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Roadmap on quantum optical systems

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Abstract

This roadmap bundles fast developing topics in experimental optical quantum sciences, addressing current challenges as well as potential advances in future research. We have focused on three main areas: quantum assisted high precision measurements, quantum information/simulation, and quantum gases. Quantum assisted high precision measurements are discussed in the first three sections, which review optical clocks, atom interferometry, and optical magnetometry. These fields are already successfully utilized in various applied areas. We will discuss approaches to extend this impact even further. In the quantum information/simulation section, we start with the traditionally successful employed systems based on neutral atoms and ions. In addition the marvelous demonstrations of systems suitable for quantum information is not progressing, unsolved challenges remain and will be discussed. We will also review, as an alternative approach, the utilization of hybrid quantum systems based on superconducting quantum devices and ultracold atoms. Novel developments in atomtronics promise unique access in exploring solid-state systems with ultracold gases and are investigated in depth. The sections discussing the continuously fast-developing quantum gases include a review on dipolar heteronuclear diatomic gases, Rydberg gases, and ultracold plasma. Overall, we have accomplished a roadmap of selected areas undergoing rapid progress in quantum optics, highlighting current advances and future challenges. These exciting developments and vast advances will shape the field of quantum optics in the future.

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[12] Guest editor of the roadmap.

Keywords: quantum optical systems, quantum measurements, quantum information, quantum gases, quantum optics

(Some figures may appear in colour only in the online journal)

Contents

1. Introduction

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Quantum optics and optical spectroscopy are at the heart of the advances in experimental quantum science. The rapid developments in this field are marked by several Nobel Prizes in recent history, starting in 1997 when a prize was awarded to Steven Chu, Claude Cohen-Tannoudji, and William D Phillips for the development of methods to cool and trap atoms with laser light [1]. This research area progressed rapidly, leading to a breakthrough in the development of quantum gases by realizing Bose–Einstein condensation [2]. Furthermore, progress in the application of quantum optics has led to tremendous advances in time and frequency standards. Optical atomic clocks are now reaching accuracies in the range of 10^{-18} and will lead to a redefinition of the second in the near future [3]. Advances in atom interferometry have established quantum optical systems in applications for inertial sensing, now with unmatched accuracy. Continuous novel developments in atom interferometry are pushing these boundaries further for applied and fundamental science [4–6]. Record precision is realized with optical magnetometers surpassing superconducting quantum interference devices (SQUID) magnetometers and impending $200\,\mathrm{aT}/\sqrt{\mathrm{Hz}}$ [7]. Due to this unrivalled precision, optical magnetrometry is applied in a wide range of applications, from geology to biology. Overall, applied quantum optics has had a tremendous impact on advanced applications and will continue in the future to disruptively progress many applied fields.

Utilizing the tools developed for quantum optics, we are now able to control individual atomic quantum systems, making these a natural choice for implementing structures for quantum information processing and simulation. Furthermore, atoms are the ideal quantum system since they are nearly non-interacting and, more importantly, are indistinguishable. Based on these advantages, we have witnessed dramatic progress in the application of ultracold atoms and ions in systems for quantum information processing [8, 9, 51]. Further progress of the already achieved advances will finally lead to quantum computers surpassing existing classical computing power for classical hard problems such as factorization, cryptography, and search algorithms. Potentially, hybrid quantum systems could lead to such advances. These systems merge the unique properties of technologically different quantum systems to overcome the obstacles individual systems are facing. Promising candidates for hybridization are ultracold atoms and superconducting quantum circuits [10–12]. On one hand, fast quantum gate operation times have been demonstrated with superconducting qubits; however, the decoherence time is still limited. On the other hand, the gate operation time of ultracold neutral atoms might be slow compared to the superconducting counterpart, but the coherence time is long. This gives rise to the possibility of combining these two systems into a quantum hybrid where the superconducting structures serve as the processor and the neutral atoms act as the memory.

A different approach to exploring solid-state devices with quantum optical systems is being pursued in the field of atomtronics [13, 14]. Already, Josephson junctions have been realized with ultracold atoms in tailored optical potentials, paving the way to mimicking advanced classical electronic and quantum electronic circuits in a parameter range not accessible by solid-state devices, enlarging the scope of quantum optics and potentially enhancing applications including quantum sensors and quantum metrology [15–17].

Starting with the first reported Bose–Einstein condensate (BEC), research in quantum gases has accelerated. At the forefront of this research are recent developments in dipolar quantum gases [18]. Heteronuclear diatomic ground state molecules can have large dipole moments of several Debye. Trapped in an optical lattice, they have next-neighbour interactions that have led to the exploration of multiparticle physics with well-defined control, leading to a testbed for quantum simulations [19, 20]. Large interactions can be achieved by Rydberg atoms as well, with the dipole moment scaling as n^2 where n is the principal quantum number. The strong dipole interaction in a frozen Rydberg gas gives rise to the Rydberg blockade mechanism [21]. This blockade mechanism piloted a rapid development of cold Rydberg gases applied in quantum information processing, quantum optics, and quantum simulation of strongly correlated many-body systems [22].

Exciting an ultracold gas beyond the Rydberg states creates ultracold plasmas. These plasmas are formed at a parameter regime, due to the extremely low temperatures, where plasma physics in the strongly coupled regime opens the possibility of developing a controllable testbed for exotic plasma, atomic condensed matter, and nuclear/particle physics accessible at moderate timescales [23].

These exciting developments and vast advances will shape the field of quantum optics in the future. Novel insights into fundamental physics as well as progress in applied science, even to device development, will result from these research initiatives and pave the way for key technologies based on quantum technologies in the near future.

This review bundles exciting developments in the study of quantum optics and gives an overview and outlook of potential future directions, with the focus on quantum optical systems research. The roadmap is structured into three main areas: quantum sensors/quantum assisted high precision measurements, quantum information/simulation, and quantum gases.

Section 2 describes optical clocks followed by a review in section 3 of atom interferometry. Optical magnetometers are discussed in section 4. The area of quantum information/simulation is described in the sections 5 and 6, focusing on quantum systems based on ions and neutral atoms. Hybrid quantum systems are explored in section 7, as well as atomtronics in section 8. Quantum gases are reviewed in the final three sections, starting with an overview of dipolar gases in section 9; Rydberg gases and ultracold plasmas are discussed in sections 10 and 11.

2. Optical atomic clocks

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Status

Optical atomic clocks have many applications in the definition of the time unit and the length unit, as well as links to other SI units, measurement of fundamental constants and their potential variations with time, testing of relativity, measurement of magnetic fields, very long baseline interferometry, deep space exploration, geodesy, and global navigation satellite systems. A generic optical atomic clock consists of three parts: a reference transition medium, a local oscillator to probe the reference transition (clock laser), and a counting mechanism (optical frequency comb), as shown in figure 1. The original difficulty in counting the very fast oscillation of a clock laser has been successfully solved with the invention of optical frequency combs. With this invention, the development of optical atomic clocks has seen great improvements over the past twenty years, as demonstrated in figure 2.

Currently, there are two possible choices of quantum absorbers that can be used to develop optical atomic clocks. One is based on neutral atoms trapped in optical lattices; the other is based on singly trapped ions in Paul ion traps. Potential choices of optical lattice clocks include Sr, Yb, and Hg, whereas potential choices of single ion species include Al^+, Hg^+, Yb^+, Sr^+, Ca^+, In^+, and Ba^+. The performance of optical atomic clocks is characterized by their accuracy and stability. The accuracy of optical atomic clocks is limited by how small the reference transition's response is to external perturbations, both of natural origin or man-made. The stability of optical atomic clocks is limited by quantum projection noise, which is proportional to $1/Q\sqrt{N}$. Here, Q is the reference transition quality factor, and N is the number of quantum absorbers involved in the transition. It is generally accepted that optical lattice clocks have better stability due to the larger number of atoms used, whereas single ion optical clocks have better accuracy due to the smaller perturbations experienced in the ion traps. At the moment, the Al^+ ion optical clock has an accuracy of 8.6×10^{-18} and a stability of $2.8 \times 10^{-15}/\sqrt{\tau}$ [24], whereas the Sr optical lattice clock has an accuracy of 6.4×10^{-18} and a stability of $3.4 \times 10^{-16}/\sqrt{\tau}$ [3].

Current and future challenges

With so many potential choices of optical atomic clock available, it is hard to pick the best one. An ideal optical atomic clock reference transition should be very insensitive to external perturbations to improve accuracy, and this transition should have a very narrow natural linewidth so that the Q value is larger to improve stability.

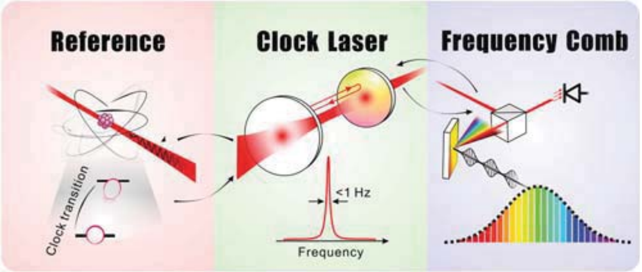

Figure 1. A generic optical atomic clock.

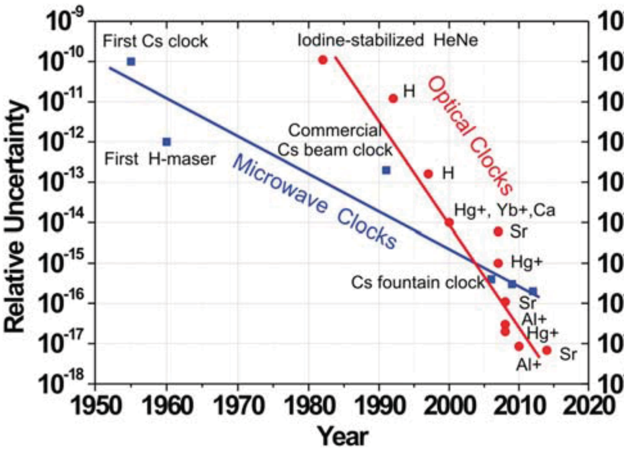

Figure 2. Development of optical atomic clocks over the years.

