-dimensional ultra-cold ensembles, BEC pancakes, trapped in a one-dimensional optical lattice [8]. A first grating defines the coherence and evolution of the atomic system. An overlayed second optical dipole potential allows the wave functions to spread first. The presence of gravity adds a linear potential, which gives rise to Bloch-oscillations. One may follow the atomic momentum over time and find a regular rephasing similar to the carpets of light originally observed by Talbot, in position space rather than in momentum space.

A Talbot setup is also proposed by Nimmrichter et al [9] to demonstrate the matter wave coherence of highly massive objects. The suggested design relies on a new type of absorptive grating based on single-photon ionization in the time-domain, which can be implemented by short laser pulses. The proposed ‘optical time domain ionizing matter wave interferometer’ (OTIMA) uses ionizing standing light waves, which can be highly regular and transmissive in the nodes whilst being highly absorptive in their antinodes. In contrast to the experiments by Mark et al [8], where the atoms rephase in a momentum–time diagram, and in contrast to a Talbot interference with light often studied in position space (an $x$–$z$ diagram), the OTIMA configuration rephases matter waves in a position and time ($x$–$t$) and therefore inherently avoids a variety of dispersive effects. The instrument is predicted to be applicable to objects of high mass, eventually up to beyond $10^6$ amu.

4. Interference of molecular Bose–Einstein condensates

In contrast to the tightly bound and often hot molecules used for OTIMA and Poisson spot experiments, Kohstall et al [10] demonstrate molecular interference with ultra-cold quantum degenerate molecular matter. They prepare two separate BECs of the weakly bound $^6$Li dimers in a double-well trap close to a Feshbach resonance and release them to observe an interference pattern. The influence of the mutual interaction is revealed as a contribution to decoherence; the collisions of atoms in the overlapping clouds may remove particles from the BEC wave function. The interference fringes can be uniquely assigned to the mass of two $^6$Li atoms instead of a single one, demonstrating the interference of the bound state.

5. Connection to quantum information science

While quantum information science is often concerned with exponential complexities, Hasegawa and Rauch [11] show that coherent neutron optics can yield insight into topological and confinement-induced phases, as well as into tests of quantum non-contextuality. Even a system as simple as a neutron—whose physical properties comprise only position, mass and spin—can be brought into a non-factorizable state. Although a single massive particle does not lend itself to a test of the locality assumptions in Bell’s inequalities, a set of single neutrons in
perfect crystal interferometry is shown to be appealing for demonstrating the Kochen–Specker non-contextuality.

Cooper and Dunningham [12] also build on the relation between quantum entanglement and interferometry to discuss the limits of quantum-enhanced metrology. Acknowledging the difficulty of generating highly entangled many-body systems such as NOON states, the authors propose to improve the sensitivity of matter-wave interferometers under real-world boundary conditions, including lossy channels. They find that a beam splitter of variable reflectivity, matched to the loss rates in each channel, can prepare a two-mode interferometer of optimized sensitivity; they propose a further generalization to multi-path interferometry.

6. Interferometry of molecules ‘from within’

The photoionization of diatomic molecules by Schöffler et al [13] puts two-particle entanglement and matter wave interferometry into a novel context. An electron ejected from the atomic core of a molecule represents an energetic matter wave that illuminates and images the molecule ‘from within’. In particular, in the case of homonuclear molecules, electron emission can be coherent between the two indistinguishable atomic centers, similar to the situation of a double slit experiment. Different symmetries in the molecular wave functions appear as shifts in the angular interference patterns of the ejected electrons. The situation becomes even more complex when the vacancy created by the emission of a single electron from a core shell is replenished and followed by the ejection of an Auger electron from a higher shell. The total of four particles, the core electron, Auger electron, and the doubly charged molecular core decaying in its two atomic components, lead to a quantum correlated, i.e. entangled, state, which leads to measurable effects in the electron interference patterns.

7. Experimental techniques for creating, steering and seeing matter waves

Matter wave optics requires the design and continuous improvement of experimental techniques including the generation of coherent particle beams and their detection. Holmgren et al [14] describe a novel technique for measuring velocities of thermal atomic beams using phase choppers in interferometers. Phase choppers are analogous to rotating mechanical discs, but rather modulate the atomic phase shifts than the atomic transmission (amplitude). This results in a high velocity selectivity and a high transmission.

