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EDITORIAL

Focus on atom optics and its applications

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Abstract. Atom optics employs the modern techniques of quantum optics and laser cooling to enable applications which often outperform current standard technologies. Atomic matter wave interferometers allow for ultra-precise sensors; metrology and clocks are pushed to an extraordinary accuracy of 17 digits using single atoms. Miniaturization and integration are driven forward for both atomic clocks and atom optical circuits. With the miniaturization of information-storage and -processing devices, the scale of single atoms is approached in solid state devices, where the laws of quantum physics lead to novel, advantageous features and functionalities. An upcoming branch of atom optics is the control of single atoms, potentially allowing solid state devices to be built atom by atom; some of which would be applicable in future quantum information processing devices. Selective manipulation of individual atoms also enables trace analysis of extremely rare isotopes. Additionally, sources of neutral atoms with high brightness are being developed and, if combined with photo ionization, even novel focused ion beam sources are within reach. Ultracold chemistry is fertilized by atomic techniques, when reactions of chemical constituents are investigated between ions, atoms, molecules, trapped or aligned in designed fields and cooled to ultra-low temperatures such that the reaction kinetics can be studied in a completely state-resolved manner.

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As early as 1933, Frisch [1] observed the transfer of momentum from light to atoms. However, a new era of atomic physics was introduced by the seminal proposals for laser cooling of atoms in dilute gases and beams made by Hänsch and Schawlow [2] and independently by Wineland and Dehmelt [3]. Since then, laser cooling and, more generally, the manipulation of all motional degrees of freedom such as velocity and position down to the limits dictated by quantum laws, have been enormously successful. About 20 years ago mirrors, beam splitters, lenses, decelerators, accelerators, and deflectors for atoms were realized experimentally for the first time [4]–[7]. Though still very far from being a realistic route for atom optical applications at that time, those experiments already demonstrated that matter waves can be handled in almost the same way as light. After the advent of Bose–Einstein condensates in 1995, atom-lasers became available as laser-like coherent sources of matter waves. Simultaneously, matter wave interferometers of different types were developed with an impressive sensitivity to inertial and gravitational effects, outperforming optical interferometers in several cases.

Today we are witnessing a rapid evolution of this field in various application-oriented directions, including developments in precision sensors, single atom fabrication, quantum emulation of macroscopic quantum phenomena, miniaturization and integration, ultra-precise metrology, trace gas analysis, and single atom controlled molecular optics. This focus issue of *New Journal of Physics*, which provides a broad view of the state of the art in this field of applied atom optics, emerged from the ATOMICS conference⁶, where a number of recent highlights in interferometry and sensing, lithography and nanostructures, metrology and clocks, quantum information, and ultra-cold chemistry were presented.

Since the early demonstration experiments, atom optics has enabled development of novel types of sensor, based on the interaction of atoms with external fields. One of the best-established atom sensing methods relies on atom–light interaction. When enhanced by an optical cavity, ultimately even a single photon and a single atom interact with one another. The novel enabling technology of fibre-optical high-finesse micro-cavities [8] can be adapted as a sensing tool for neutral trapped atoms, Bose–Einstein condensates or single trapped ions, working as well for these as for solid state quantum emitters delivering single photons in quantum communication protocols. Further topics of interest in atomic sensing include surface–atom interactions, inertial effects, gravitational and weak electric or magnetic field detection. For example, Rydberg atoms are highly susceptible to electric fields and the resulting type of sensor may be tuned and optimized by an additionally applied radio frequency field [9]. Alternatively, if ultra-cold atoms are brought close to a superconducting surface they experience the modified noise spectrum of this body. This measurement is one of the very first to join ultralow temperatures of atoms with a nearby cryogenic surface [10, 11]. Interference effects in a lattice potential for atoms may be useful as gravity sensors at the micrometer scale [12]. The interference of matter waves is also a very sensitive probe for interactions among atoms [13, 14]. Besides interferometric sensors transport measurements, e.g. in multi-well potentials, are also affected by interaction effects [15].