The accuracy of optical atomic clocks can be affected by Doppler shifts, Zeeman shifts, Stark shifts, collision shifts, blackbody radiation (BBR) shifts, etc. Careful control of the experimental parameters can minimize or stabilize many of these shifts. The Stark shift due to BBR constitutes one of the largest perturbations to the reference transition frequency, and is also one of the hardest to be evaluated. Among all optical atomic clocks under development now, the Al^+ optical clock has the smallest BBR shift at a level of 4.0×10^{-19} [25]. For all other optical clock choices, accurate evaluation of the BBR shift requires knowledge of the atomic response to BBR and knowledge of the BBR environment, as given by the temperature. This still remains a current challenge.

To realize the full potential of high Q reference transitions, a long clock laser probing time is required. This places stringent requirements on the phase coherence of clock lasers. This is commonly done by locking a free running clock laser to an ultrastable Fabry–Perot reference cavity through the Pound–Dever–Hall (PDH) technique. The reference cavity is made of ultralow thermal expansion materials, such as ultralow expansion glass (ULE) or Zerodur. The cavity mirrors are coated with dielectric materials with very high reflectivity. The reference cavity has to be placed in a vacuum chamber with the chamber temperature actively stabilized to the mK level. The chamber has to be vibration isolated and acoustically shielded. After doing all these, it turns out that the best clock laser stability one can achieve is a little bit less than 10^{-15} at room temperature with a normal size cavity (around 10 cm long). This is limited by the thermal noise of the reference cavity [26]. How one can lower the thermal noise such that a clock laser stability of 10^{-17} or even lower can be realized is currently a hot research topic.

Finally, the quantum projection noise limit that one hopes to achieve in an optical atomic clock corresponds to fluctuations associated with the interaction process between the quantum absorbers and the photons. This has reached the standard quantum limit (SQL) but not yet the Heisenberg limit. It is a great challenge to come up with an experimental scheme to reach the Heisenberg limit, where the stability of optical atomic clocks is proportional to $1/N$ instead of $1/\sqrt{N}$.

Advances in science and technology to meet challenges

To solve the BBR shift problem, one possible solution is to put the whole experimental apparatus into a cryogenic environment. This will put very heavy requirements on the experimental setup, although there has been great progress in this direction [27]. The preferred method is to find BBR shift insensitive electronic transitions, like in Al^{+}, or even nuclear transitions. In comparison to electronic states, nuclear states are more immune to external perturbations. One potential choice is the ^{229}Th nucleus [28]. A long-lived isomeric state of the ^{229}Th nucleus with suitable optical transition has been suggested. Although the exact transition wavelength has not been measured, it is estimated to be in vacuum in the ultraviolet. The best hope for reaching this wavelength range is through a non-linear wave mixing process in the newly invented KBBF (potassium beryllium fluoroborate) crystal [29].

Thermal noise may be reduced by using longer cavities, or by using larger diameter optical modes. Of course, this would put higher requirements on vibration isolation. Another solution is to keep the reference cavity at cryogenic temperature. At cryogenic temperature, ULE and Zerodur have h.c. of thermal expansion (CTE) than that at room temperature. Thus, the cavity spacer and mirror substrate materials have to be changed to silicon or sapphire. Silicon has zero crossing of CTE at low temperature, whereas sapphire's CTE is proportional to T^4. After these measures, the dominant thermal noise contribution will be due to the amorphous multilayer mirror coating materials. One way to lower the thermal noise contribution of the coating materials is to directly bond monocrystalline AlGaAs multilayers to the mirror substrates [30]. The much higher Q value of these crystalline layers significantly lowers the coating materials thermal noise contribution.

There exist other methods to solve the thermal noise problem. One method involves replacing the 'good' Fabry–Perot reference cavities with 'bad' cavities [31]. In this case, narrow transition line quantum emitters are placed in a 'bad cavity', the stability of the emitted laser will be minimally affected by the bad cavity fluctuations, including the thermal noise effect. Another method is through spectral hole burning in cryogenically cooled crystals [32]. Here, the clock laser frequency is compared to the spectral holes burned in the absorption spectrum of the crystal, and an error signal is derived to stabilize the clock laser.

Finally, the Heisenberg limit can be approached by using specially prepared quantum states with well-chosen quantum mechanical correlations. Possible choices include entangled states or spin-squeezed states. Preparation of ions or neutral atoms in spin-squeezed states has been demonstrated, and the SQL has been surpassed, although the limit has not yet reached the Heisenberg limit [33].

Concluding remarks

With the rapid development of optical atomic clocks, it is reasonable to think that optical atomic clocks can reach an accuracy level of 1×10^{-18} in the near future. At this level of performance, the intercomparison of optical clocks becomes an issue. This can be solved with optical fiber links. Since the uncertainty of the gravitational potential on the geoid can contribute an uncertainty of 1×10^{-17} to the clock relative frequency, so with this fiber link network, one can also perform optical clock based geodesy. Finally, at the level of 1×10^{-18}, the surface of the Earth is no longer an ideal location to place optical atomic clocks for the ultimate timing accuracy. One might envisage in the future putting our best clocks in a microgravity environment to serve as our 'Master Clocks'. These 'Master Clocks' will be placed on dedicated satellites with known position and velocity, and ground clocks can then be calibrated through these 'Master Clocks'.

3. Inertial sensing with cold atoms

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Status

At their heart, all inertial sensors are based on a freely flying test mass that defines an inertial frame (one where Newton's laws apply) and a measurement system tied to a laboratory frame the acceleration of which we wish to determine. We include rotation and gravity in our definition of acceleration. In an accelerating frame, the measured trajectory of the test mass deviates from that predicted by Newton's laws, and the acceleration of the laboratory frame can be determined.

We consider devices that exploit cold atoms as the test mass. The lab-based measurement system is provided by highly stabilized lasers that manipulate and probe the atoms. The considerations underpinning this design are sound. The quantity that we measure with highest precision is time or frequency, and all high precision measurements should be traced back to a highly stabilized frequency reference or clock. In this case, the 'clock' is the frequency-stabilized lasers that define the optical ruler and stable microwave sources that are used to control the optical ruler.

Cold atom inertial sensors occupy the high precision, high accuracy, low drift, (currently) large form factor, and high cost segment of the inertial sensing technology map. High precision inertial sensors are promising for fundamental science such as for tests of the equivalence principle [4], measurement of the gravitational constant [5, 6], and gravitational wave detection [34]. Precise navigation in GPS denied scenarios, water table monitoring, oil well monitoring, mineral exploration, and possibly carbon sequestration monitoring are promising applications. Determining location in the absence of GPS is relevant in civilian and military contexts and is attracting increasing funding worldwide. All state-of-the-art cold atom inertial sensors realized to date have exploited cold thermal atomic sources (rather than Bose-condensed or atom laser sources) that, at best, operate at the atomic shot noise limit and more usually are limited by classical effects. Although several labs have demonstrated large momentum transfer (wide angle) beam splitting, no state-of-the-art device has exploited this technology to date.

Current and future challenges

In theory, the precision of a cold atom inertial sensor is proportional to the space-time area enclosed by the two arms of the atom interferometer and, in theory, the precision scales as the square root of the product of the atomic flux and the integration time, assuming the device is operating at the atomic shot noise limit.

In practice, current state-of-the-art devices are limited by classical noise and technical effects such as wave front distortion of the beam-splitting lasers coupled with sub-optimal mode matching of the atomic beam to the beam splitters, the Coriolis effect, and vibrational noise, among a host of other effects. Current state-of-the-art devices are not limited by available atomic flux.

The outstanding short-term challenge is to reduce the classical noise that limits current devices, so that we achieve quantum noise limited sensitivity at the highest available atomic flux. Achieving the scaling described above will lead to improved sensitivity and increased bandwidth, which will enable compact, more robust, field-deployable devices with better long-term stability and increased immunity to environmental effects such as temperature drifts, vibration, and DC and AC electromagnetic fields.

The outstanding future challenges are to (i) mitigate the classical effects that currently limit cold atom sensors through the development of new atomic and optical sources, (ii) develop technology that boosts atomic flux and therefore bandwidth and precision, (iii) increase the space-time area dramatically while retaining fringe visibility to improve precision, and (iv) to refine and simplify the techniques and apparatus to further align the sensors with field-ready applications. A secondary, more blue-sky future challenge is to develop and assess the application of atomic squeezing to improve measurement precision [35].

Advances in science and technology to meet challenges

The most pressing immediate concern is to understand, measure, and remove the technical effects that limit the current generation of ultra-high precision atom based inertial sensors.

Recent research suggests that many of the effects that limit the current generation of sensors can be mitigated by upgrading the cold atom source from thermal sources to low number-density, high-flux atom laser sources [35]. It is the brightness, low divergence, spatial mode structure, and the classical amplitude and frequency stability that make optical lasers the source of choice in many precision measurement applications. Atom lasers share many of these coveted properties, and a similar argument can be brought to bear on their application for inertial sensing.

From these considerations, it is reasonable to expect that atom laser sources will remove much of the technical noise currently limiting the state-of-the-art [36]. Further development of Bose-condensed sources and the comparison of BECs and thermal inertial sensors (under otherwise identical conditions) is an important direction for the field.

In addition to investigating the use of advanced sources for interferometry, a number of contributions to noise will still need to be solved. Challenges include reducing laser phase noise, improving mode quality, and increasing laser power, while improvements to vibration isolation systems are critical in some applications.