The use of cold atoms instead of thermal atoms allows the miniaturization of atom interferometers while keeping the enclosed area large. This is important as the sensitivity to inertial forces, such as for instance the Coriolis force associated with the interferometer rotation, increases linearly with the area coherently enclosed by the delocalized atoms. Tackmann et al [15] report on the realization of a compact large area Mach–Zehnder interferometer. However, the use of cold atoms requires an accurate angular alignment and a high wave-front quality of the laser beams that induce the splitting, reversal and recombination of the atomic matter wave. The authors discuss how to achieve an accuracy down to the level of microradians.

Ultra-cold atom experiments often rely on information extracted from the images of atom clouds. Pappa et al [16] show that diffractive dark-ground imaging can be a highly sensitive imaging technique. Using standard off-the-shelf optics, they demonstrate imaging down to seven atoms with shot-noise limited imaging down to 30 atoms.
A minimal disturbance technique for determining the atomic density is presented by Kohen et al [17]. An off-resonant two frequency light interferometer is sensitive to measure a phase shift induced by the presence of a cloud of cold atoms compared to the phase noise without atoms. Only 3% of atoms are lost due to detection by this technique.

Matter-wave phenomena become particularly obvious for large wave lengths as achievable in BEC. Jacob et al [18] report on the realization of an all-optical sodium BEC in a red-detuned tightly focused optical dipole trap that is formed by two laser beams crossing in a horizontal plane with a third beam.

Bernon et al [19] report on a novel experiment that generates non-classical atomic states via quantum non-demolition measurements on cold atomic samples prepared in a high-finesse ring cavity. The same heterodyne technique can be applied as a detection tool to follow non-destructively the internal state evolution of an atomic sample when subjected to Rabi oscillations or a spin-echo interferometric sequence.

8. Matter-wave transport

Sensitive matter-wave interference often requires the possibility of guiding the matter waves. Interferometers utilizing free-falling atoms require a large apparatus for long coherence times and are thus limited in their ultimate sensitivity. Wave-guides and ‘quantum levitators’ may cancel the Earth’s gravitational field and open the field for longer interaction times. Quantum levitators consist of a series of (near) resonant light pulses that can support the atoms against gravity. Impens et al [20] present for the first time a unified theoretical framework for quantum levitators based on travelling waves. Due to the multitude of interactions with light, quantum levitators are believed to be promising candidates in combinations with atomic clocks and gravimeters.

Transport of an ultra-cold cloud of $^{87}$Rb atoms over a distance of more than one centimetre to a dielectric surface is demonstrated by Marchant et al [21] using the combination of a magnetic quadrupole field with an elongated optical dipole trap. This technique shall assist the loading of a BEC into a surface trap. Ultra-cold atoms close to surfaces are interesting and important as they are sensitive to local fields, van der Waals forces, magnetic forces and eventually even deviations from Newtonian gravity over short distances.

Hoffrogge and Hommelhoff [22] propose and analyse a novel scheme for guiding electron beams on a microchip. Raised microwave electrodes can provide an electron guide with radial confinement frequencies of 144 MHz. As in atom chips, a general challenge consists of the preparation of low lying trap states and the maintenance of coherence in the guiding process. High trap frequencies are helpful in better separating the different trap states.

In contrast to photons, atoms may interact with each other, even when they are delocalized. This becomes apparent at the example of a matter-wave soliton—a topological excitation which can travel in a BEC without changing its shape. Khawaja and Stoof [23] show that bright matter-wave solitons can form ‘molecules’, i.e. that two solitons can form a stable pair. They analyze the necessary conditions and find that soliton molecules could be realized in existing BECs for atoms of negative scattering length.

Grond et al [24] analyze an atomic matter-wave version of the Shapiro effect. While with electrons in a solid-state superconducting Josephson junction, the Shapiro effect allows a precise definition of the voltage, a similar effect with atomic matter waves might help to measure gravity over very short distances. The authors show that by modulating the bias potential and
the coupling between two traps on an atom microchip, one can observe enhanced Shapiro resonances.

Bernard *et al* [25] set out to theoretically analyze the flux properties of an atom laser that is generated by radiofrequency-outcoupling atoms from a BEC and guiding them horizontally in an optical trap. In contrast to vertically outcoupled beams, gravity does not play any role and the extraction is based on the repulsive atomic interactions, as well as on details of the magnetic field configurations in the emission process. The authors compare the flux limits of horizontally and vertically extracted atom laser beams and the effect on quantum transport experiments.

9. Precision measurements

Originally conceived as an element of basic research, atom interferometry has already contributed a number of important applications to the field of precision measurements.

Advanced matter-wave interferometers now allow the realization of some of the most precise atomic clocks. The advent of laser-cooled atoms and the move towards optical frequencies promises to push the absolute frequency accuracy beyond $\Delta \nu / \nu = 10^{-16}$. In this issue, Friebe *et al* [26] compare the frequency of the Caesium fountain at the Physikalisch Technische Bundesanstalt with that of a Ramsey–Bordé spectrometer using laser-cooled $^{24}$Mg. Magnesium is a candidate for a future optical frequency standard due to its convenient optical transition frequencies and the low black-body shift.