In view of these applications, a continuous high-flux source of degenerate quantum matter is the focus of [16]. If successful, such a device would deliver in a steady-state fashion a coherent atomic matter wave, quite similar to the well-known stimulated light emission from a cw-laser.

In a different direction, quantum manipulation of individual atoms is making impressive progress. Beautiful examples illustrating this point include the counting of atoms one by

⁶ Conference organized by the editors and the Landesstiftung Baden–Württemberg in 2009 (<http://www.atomics09.de/>). ATOMICS is the acronym of Applied Atom Optics.

one [17], trace analysis of very rare isotopes to determine the age of water samples [18], and likewise single atom counting [19] or high-resolution positioning of single atoms. Here one relies on single atoms or ions to place them with high spatial resolution into a solid state crystal. In this way, atom optical experiments constitute an enabling technology for modern solid state physics at the nm-scale [20, 21]. One of the applications of such single ion delivery is the deterministic formation of nitrogen vacancy centers in diamonds, as discussed in [22].

In addition to the fabrication side, the modeling of strongly correlated materials and their nonequilibrium quantum dynamics are intriguing directions for research, in particular for ultra-cold atomic ensembles in optical lattices. However, they represent major theoretical challenges, and new approaches have to be developed to describe the time evolution of such strongly interacting bosonic/fermionic systems that exploit the availability of Feshbach resonances for continuously tunable interactions. A detailed knowledge and understanding of the ultra-cold collision dynamics represents a key ingredient for the design and modeling of the corresponding many-body systems. Inelastic collisions, in particular those involving metastable partners, lead to a quantum gas governed by energy and spin excitation transfer processes [23]. Generalized dynamical mean-field theory is used to detect novel quantum phase transitions, leading to fermionic Mott insulators at half filling [24]. Preparing arbitrary patterns of neutral atoms in optical lattices in a controlled way is a key ingredient for designing new structures and materials, reaching novel quantum dynamics and for quantum information and simulation. Single site precision can be achieved by using microwave radiation in a magnetic field gradient [25]. Dipolar Bose–Einstein condensates are envisaged by exploiting the long-range interactions of, e.g., ultra-cold heteronuclear dimers in electric fields. Already on the mean-field level, dipolar condensates show novel phase diagrams and structured ground states [26]. Aspects of trapping ultra-cold heteronuclear molecules are presented in [27]. The geometry of quantum spins in a lattice governs its properties, as proposed for a frustrated anti-ferromagnet [28]. It is surprising how such atom optics experiments emulate the behavior of solid state Hamiltonians, using very clean and tunable interaction strengths and geometries [29, 30]. Hardly possible for a real world solid state system, but realized in the atom optics setting, the dynamics of the Mott-insulator-to-superfluid phase transition was observed, and future investigations will address Neel ordering and spin liquid phases. Yet another way to position atomic spins in arbitrary lattice shapes is presented in [31], where micro-structured planar Penning trap arrays are employed. Traps for ions and molecular ions are optimized to study chemical reactions at low temperatures under well-controlled conditions [32].

Atomic clocks and frequency standards are within the traditional *métier* of applied atomic physics, either with single trapped ions [33] or with ensembles of a large number of neutral atoms [34]. These devices show an improvement in performance when entangled atoms are used, as reported in [36]. Lattice clocks employ many neutral atoms, but in order to avoid their collisional frequency shifts and uncertainties they are trapped in appropriate optical lattices [35, 37]. The coherent-population-trapping atomic clock is based on the quantum interference of excitations of two clock states into a third level. Here, a compact but still highly accurate frequency standard is envisioned [38]. A magic coating and the buffer gas filling increase nuclear spin T_2 coherence times such that even a low-cost device can serve as either a sensitive magnetometer or an atomic clock.

This collection of papers can only give a first impression of the depth and breadth of modern developments in atomic physics and their interesting applications. However, it reflects

our clear expectation that in the near future, we will see many applications of atomic quantum matter in everyday tools based on the Schrödinger equation, Heisenberg's uncertainty relation and Born's wave function interpretation.

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