Assuming that the technical and classical noise sources currently limiting the state-of-the-art can be removed, then the long-term challenges in the field come to the fore. In the ideal situation where atom-based inertial sensors are limited by atomic shot noise, the development of technologies to boost atomic flux and squeeze the measurement noise are critical [35].

One such technology is the continuous atom laser [35]. In this device, currently under development, a high flux thermal source of atoms is continuously cooled and Bose-condensed with little or no loss in atom flux, producing a beam of atoms with all the useful classical properties of a lasing source that provides immunity to many sources of technical noise. Advances in laser cooling offer a promising way forward for producing such a device [37]. Although a continuous atom laser may give high signal and reduced susceptibility to classical noise sources, squeezing offers the tantalizing possibility of reducing the fundamental noise limit in an atom interferometer [38]. Metrologically relevant squeezing has yet to be demonstrated, and will only be relevant provided that sources are already at the shot noise limit. Metrologically, squeezing will be useful if it offers the path of least resistance (compared, for example, with increases in flux) to higher precision.

Atom interferometers offer the intriguing opportunity to boost sensitivity through very large momentum transfer (VLMT) beam-splitting. Large momentum transfer beam splitting has been explored by a variety of labs around the world, primarily with thermal sources. In all cases, fringe visibility is observed to decrease as the momentum imparted in the beam-splitting process increases, leading to a loss in sensitivity. No state-of-the-art device has exploited large momentum transfer beam-splitters. The results to date are summarised in figure 3.

The most critical developments for applications will occur in the on-going simplification and refinement of atom interferometer engineering. There is significant scope for improvements in size, weight, long-term stability, and power consumption by applying advances in materials science, vacuum technology, and laser sources.

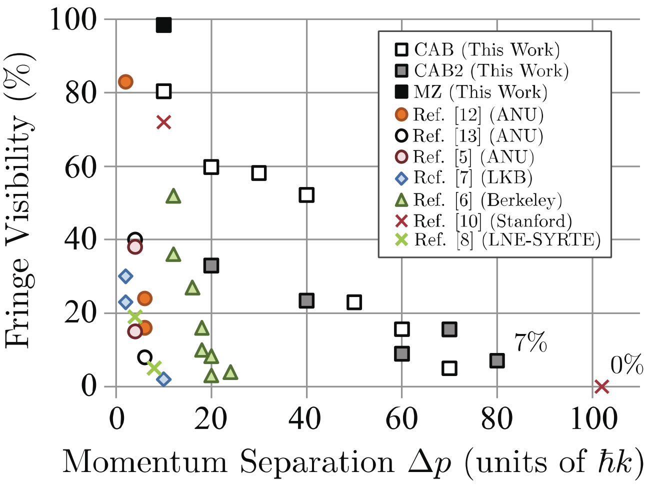

Figure 3. Fringe visibility for various LMT accelerometer experiments as measured by the peak-to-peak amplitude of a sinusoidal fit to each fringe set. A standard 10 *hk* Mach–Zehnder (MZ) and both the constant-acceleration Bloch (CAB) and CAB2 pulse sequences used in our labs are displayed. It should be noted that the fringe visibility of the interferometer in reference [50] is zero, as phase noise prevented any phase measurement from being performed. References in this figure refer to those in reference [39]. Reprinted with permission from [39], copyright 2013 American Physical Society.

Concluding remarks

Interest and activity in the field of cold atom inertial sensing is rapidly increasing worldwide, reflecting the great promise these sensors hold for improved fundamental tests in physics and for a range of applications, from inertial navigation to mineral exploration and the monitoring of a variety of large-scale fluid flows. The continuous, high-flux, squeezed atom laser is a promising tool to advance this field and a fascinating goal for the community. There are alternative and promising approaches that do not require a continuous-wave atom laser (there is substantial literature on this subject, too broad to review here), and although we have highlighted the promise of the atom laser to inertial sensing, it is important that the field explore a range of approaches.

4. Optical magnetometers

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Status

The accurate measurement of the modulus (or components) of a magnetic field, or, alternatively, the sensitive determination of changes thereof is a challenging metrological task. Precision magnetometric information is key to many precision fundamental physics experiments and for applications spanning from geological prospection and archaeometry to unexploded ordnance detection, and, more recently, biomedical imaging. Optical magnetometers (OM), also known as atomic or optically pumped magnetometers—introduced in the late 1950s—are robust and very versatile instruments that can be used for multiple magnetometric tasks. Their operation principle combines optical preparation and optical readout with magnetic resonance in spin-polarized atomic vapors. OMs have challenged SQUIDs—introduced in the mid-1960s —for many years in terms of sensitivity. The so-called SERF (spin-exchange relaxation-free) variant of optical magnetometry was demonstrated to break the $1\ \mathrm{fT/Hz^{1/2}}$ limit in 2003 [7] and now approaches the $200\ \mathrm{aT/Hz^{1/2}}$ level.

Early OMs were operated by using resonance radiation produced by spectral discharge lamps. The past 20 years have witnessed the development of a wealth of novel OM methods and applications owing to the use of laser radiation. Solid-state diode lasers in particular offer the advantage of being compact, tunable, and relatively low-cost. Further benefits are their lower power consumption (compared to lamps), their capability to modulate their frequency/intensity up to the microwave range and the fact that laser radiation can be easily carried over long distances by optical fibers, allowing positioning of the actual sensors at remote locations from the light source.

Sensitivity is only one characteristic OM parameter, other (often mutually exclusive) properties being accuracy, bandwidth, dynamic range, scalar versus vector information, quasi-static versus RF field detection, heading errors, orientation dead zones, weight, volume, and power consumption. Developing OMs with optimized parameter combinations is an ongoing challenge, which, for laboratory-installed magnetometers operated in a magnetic shield and portable OMs operated in an unshielded environment, often pose complementary parameter requirements.

Reference [40] gives an excellent compact review of the field and a more comprehensive review of the contemporary state-of-the-art of OM methods and applications was published in 2013 [41].

Current and future challenges

Pushing the current sensitivities further below the current fT level is not a major future issue, among others, because there is no natural or man-made environment on Earth that is ‘magnetically quiet’ at that level. Although OMs can detect field changes in the lower fT range, their absolute accuracy may be in the upper pT range. For many fundamental physics applications, OM accuracy paired with high sensitivity is a neglected issue that needs further future attention [42].

Future research issues and challenges lie in the development of light-weight portable OMs and in combining sensors into arrays for biomedical imaging, field mapping, material research, and large-scale prospection. The single-beam M_x magnetometer, for example, requires only a few μW of resonant laser power, so that a single diode laser can drive hundreds of remote sensors.

Laser-driven multichannel OM systems have been used to record dynamic maps of the human magnetocardiographic (MCG) [43] and magnetoencephalographic (MEG) field [44]. SQUID-based MCG has been around for some decades and there is hope that further developments of OM-based MCG, recently extended to fetal MCG signals [45] (see also figure 4), will pave the way for the acceptance of MCG diagnostics by clinical practitioners.

Microfabricated OM sensors—each including its own laser—have emerged in the past decade and show promising applications for magnetic source localization in MEG by multisensor recordings [41]. In terms of spatial resolution (albeit at the cost of magnetometric sensitivity), the emerging OMs based on nitrogen vacancy centers in diamond (with atom-like magneto-optical properties) promise a great future [46].

OMs have further allowed nuclear magnetic resonance (NMR) detection [41] to be extended towards substantially lower fields (frequencies), bypassing the decreased efficiency of conventional pick-up coil detectors. Ultralow field magnetic resonance imaging (ULF-MRI) employing OMs is rapidly developing, yielding already impressive images [47] (figure 5). Functionalized magnetic nanoparticles (MNP) are being developed for targeted drug delivery in cancer therapy. The MNPs’ superparamagnetism makes OM ideally suited for monitoring the distribution of bound MNPs in biological tissues (using magnetorelaxometry, MRX, [48]) or AC susceptometry (ACS, [114]) for their mapping in biological fluids.

Finally OMs play an import role in fundamental physics experiments, such as in the search for a neutron electric dipole moment [115], or for the Earth-based detection of cosmic-scale structured axion fields [116].

Advances in science and technology to meet challenges

The development of novel OMs and their applications goes hand in hand with technological advances, the rapid progress in diode laser technology being one prominent example. Multisensor and portable OM applications will profit from further progress in diode lasers with improved passive frequency and amplitude stability.

Data acquisition and processing is an issue that will take advantage from advances in digital signal processing

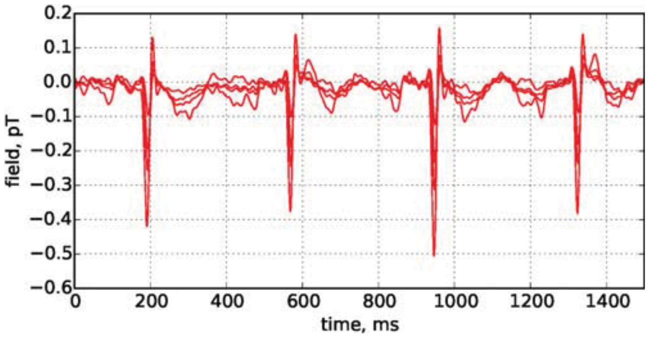

Figure 4. Measurement of the magnetocardiogram from a 25 week gestation fetus by using a four-channel OM array. (Figure courtesy of T Walker, University of Wisconsin).