Altin *et al* [27] use the hyperfine clock transition to demonstrate atom interferometry in a large BEC sample of $^{87}$Rb atoms. Combining wide beam splitting and squeezing hold the promise of increased sensitivity and precision. This study presents a detailed analysis of the signal and noise factors.

Gravity measurements are among the most precise applications of atom interferometry today. Further advances in the field are, however, challenged by spurious effects related to the motion of the atoms, even at the level of velocities that are unavoidably induced by the coherent beam splitting in a matter-wave gravimeter. They are induced by the rotating Earth, i.e. the Coriolis force, and due to the wave-front distortions of the laser’s fields used to split the atom wave. Louchet–Chauvet *et al* [28] now separate both effects and correct for the Earth’s rotation to achieve a long-term stability of gravimetric measurements of the order of $10^{-9}$ g in 5000 s.

A new approach to testing gravity on small distances becomes accessible through experiments in neutron interferometry by Abele *et al* [29]. When cold neutrons are vertically reflected by a flat plane, gravity will pull them back and act as a mirror in a ‘gravitational cavity’. The quantized resonances are studied in detail and enable new tests of Newton’s law of gravity in a regime which is very hard to reach with any other elementary or composite particle. The neutron is equipped with nothing but mass and spin and it’s polarizability is so tiny that van der Waals forces are negligible.

10. Concluding remarks

Matter wave optics and interferometry is a dynamic and exciting field of modern research which combines fundamental quantum physics with new and emerging applications. While we mentioned in particular a subset of atomic sensors—such as inertial sensors—among them rotation sensors and gravimeters—or atomic clocks, our present issue could not even touch upon the many applications in electron and neutron diffraction, which are already out in the field in
daily use for materials research, surface science, crystallography, as well as superconducting
quantum interference devices such as SQUIDS which are already highly commercialized. Electron
diffraction finds routine application in cluster science and we see growing activities
towards ultra-short pulse electron diffraction, too.

In spite of its tremendous success, the concept of matter waves still puzzles most of us,
since we still have not resolved the discrepancy between our classical intuitions and the factual
observations. It is still not evident which concepts of space, time and reality will finally have to
yield for a coherent interpretation of our world. Some answers may be obtained by exploring
matter wave physics for a range of highly massive nano-objects.

We still expect enormous developments in matter wave sensing. More brilliant sources, the
continuous loading of Bose–Einstein condensates and the microgravitational environment of
outer space are high up on the wish list of the current roadmap for atom interference, as are ever
refining theoretical concepts and advanced pulse shapes and sequences for atom interferometry.
It is still a challenge to extend the studies from single atom interference to many-body quantum
correlated ensembles, but we expect rapid progress in the near future. The increasing complexity
of interferometers with entangled atomic systems will provide a plethora of important research
questions.

Complementary to that, the exploitation of de Broglie coherence in complex molecules
has only just begun. Gaining higher control over the internal and external states of polyatomic
systems is a grand challenge that an increasing number of groups is now facing and working
on. This is also complemented by recent efforts in the micromechanical community to prepare
cold nanoparticles and freely suspended mechanical oscillators, which might eventually also be
subject to de Broglie interference.

The ‘de Broglie’ coherence of electronic excitations in biological systems is a
complementary and yet very related field which has also gained importance very recently.

We therefore foresee a growth of matter wave physics with very important interdisciplinary
cross links from atomic physics, solid state science, molecular physics, chemistry, metrology
and nanoscience.

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References

[1] McGregor S, Bach R and Batelaan H 2011 Transverse quantum Stern–Gerlach magnets for electrons
New J. Phys. 13 065018
[2] Reisinger T, Bracco G and Holst B 2011 Particle-wave discrimination in poisson spot experiments
New J. Phys. 13 065016
[3] Zhao B S, Meijer G and Schöllkopf W 2011 Emerging beam effects in out-of-plane grating diffraction of He
atom beams New J. Phys. 13 065017
[4] da Paz I G, Saldanha P L, Nemes M C and Peixoto de Faria J G 2011 Experimental proposal for measuring
the Gouy phase of matter waves New J. Phys. 13 125005