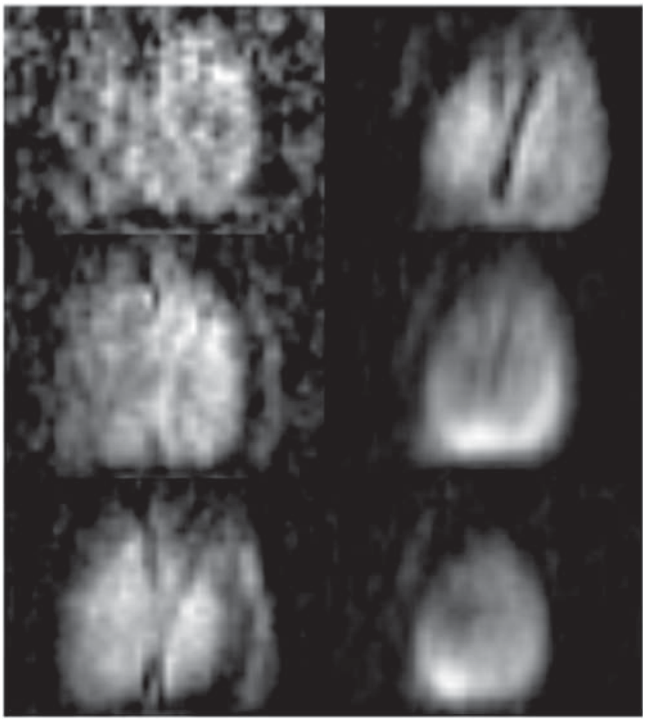

Figure 5. ULF-MRI brain images obtained with OM: 3 mm in-plane resolution; 5 mm slice thickness; depths from the top to bottom and left to right 5, 10, 15, 20, 25, 30 mm; ≈100 mm field of view; 13 min scan time; 450 ms prepolarization time; 100 ms acquisition time. (Reproduced with permission from [47]. Copyright 2013, AIP Publishing LLC).

electronics. Because of the OMs' signal/noise ratio, which is in the order of one million, high resolution (20 bit or larger) fast ADCs and multichannel phase-sensitive detectors (lock-in amplifiers) in combination with digital filters and feedback algorithms laid out in digital circuitry (for example, field-programmable gate arrays, digital signal processors, and general-purpose computing graphics processing units) are prerequisites for the real-time parallelized operation and read-out of the magnetometers. Technological progress in micro-electronic-mechanical systems will have a direct impact on OM sensor miniaturization, a sub-field that successfully addresses specific applications [41, 45].

Ensuring long-lived atomic spin coherence is key to optimizing magnetometer performance. It is achieved either by adding suitable buffer gas(es) to the atomic vapor or by applying suitable depolarization-preventing coatings to the sensor cell walls [41]. Buffer gas cells suffer from depolarization by field inhomogeneities and thus work well in small volume sensors, whereas coated cells effectively average out odd field gradients, thus leading to the best-performing room-temperature magnetometers. Buffer gas cells are relatively easy to produce and are available commercially, whereas high performance coated cells can currently not be purchased. Considering the growing number of emerging OM applications, one can anticipate a future need for coated cells, and the development of coating methods suitable for large-scale industrial manufacture is an open challenge.

An often neglected aspect of high performance magnetometry is the stability of the applied magnetic field. Note, for example, that taking full advantage of a 10 fT-resolving OM operated in a 10 μT field needs a coil current with a relative stability of 10^{-9}, a performance that is not reached by commercial current sources. Conversely, an OM referenced to an atomic clock may be used as an ultrastable current source, an aspect that has not been given much attention so far.

Concluding remarks

Some 60 years after their introduction, optical magnetometers have received a new boost due to the use of laser radiation. The field is in full bloom and one can expect in the next decade a consolidation of recently introduced methods and the development of exciting new approaches extending the range of OM applications, in particular in the fields of material characterization (NMR, MRX, ACS) and biomedical imaging (MCG, MEG, ULF-MRI, MRX, ACS). The growing interdisciplinary potential of performing OMs will lead to a growing number of hybrid applications (such as magnetic resonance or magnetic particle imaging), in which OMs are central components of more complex systems. Although most recent developments deal with laboratory magnetometry, it is to be expected that novel portable multisensor applications for terrestrial, under water, airborne, or space applications will make their appearance soon.

5. Ion traps as quantum information processors

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Status

In 1994, Peter Shor developed a new number factoring algorithm [49] based on quantum mechanics and in the same year Artur Ekert [9] introduced the basics of computing based on quantum mechanics to the atomic physics community, kick-starting experimental activities in the field of quantum information processing using atoms. A year later, Cirac and Zoller came up with a concrete proposal to implement the ideas of basic quantum computing by using trapped ions in their seminal paper [50]. Quantum information processing (QIP) consists of two broad technologies sharing common hardware as depicted in figure 6(a): computation as in figure 6(b) and communication as in figure 6(c). Since 1995, different experimental groups around the world have implemented proof-of-principle level QIP, namely rudimentary quantum algorithms, large-scale (14 qubit) entanglement generations, quantum teleportation, etc, with relatively high degrees of fidelity. Despite such strides in deterministic QIP with trapped ions, realistic problem solving requires even higher *fidelity* (error per gate operation $<10^{-4}$ for fault tolerant operation) and more importantly *scalability* [9]. As technology advances to address these problems, already existing technologies provide opportunities to explore quantum simulation, quantum metrology, and related applications in sensors [51]. Realistic quantum computers where computing with even a hundred qubits will surpass existing classical computing power in solving factorization problems, cryptography, database searches, etc, will be possible in the near future. The communication aspect, though started a bit later [52], could catch up to provide commanding experimental proof of its potential [9]. An experimentally demonstrated basic building block is a node that transfers the quantum state of trapped ions (as a computation qubit or memory) to photons (so-called flying qubits) and vice versa. In achieving such, one requires a high-finesse cavity surrounding the trapped ion for deterministic transfer or it can also be transferred in a heralded fashion without having the cavity, as shown in figure 6(c). Forming a cavity and a single trapped ion in the strong coupling regime, which is needed for deterministic transfer, is still a challenge [9]. The ultimate goal of quantum communication is to faithfully transfer a quantum state between two or more distant locations, aiming to establish a communication network and even a quantum internet [9].

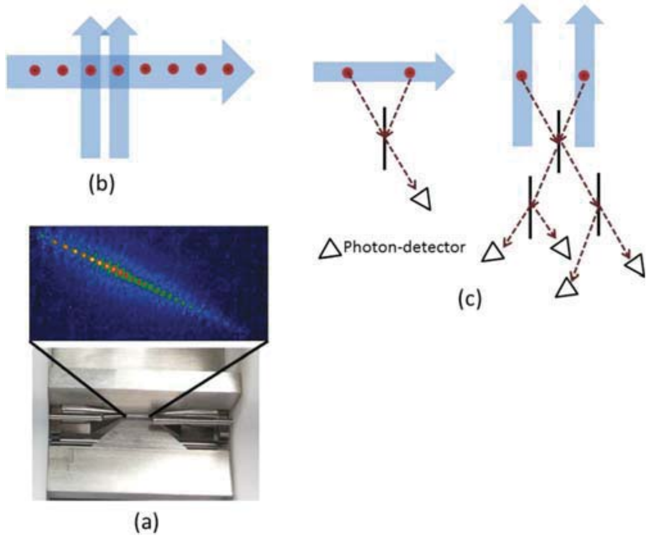

Figure 6. Schematic of quantum information processing (QIP) using trapped ions: (a) a linear ion trap with blade structure and a large ion crystal that forms the hardware for both quantum computation (b) and communication (c). Two ion gates are operated by using individual addressing as in (b) for computation. The heralded communication scheme in (c) can be made deterministic by having a cavity around each ion trap.

Current and future challenges

Moving forward from a few qubit operations and implementation of rudimentary gates towards a fully functional quantum computer requires high *fidelity* gate operations and *scalability* of the ion trap technology. Fidelity, in terms of gate operation, means if the gates are operated reversibly (classically it is not possible), how well can one reproduce the initial quantum state after a complete cycle of reversible operation. The higher the fidelity, the lower the error propagation as more and more gate operations are performed starting from an initial state. The fidelities in certain gate operations using trapped ions [53] have now reached 99.99%, which is where fault tolerant computation can just be performed. To have higher fidelity, the gates also need to be faster and simpler in operation so that de-coherence can essentially be neglected during the computation time. Addressing the *scalability* problem to implement a realistic quantum algorithm like the factorization of numbers, which cannot be presently done with any classical algorithm, requires at least hundreds of qubits, which poses a considerable challenge due to an increase in de-coherence or heating rate as the ion number increases. In recent years, a number of different trap technologies have been experimented with, with some success, namely 3D-chip traps, 2D-surface traps, distributed computation schemes, etc. The most promising architecture emerging out is the surface ion trap where the ions are trapped over surface electrodes and, depending on the applied voltages, the ions can be shuttled around the trap region. This allows dedicated sections of ion production, memory, and processor unit and, more importantly, the possibility to scale up [54]. However, due to the reduction in size, these ion traps, unlike the linear ion traps, shows considerably high motional heating rates. Now, we will shortly discuss the challenges posed in the communication sector. Although entanglement between distant ions via flying photons has been demonstrated by using a heralded scheme as shown in figure 6(c), its applicability is limited by state *transfer fidelity* and the *probability* of that transfer [9]. The ion trap as a memory is rather robust and writing and retrieval of data has been demonstrated with high fidelity, making it a formidable choice for node memory.

Advances in science and technology to meet challenges

Advances in microfabrication technologies along with a better understanding of surface physics is gradually making surface trap technology more robust. As an example, the NIST group [55] reported considerably low heating rates with traps operated after an *in situ* ion beam cleaning. Similarly, the Innsbruck group utilized the advantage of a silicon-based fabrication technique to make surface traps with low heating rates, provided the impurities are frozen out at low temperature [56]. Another technology that is playing a pivotal role in the advancement of ion trap based QIP, is device integration that integrates optical fibers, micro-lenses, and micro-mirrors within or close to the trapping zone, leading to a high efficiency in the detection of quantum states, thereby reducing the operation and readout time [9]. Moreover, from the communication perspective, integration allows efficient coupling of two quantum systems; namely, the ion and the photon, which has recently been extended to include phonons of the ion oscillator to form modular structures that are scalable [57]. The possible future technologies that are going to play a dominant role in addressing the bottleneck of ion trap QIP can be summarized as (the problems that these technologies are going to address are shown in brackets):

1. Microfabrication and surface treatment (*scalability*)
2. Device integration (*scalability* and *fidelity*)
3. Ion traps and cavities in the strong coupling regime (*fidelity*)
4. Theory and experiment on weak probes to reconstruct final states (*scalability* and *fidelity*)
5. Holonomic computing (*scalability*)
6. Hybrid systems combining ion trap memory, superconducting processors, and flying photons (*scalability* and *fidelity*)

It is evident that any advancement in (1), (2), (4), and (6) requires diverse expertise, which can be met by collaborative work. One common element that is going to play an important role in both hybrid systems as well as in miniaturized ion traps is cryogenics. In cryogenic environments, it may well be possible to design strong interactions between any pair of ions in a long chain by introducing interactions mediated by a superconducting (SC) wire. In such an architecture, the head (SC wire) moves instead of the qubits (ions), thereby increasing *coherence time* and *scalability*.

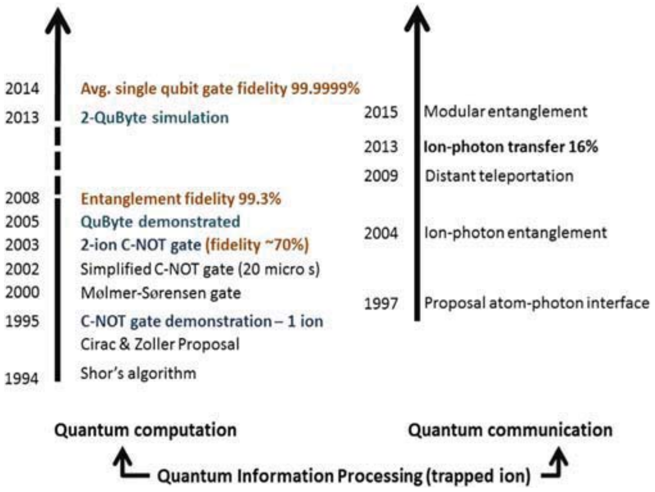

Figure 7. Evolution of QIP strands: quantum computation (left) and quantum communication (right). Only a few of the milestones are shown for clarity with emphasis on the most stringent requirements, namely fidelity (brown) and scalability (blue) for computation. The figure-of-merit in communication is mainly the transfer probability (bold) and fidelity (which has not been significant until recently).

Concluding remarks

Figure 7 summarizes the roadmap of ion trap based QIP that has been followed so far in both computation as well as communication. The field of QIP using trapped ions has just crossed its infancy and is maturing to provide a platform for many diverse applications. In the near future, we expect to see more applications for simulating more complex quantum systems, possible usage as a sensor employing quantum entanglement, and precision metrology. Some of these are already in existence on a small scale, which is bound to be scaled up with the strides being made in the microfabrication of ion traps. On the other hand, in the longer term, it is expected that robust quantum processors will be developed that can possibly perform quantum algorithms with a few hundreds of qubits, thereby challenging the classical intractable algorithms such as number factorization. Unlike in computation technology, communication technology is expected to see faster growth as some of the coupling technology is in an advanced stage to implement devices such as a quantum repeater. However, it is expected that clubbing these devices with systems based on other quantum devices, for example, superconducting qubits and/or photons, will allow optimization of the best of many worlds.

6. Quantum information processing and quantum simulation with neutral atoms

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Status

Neutral atoms were at the epicenter of the original ('first') quantum revolution: quantum physics was initiated by the investigation of the interaction of light and atomic matter at the beginning of the 20th century. Optical spectroscopy of the internal structure of atoms played a key role in the development of quantum mechanics. Tremendous scientific developments over the following decades have kept the field of atomic quantum physics at the forefront of scientific achievements. Being able to only name a few of the important recent developments here, I would like to mention the development of techniques to control the external degrees of neutral atoms by laser cooling and trapping [1], the experimental achievement of Bose–Einstein condensation in dilute gases generating ultracold atomic matter [2], and the control of individual quantum systems based on the interaction of individual atoms and single photons [58].

A wide range of principles, techniques, and technologies are now available to reliably prepare neutral atom samples ranging in number from exactly one upwards to a few billion, held steady for durations of up to minutes. Manipulation of the internal quantum states, including initialization and detection, are well established and the manipulation of the external degrees of freedom allows for the cooling of atoms to almost absolute zero or the ground states of external trapping potentials. This also has turned out to be an excellent basis for the investigation of quantum information processing and quantum simulation (QIPS) with neutral atoms [8]: the unit of quantum information (quantum bit or qubit) can be encoded reliably in internal and external degrees of freedom. Full control of single-qubit gate operations has been achieved routinely. A number of proposals for two-qubit gate operations have been discussed and several of them implemented. The full set of these developments paves the way for gate-model quantum processors in the near future. Adding multi-particle quantum systems, such as BECs as a supplementary resource, has opened up an additional branch: analog quantum simulation, already successfully used to experimentally investigate solid-state problems such as the Bose–Hubbard Hamiltonian [59]. Not surprisingly, neutral-atom quantum physics also turns out to play a key role in the 'second' quantum revolution as well: right now, the application of original quantum principles is exerting a disruptive effect on the course of science and technology—quantum technology is at our doorsteps.

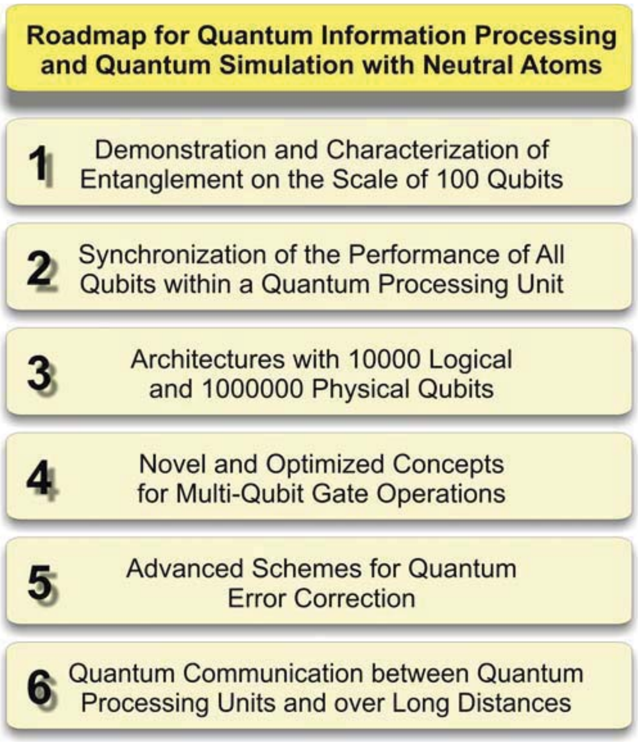

Figure 8. Roadmap for neutral atom quantum information processing and quantum simulation.

Current and future challenges

Although there is a set of major advantages connected to neutral atom quantum information processing, namely the identical properties of all qubits, scalability, and full control of the strength and the temporal profile of interactions between qubits, a number of advances are needed to fully exploit their potential: (1) Based on the successful demonstration of two qubit entanglement [60] and the availability of more than 100 qubits in a single architecture [61], their combination has to be demonstrated in a way to produce massive entanglement throughout the full architecture, including elaborate means of quantifying the degree of entanglement in an efficient fashion. This needs to surpass the limit of tens of qubits, which seem to be accessible as a maximum in single ion chain configurations. (2) The intrinsic identity of atomic qubits has to be complemented by a quantum architecture acting identically on all of the qubits by itself or via a suitable external control that enforces this in a well-defined and stable fashion. (3) Quantum processing architectures able to generate, maintain, and refresh on the order of 10 000 physical qubits and 1 million logical qubits have to be developed and implemented. A sufficiently stable and continuous supply of qubit resources has to be guaranteed. (4) Rydberg-state, collision, cavity, or tunneling-mediated qubit interactions have been proposed (among others) and in part have been implemented in small-scale systems already. Nevertheless, the optimum two-qubit-gate scheme might still not be realized. More work towards optimized and additional approaches is required. (5) The same holds for the development of advanced quantum error correction schemes that are ultimately needed for large-scale processors. (6) Although for neutral atoms scalability to 10 000 qubits and beyond within a single qubit register will be possible, quantum communication with the outside world and between several of these registers will be essential. Here, efficient means of quantum state transfer between atomic qubits on one side and photonic or electronic qubits on the other side have to be demonstrated. Approaches based on cavity quantum electrodynamics (cavity QED) or emerging from the novel field of hybrid quantum systems seem to be very promising, but significant additional developments are needed.

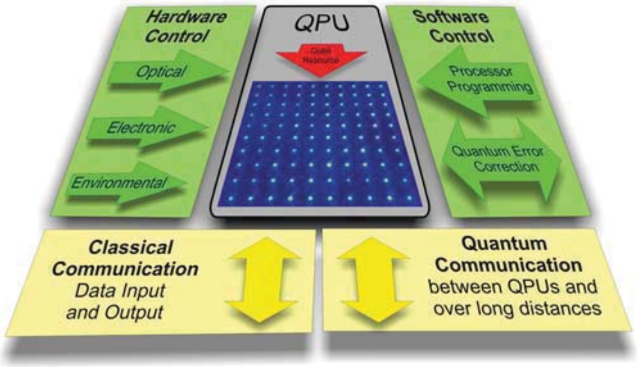

Figure 9. Block diagram of a neutral atom quantum processing unit (QPU), consisting of a ‘qubit RAM’, expected to contain on the order of 10 000 qubits, embedded in the required control and communication periphery.