New Journal of Physics 14 (2012) 125006 (http://www.njp.org/)
[5] Chwedenczuk J, Piazza F and Smerzi A 2011 Phase estimation from atom position measurements New J. Phys. 13 065023
[6] Schmied R and Treutlein P 2011 Tomographic reconstruction of the Wigner function on the Bloch sphere New J. Phys. 13 065019
[7] Lee S K, Kim M S, Szewc C and Ulbricht H 2012 Phase-space tomography of matter-wave diffraction in the Talbot regime New J. Phys. 14 045001
[8] Mark M J, Haller E, Danzl J G, Lauber K, Gustavsson M and Nägerl H-C 2011 Demonstration of the temporal matter-wave Talbot effect for trapped matter waves New J. Phys. 13 085008
[9] Nimrichter S, Haslinger P, Hornberger K and Arndt M 2011 Concept of an ionizing time-domain matter-wave interferometer New J. Phys. 13 075002
[10] Kohstall C, Riedl S, Sánchez Guajardo E R, Sidorenkov L A, Hecker Denschlag J and Grimm R 2011 Observation of interference between two molecular Bose–Einstein condensates New J. Phys. 13 065027
[11] Hasegawa Y and Rauch H 2011 Quantum phenomena explored with neutrons New J. Phys. 13 115010
[12] Cooper J J and Dunningham J A 2011 Towards improved interferometric sensitivities in the presence of loss New J. Phys. 13 115003
[13] Schöfler M S et al 2011 Matter wave optics perspective at molecular photoionization: K-shell photoionization and auger decay of N2 New J. Phys. 13 095013
[14] Holmgren W F, Hromada I, Klauss C E and Cronin A D 2011 Atom beam velocity measurements using phase choppers New J. Phys. 13 115007
[15] Tackmann G, Berg P, Schubert C, Abend S, Gilowski M, Ertmer W and Rasel E M 2012 Self-alignment of a compact large-area atomic Sagnac interferometer New J. Phys. 14 015002
[16] Pappa M, Condyli C P, Konstantinidis G O, Bolpasi V, Lazoudis A, Morizot O, Sahagun D, Baker M and von Klitzing W 2011 Ultra-sensitive atom imaging for matter-wave optics New J. Phys. 13 115012
[17] Kohnen M, Petrov P G, Nyman R A and Hinds E A 2011 Minimally destructive detection of magnetically trapped atoms using frequency-synthesized light New J. Phys. 13 085006
[18] Jacob D, Mimoun E, De Sarlo L, Weitz M, Dalibard J and Gerbier F 2011 Production of sodium Bose–Einstein condensates in an optical dipole trap New J. Phys. 13 065022
[19] Bernon S, Vanderbruggen T, Kohlhaas R, Bertoldi A, Landragin A and Bouyer P 2011 Heterodyne non-demolition measurements on cold atomic samples: towards the preparation of non-classical states for atom interferometry New J. Phys. 13 065021
[20] Impens F, Pereira Dos Santos F and Bordé C J 2011 The theory of quantum levitators New J. Phys. 13 065024
[21] Marchant A L, Händel S, Wiles T P, Hopkins S A and Cornish S L 2011 Guided transport of ultracold gases of rubidium up to a room-temperature dielectric surface New J. Phys. 13 125003
[22] Hoffrogge J and Hommelhoff P 2011 Planar microwave structures for electron guiding New J. Phys. 13 095012
[23] Al Khawaja U and Stoof H T C 2011 Formation of matter-wave soliton molecules New J. Phys. 13 085003
[24] Grond J, Betz T, Hohenester U, Mauser N J, Schmiedmayer J and Schumm T 2011 The Shapiro effect in atomchip-based bosonic Josephson junctions New J. Phys. 13 065026
[25] Bernard A, Guerin W, Billy J, Jendrzejewski F, Cheinet P, Aspect A, Josse V and Bouyer P 2011 Quasi-continuous horizontally guided atom laser: coupling spectrum and flux limits New J. Phys. 13 065015
[26] Friebe J et al 2011 Remote frequency measurement of the $^1S_0 \rightarrow ^3P_1$ transition in laser-cooled $^{24}$Mg New J. Phys. 13 125010
[27] Altin P A, McDonald G, Döring D, Debs J E, Barter T H, Robins N P, Close J D, Haine S A, Hanna T M and Anderson R P 2011 Optically trapped atom interferometry using the clock transition of large 87 Rb Bose–Einstein condensates New J. Phys. 13 119401
[28] Louchet-Chauvet A, Farah T, Bodart Q, Clairon A, Landragin A, Merlet S and Pereira Dos Santos F 2011 The influence of transverse motion within an atomic gravimeter New J. Phys. 13 065025
[29] Abele H and Leeb H 2012 Gravitation and quantum interference experiments with neutrons New J. Phys. 14 055010