Advances in science and technology to meet challenges

At the heart of every successful implementation of quantum technology devices in general, as well as quantum information processors specifically, there has to be a well-developed physical architecture and a reliable technological periphery of control circuits to operate the device (figure 9). The central elements of the required experimental techniques and technologies have been demonstrated over recent decades: reliable preparation of atomic quantum systems by the interaction of neutral atoms with electromagnetic fields (electric, magnetic, and laser fields) has generated trapped atomic quantum systems in a wide range of configurations. Full control of the resulting quantum states by the available technology culminated in the demonstration of the best currently available measurement devices: atomic clocks, where devices based on neutral atoms perform a head-to-head race with clocks based on atomic ions, both using the same relevant techniques.

Thus, the basic concepts and technologies for a neutral atom quantum device have been demonstrated very successfully already and the required upgrades can be envisioned as well: for further advancing the field of neutral atom QIPS, the laboratory-scale systems have to be brought to rack-size dimensions, at the same time increasing the number of qubits in operation to a level of 10 000. Already, large-scale and integrated architectures, such as atom chips [62] or micro-optical devices [63] for atom manipulation at this scale have been proposed and investigated experimentally. Using a two-dimensional register of optically trapped atoms [61] as an example to gain some numbers, a ‘qubit RAM’ with 40 000 memory sites as the central element of a quantum processing unit (QPU) (see figure 9) can be created on a physical area of 1 mm^2. Compare this to the available sizes of micro-optical elements, which are in the range of tens of cm^2 and scaling the number of qubits into the millions gets accessible. On the other hand, major investments are needed to convert these ideas into real devices and bring them into the laboratory and into the hands of ‘quantum technicians’. Concerning the control periphery required around this QPU, multichannel laser sources, high quantum efficiency detectors, and versatile control electronics have to be developed, aiming for hands-off operation, a high degree of reliability, and sufficient redundancy.

Concluding remarks

Although being in competition with a number of other physical systems, spanning much of modern physics (for an overview see [64]), the exquisite degree of control at the single quantum level and the unprecedented quality of decoupling from environmental influences, will make neutral atom based quantum technology a key player in the future. For many decades throughout the development of quantum physics, atomic quantum systems have served as a testbed for dramatic advances in the field. Theory and experiment in concert will continue to drive common progress efficiently. Novel concepts, operational principles, and functional building blocks for more complex quantum devices are actively pursued. Small-scale quantum simulators are able to implement problems, which for decades could only be discussed as *gedankenexperiments*. What do we expect for the near future? Technological progress will allow for a continuously larger number of qubits to be accessed. Scalability, which is one of the strongholds of this approach, will play out towards more advanced quantum information processing and simulation. Soon, the increasing number of qubits available will allow for the implementation of problem sets with sizes surpassing the abilities of classical computation. In parallel, large-scale integration, advanced control periphery, and progress in quantum error correction will help to develop ever more complex quantum processing units as well as networks of QPUs connected via quantum communication protocols.

7. Superconducting atom chips and hybrid quantum systems

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Status

In recent years, microtraps for neutral atoms based on superconductors, i.e., 'superconducting atom chips' have become a subject of intensive research. Motivated by the prediction of extremely low magnetic and thermal noise compared to normal conductors [65], superconducting atom chips have first been implemented in the expectation of improving the coherence of atomic quantum states close to surfaces by several orders of magnitude. This boost in coherence time holds promising expectations for quantum information processing applications. In particular, superconducting atom chips are ideal candidates for the realization of hybrid quantum systems between atomic and superconducting solid-state qubits, merging the fast gate operation times for superconducting qubits with the long coherence times of atomic qubits.

The first experimental realization of superconducting atom chips was shown nearly a decade ago [66], by using Nb and MgB_2 as superconductors. Since then, superconducting traps have been demonstrated by several groups [67]. The first experiments on superconducting atom chips gave encouraging results for future applications. It was shown that superconducting atom traps can routinely be used to produce quantum degenerate gases, a cornerstone in atomic physics [67]. Also, utilizing the peculiar properties of superconductors, trapping structures based on persistent currents and vortex patterns have been investigated, as well as the quantized flux in a superconducting ring [66–68] (see also figure 10). Another major step was the demonstration of long coherence times for atomic qubits. It was confirmed in two experiments that both ground states as well as Rydberg states show extremely long coherence times in cryogenic environments [70]. Furthermore, transitions in Rydberg atoms where coherently driven using a superconducting resonator [71].

These developments are now paving the way towards integration of atomic quantum systems and superconducting circuits. Combining neutral atoms with superconducting qubits will integrate the distinct advantages of the two quantum systems in a single device (see figure 11).

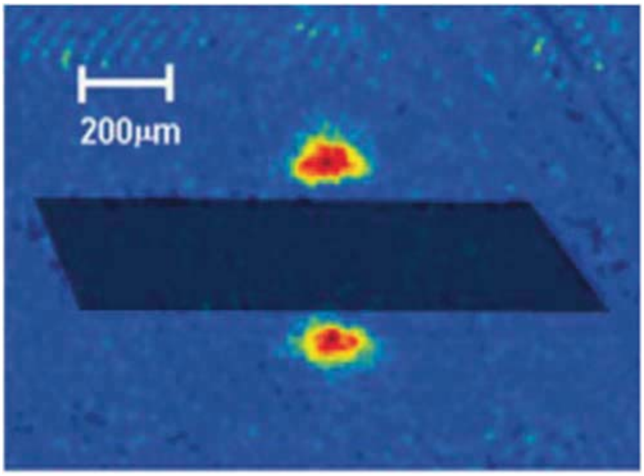

Figure 10. Atoms levitating in a magnetic field generated by a distinct vortex pattern in a superconducting square (indicated by dark blue area). The lower cloud is a reflection of the atomic cloud from the surface.

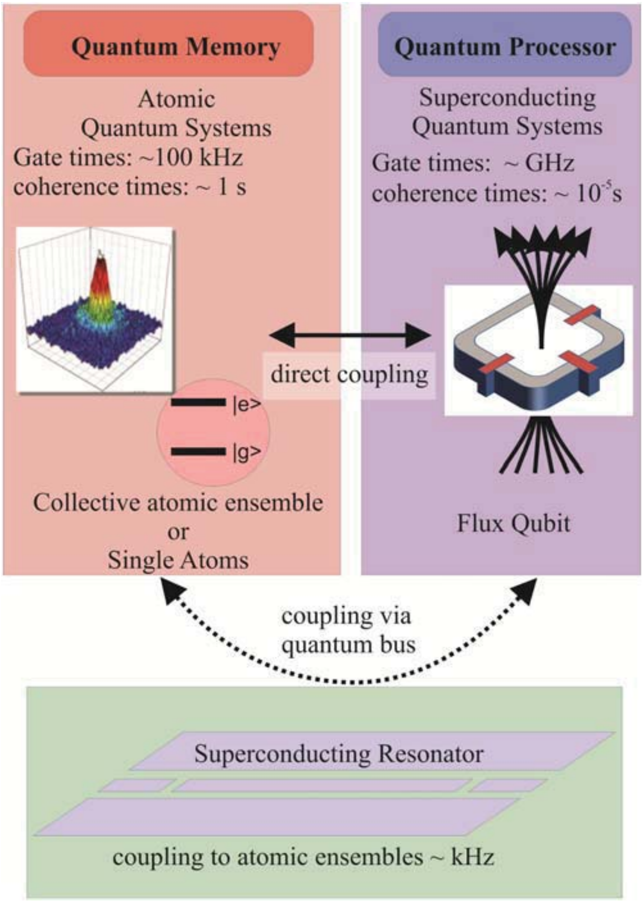

Figure 11. Vision of a hybrid quantum device: quantum states are processed in a superconducting circuit and stored in an atomic ensemble. The coupling is mediated either directly or via a quantum bus.

Current and future challenges

The major challenge in this research area remains the coherent coupling of atomic qubit systems with superconducting qubits. Atomic and superconducting qubits have been realized on their own in several experiments and coupling between quantum states is established in both systems separately [72]. However, the hybridization remains a challenging task. To couple both systems, they have to be brought in close vicinity to each other, typically in the range of micrometer distances, which is technically challenging to achieve. Several technologies that are used for the atomic and solid-state experimental setups have to be integrated into one system. Neutral atoms are typically prepared and manipulated with magnetic and optical fields in room-temperature ultra-high vacuum chambers. This situation is in most parts detrimental to solid-state qubits, which work in milli-Kelvin temperature environments with very low cooling power and hence do not allow high optical power. Currently, two approaches are being followed to bring atoms close to milli-Kelvin platforms. One is the optical trapping of atoms along a tapered optical fiber [73] in which the trapping light field is confined to a small range around the fiber. It is expected that with this technique atom–surface distances below 10 micrometers can be realized without significant heating of the cryogenic surface. Another technique uses the magnetic transport of atoms [73]. In this way, heating is circumvented by avoiding light fields. However, using magnetic fields might lead to other challenges in the form of vortices or unwanted shielding currents. Vortices might be trapped in type II superconducting materials or Josephson junctions while applying external magnetic fields, leading to a reduced coherence of the superconducting and atomic qubits caused by magnetic field noise of the vortices. To reduce vortex creation, one has to establish precise control of the field strength and direction or use shielding techniques to protect the superconducting structures.

Furthermore, due to the Meissner effect, magnetic traps deform close to surfaces, leading to spatial magnetic field changes and with this to a potential increase in dephasing of atomic qubit states. This dephasing can be highly suppressed by applying a bias magnetic field and additionally dressing the atoms with an RF field [74].

It has been found that atomic adsorbates on atom chips pose a major problem for the coherent manipulation of atomic quantum states close to cryogenic surfaces [75]. Especially when using highly excited atoms, the inhomogeneous electric field produced by adsorbates strongly suppresses coherence. It has been demonstrated recently that this effect can be attenuated by saturating the surface with adsorbates [75].

Advances in science and technology to meet challenges

The hybridization of atomic and superconducting quantum states will bring considerable advances in technology and fundamental quantum science. New cryogenic experimental setups are being developed to allow the preparation of cold atomic gases in milli-Kelvin environments. These temperatures are typically generated by dilution refrigerators, which need to be adapted in several ways [73]. To manipulate and detect ultracold atoms it is necessary to develop cryostats with sufficient optical access, without introducing heat sources. Also, atomic quantum states are very prone to collisions with residual background gases and hence it is important to create an ultra-high vacuum environment inside the cryostat. In consequence, materials that are used for the construction of the cryostat have to be selected carefully for their outgassing rate to obtain the lowest background pressures.

Superconducting resonators are the backbone of interfacing atomic with solid-state quantum systems. Typically, the hyperfine ground states of alkali atoms are used as long-lived qubit states. To address these states, the resonance frequency of the resonator has to be precisely controlled, matching the atomic structure. Practically, it is difficult to design a resonator with a fixed resonance that matches exactly the atomic hyperfine splitting. Several techniques to change the fixed resonance frequency of the superconducting resonator without altering the Q-factor have been demonstrated [76].

Although superconducting resonators are operated at cryogenic temperatures, coupling noise due to thermal photons could degrade the quantum state transfer. Robust and thermally insensitive gates have to be developed. Recently, a protocol for thermally occupied resonators was proposed to implement a universal Rydberg quantum gate [77].

In addition to coupling with a bus system, direct coupling mechanisms have been proposed in which the magnetic spin of an atomic ensemble is coupled to a flux qubit. Utilizing the Bose enhancement, strong coupling could be achieved in principle [13].

By integrating these scientific and technological advances in a single experimental setup, hybrid quantum systems become feasible and hold many promises for fundamental science and quantum technologies.

Concluding remarks

Interfaces between distinct quantum systems, so-called hybrid quantum systems, will have many implications in the field of fundamental quantum science as well as in quantum information processing and quantum simulation. Currently, several groups are working towards experimental platforms that combine atomic gases with superconducting circuits. Even though considerable progress has been made in this field, the implementation of a coherent interface between atoms and superconducting circuits still remains a challenge. However, recent demonstrations with superconducting atom chips have shown that atomic and solid-state technologies can be merged into one platform. These developments are extremely encouraging and suggest that the demonstration of simple coherent interfaces between atoms and superconductors are within reach in the near future.

Acknowledgments

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8. Atomtronics

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Status

Atomtronics is an emerging field seeking to realize atomic circuits exploiting ultracold atoms manipulated in micro-magnetic or laser-generated micro-optical circuits [13, 14]. Compared with conventional electronics, the concept of atomtronics has several key aspects. First, current-flows in atomtronic circuits are made of neutrally charged carriers put in motion by applying a ‘potential drop’ induced by a bias in the chemical potential or by phase imprinting techniques, or by stirring the atomic gas with a laser beam ‘tea spoon’. Second, the carriers in the circuit can be of different physical nature, i.e., bosons, fermions, or a mixture of thereof, and with mutual interactions that can be tuned from short to long range, from attractive to repulsive, etc. Finally, quantum coherence is a characteristic trait of the systems harnessed in the circuit.

The typically low decoherence/dissipation rates of cold atom systems and the high controllability and enhanced flexibility of potentials for ultracold matter make atomtronics very attractive for enlarging the scope of existing cold-atom quantum technology [78]. Both technological and fundamental issues in physics can be addressed.

Elementary atomtronic circuits have already been realized, mimicking both conventional electronics such as diodes, PNP junctions [13, 79], and elements of quantum electronics such as Josephson junctions and SQUIDs [15–17]. Atomtronics, however, is not strictly limited to developing electronic-like components: it aims at providing new concepts of quantum devices, integrated in a circuitry that may be of a radically new type. A remarkable impact in the diverse subfields of quantum technology, including quantum metrology, quantum information, and quantum computation, is expected. Indeed, interferometric high precision sensors with matter waves promise a considerable gain in sensitivity compared with the existing solutions (for rotation sensing, in particular, the gaining factor compared with light-based technology can be up to $\sim 10^{10}$, for equal enclosed areas) [83]. New hybrid cold-atom/solid-state systems have been conceived, both to assemble devices with enhanced quantum coherence and to develop a new avenue for the diagnostics of the interfaced systems [81, 82].

With atomic flows and high flexibility in the confinement geometry offered by atomtronics, several problems that cannot even be defined within standard quantum simulator architectures could be addressed [78]. The situation is comparable to the development of solid-state physics: a fruitful avenue in that field is the study of (electronic) current in the system as a response to an external perturbation. With the same logic, key issues in many-body physics, such as frustration effects, topological constraints, quantum Hall edge currents, etc, can be addressed by atomtronics with unprecedented flexibility in parameters.

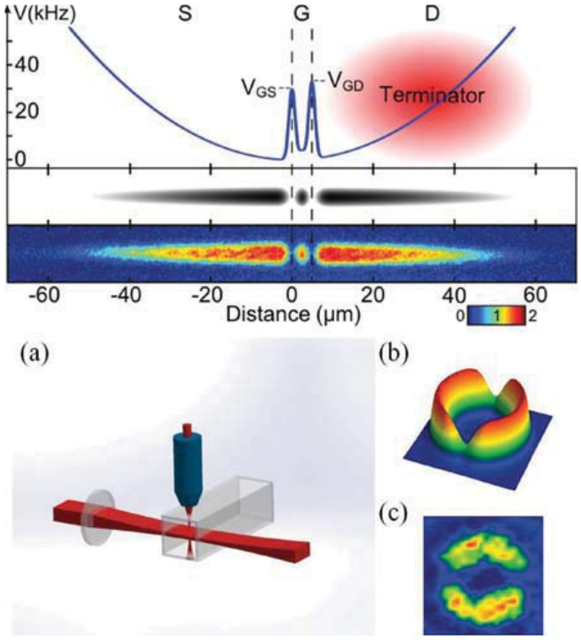

Figure 12. Upper panel: the atomtronic transistor. Source, gate, and drain wells labeled S, G, and D, respectively, are created with a hybrid magnetic and optical potential. The middle panel is a calculated potential energy density plot whereas the lower panel shows a false color in-trap absorption image of atoms occupying all three wells. An optical density scale is shown below the horizontal axis (from [79]). Lower panels: the DC-atomtronics quantum interference device (AQUID) (b), (c) realized with painted potential techniques (a) (from [17]).

Current and future challenges

Although several proof-of-principle schemes to assemble atomtronic integrated circuits have been carried out, specific protocols to design and benchmark elementary circuits are still under discussion. Flexible-geometry wave guides, matter wave beam splitters, ‘inductors’, etc, need to be tailored and specific schemes for assembling the conceived circuital elements need to be provided (see [83–85] for recent design approaches). It would be desirable to work out a heuristic approach to the circuitry, leading, for example, to lumped parameter models analogous to conventional electronics.

In metrology, it is certainly interesting to realize structures with extended storage times with concomitant improvement in measurement precision (see figure 13).

Atomtronics has the potential to provide a new platform for quantum signal processing and a new quantum–classical interface. Combining some of the virtues of Josephson junction flux qubits (such as macroscopic quantum coherence) with the advantages of cold atoms (reduced decoherence), ‘atomic flux qubits’ can open up a new direction in physical implementations of quantum computation. A specific avenue to such goals is to analyze a system of quantum degenerate particles confined in ring-shaped potentials with few localized weak links. Although the emergence of qubit dynamics of clockwise and anticlockwise atomic coherent flows in a mesoscopic ring lattice of BECs has been predicted in realistic situations [86], Rabi oscillations have not yet been observed experimentally. Also, protocols have been provided for tunable ring–ring (qubit–qubit) coupling quantum devices. Quantum gates remain to be devised.

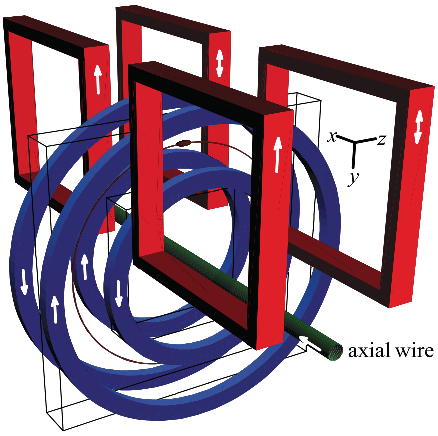

Figure 13. The large storage vertical ring for BECs realized by the Arnold group (average diameter 10 cm). (Reproduced with permission from [80], copyright 2006 by the American Physical Society).

Atomtronics is instrumental for devising new concepts for quantum simulation. Several ramifications can be envisaged. Issues in quantum material science such as topological matter, spin liquids, etc, can be studied by analyzing the flowing current responding to 'potential drops'. Exploiting the power of ultracold gases for studying far-from-equilibrium systems [87], non-equilibrium statistical mechanics, and quench dynamics could be addressed by inspecting the dynamics of atomic flows in different geometries.

It is intriguing to explore physical systems in mesoscopic regimes. Any configuration (compatible with the spatial resolution of the atomtronic circuit) can be studied, in principle. Finally, interfacing cold-atom and solid-state systems in hybrid structures is certainly one of the most interesting avenues to follow. On the one hand, cold atoms could be utilized to diagnose the proximal solid-state/mesoscopic system. On the other hand, the hybrid platform could define quantum circuits with enhanced coherence time, where quantum states are are stored and exchanged between the solid-state and the cold-atom systems [81].

Advances in science and technology to meet challenges

The accelerating growth of atomtronics is in part due to recent progress in optical microfabrication. This technology allows central issues of cold-atom systems, such as scalability, reconfigurability, and stability, to be feasibly addressed [14]. In many current and envisaged investigations, there is a need to push for further miniaturization of the circuits. The current lower limit here is generically imposed by the diffraction limit of the employed optics. With current technologies, the different confining potentials (in shape and intensities) can be controlled on the micrometer spatial range, achieving a 5% rms smoothness. Going to the sub-micron regime, although challenging, might be accessible in the near future. A milestone in this regime would be to simultaneously optimize laser and vacuum technology as well as optical delivery systems. Even at the current spatial scale, mesoscopic quantum effects could be accessed. In particular, ring-shaped potentials of tens of micrometer radii have great potential both for practical and fundamental research, for instance, as quantum memories and quantum simulators. The scalability of multiple-ring structures will be certainly fostered by tailoring optical potentials beyond the Laguerre–Gauss type (e.g., by employing Bessel–Gauss laser beams). Challenges such as the detection of 'cat states' and the creation of ring–ring interactions are expected to be reduced by modulating the confinement along the ring (or ring lattice) potentials.

For most, if not all, applications, it would be useful to achieve better coherence times (>1 s). For high precision interferometry, higher repetition rates (>1 Hz), with larger thermal/condensed atom numbers ($>10^6/10^9$) with sufficiently low densities are important.

A central issue for creating complex atomtronic integrated circuits is minimizing the operating time of the circuit and speeding up communication among the different circuit elements. Currently, typical timescales are in the ms range, but a thorough analysis of the parameters and physics controlling timescales is still missing. A seemingly feasible perspective, provided by such new quantum technology, is to create schemes in which components and connectors can be changed dynamically in the course of the circuit life [84]. In this context, it would be important to study to what extent chemical potential and other effective 'potential drops' changes can be detected as a function of time.

Finally, novel avenues for diagnostics of the atomtronic system's current state, beyond the current absorption imaging techniques, should be developed. Non-destructive techniques will be particularly useful.

Concluding remarks

Atomtronics is expected to provide novel designs for quantum devices exploiting quantum phenomena such as superposition and entanglement and to extend the scope of quantum simulation. Although the initial inspiration came from existing devices in solid-state electronics, atomtronics has the potential to define a new class of questions and answers in basic science and technology, complementing standard electronics and integrated optics. Prototypes of instruments for sensing, quantum gates, quantum memories functioning with cold-atom currents in ring-shaped architectures, and realizing data busses seem to be accessible short-term goals. An improved understanding of real electronic systems may also be achieved.

It appears very likely that atomtronics will contribute to breakthrough technology developments in the years to come. To enhance the knowledge transfer between basic science and technology and to develop basic science into devices and instruments, it is highly desirable that industrial partners take part in this activity: the melting-pot that historically has been the core arena for scientific progress would thus be realized in this exciting new field.

9. Ultracold dipolar molecules in optical lattices

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Status

Gaining quantum control over the physics of dipolar quantum gases is a long standing goal with particular interest for the rich many-body physics in optical lattices. Over recent decades, vast progress has been made with the observation many-body physics phenomena with bosons and fermions. Much of this activity was fueled by tunable, short-range interactions that become available by magnetic field tuning around Feshbach scattering resonances. The dipole–dipole interaction adds to this due to its long-range and non-isotropic nature. This offers the perspective of studying a variety of many-body quantum phenomena by relying on the interaction between particles on different optical lattice sites, for example, in spin-lattice models. The non-isotropic nature of the dipolar interaction has been demonstrated with neutral atoms that have large magnetic dipole moments. Although, in particular, chromium has been successfully studied in bulk traps, neutral atoms do not offer strong enough dipoles for significant nearest-neighbor interactions in lattice geometries. Much stronger dipoles can be realized with Rydberg atoms, where the long-range nature of the interaction has been observed in the form of the Rydberg blockade. Due to the finite lifetime of the excited states such experiments have to be performed on timescales shorter than that of many-body dynamics. Heteronuclear molecules of alkaline atoms in their electronic, vibrational, and chemical ground state offer long lifetimes combined with electric dipole moments of several Debye. This corresponds to non-isotropic nearest-neighbor interactions in optical lattices with typical strengths of hundreds of nano-Kelvin. The dipole interaction in ground-state molecules hence dominates the temperature scale, turning heteronuclear molecules into suitable subjects for the study of dipolar quantum gases.

For the production of ultracold dipolar molecular gases, one approach is to use laser cooling. Direct laser cooling of molecules has been difficult due to the rich internal structure, which leads to a lack of cycling transitions necessary to sustain the cooling process. Nevertheless, tremendous progress has recently been made with selected molecules cooled by multiple laser sources. An already successful approach is to make use of laser-cooled atoms. Using photoassociation is then a comparatively simple way to get small samples of molecules in the dipolar ground state. A much more efficient way to create diatomic molecules is to use magneto-association at a Feshbach scattering resonance. This technique was pioneered first for the homonuclear case and soon after was applied to heteronuclear molecules. As such molecules are created in highly excited vibrational states, they have to be transferred to the dipolar ground state by employing the long-known stimulated Raman adiabatic passage technique (STIRAP, see figure 14). To maintain low temperatures, this typically requires a pair of lasers at wavelengths tens of nanometers apart, with a frequency difference stabilized to better than a kilohertz. This can be achieved by making use of an optical frequency comb or a transfer cavity. For dipolar molecules this technique was first pioneered by experiments resulting in the production of ultracold dipolar molecules of KRb at JILA [18]. After these ground breaking experiments many new experiments using other alkaline combinations with higher dipole moments are on the way. Ground state production by STIRAP was reported for RbCs [88, 89] and more recently for NaK [90].

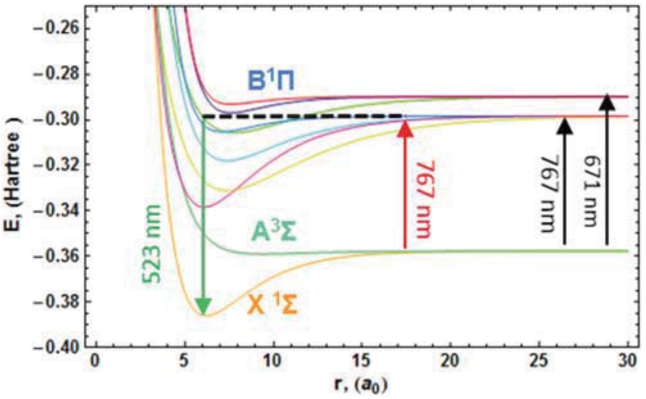

Figure 14. Raman transfer to the electronic and vibrational ground state for LiK molecules. The initial state is a vibrationally highly excited Feshbach molecule in a superposition of hyperfine states of the singlet and triplet ground-state potentials. The transfer to the vibrational ground state of the $X^1\sum$ potential can be performed via stimulated Raman adiabatic passage (STIRAP), which involves addressing the $B^1\prod$ electronically excited potential, corresponding to the D line of potassium.

The experiments on KRb stimulated a broad variety of theoretical work. Studies range from two-body scattering processes of dipolar particles to the many-body quantum physics in optical lattices. For the latter, for example, quantum simulation of spin-lattice models, interlayer pairing, the supersolid phase, topological phenomena in spin–orbit coupled systems, and quantum information with dipolar interaction are envisaged [91, 92].

Current and future challenges

After the achievement of dipolar molecules of KRb, there was tremendous progress in this seminal experiment. To switch on the electric dipole interaction it is necessary to bring the molecule into a superposition of rotational states to break the parity symmetry of the rho-vibrational ground state. This was achieved in two ways: by either employing a strong static electric field, or by driving microwave transitions between the rotational states. Early experiments experienced technical difficulties by relying on electric field electrodes outside the vacuum, which produced limited field homogeneity and charged up the vacuum cell. First, many-body experiments were performed as the molecules were loaded into an optical lattice and spin-exchange interactions between neighboring sites were observed [93]. Soon after the achievement of ground-state KRb, it was realized that the lifetime of KRb molecules is limited due to inelastic chemical decay. This process allows, in a collision between two KRb molecules, Rb_2 and K_2 molecules to be formed. For KRb and most other alkaline combinations of heteronuclear molecules, this reaction is exothermic and leads to the decay of the gas. There is a theoretical prediction that for NaK the reaction would be endothermic, and hence the gas would be stable. However, other theoretical studies point out that, in contrast to atomic gases, where the physics are governed by a few states and sparsely distributed resonances, the number of resonances in molecular scattering is much higher and often scattering resonances are too close to each other to be resolved [94]. This leads to a scattering behavior of molecular gases vastly different from atomic gases even in the ultracold regime, including phenomena such as ‘sticky states’, which even for NaK could limit the lifetime of the gas.

One theoretically proposed way of avoiding inelastic decay is to investigate lower dimensional trapping geometries. If, for example, in a 2D trap, the dipoles are aligned side by side in a direction transverse to the plane of the trap, the repulsive interaction will suppress inelastic collisions. Theoretically predicted rate constants [95] for such a situation promise several seconds of lifetime at sufficiently high densities. This might prove a useful strategy for molecules such as LiK or LiCs, which have comparatively high dipole moments.

Advances in science and technology to meet challenges

One first strategy to avoid inelastic decay due to chemical reactions was realized in KRb by loading the atoms into a deep optical lattice before the formation of molecules [93]. After the loading, ground-state molecules were produced by magneto-association of Feshbach molecules and subsequent STIRAP transfer. The absence of tunneling in the deep lattice then mitigates the decay of the gas. The effectiveness of such a loading scheme depends on the resulting filling factor of the lattice with double occupancies of the two atomic species. This is limited by the degree of quantum degeneracy after the cooling. In this context, the achievement of mixtures in a dual Mott insulator state is an interesting development [96] that demonstrates that sufficiently high filling factors of the lattice can be achieved. As bosonic LiK molecules made from two fermionic species exhibit long lifetimes, it might be a possible route to start from a BEC of such molecules, and directly transfer into the Mott insulator in the lattice. Such a step would create a very good starting point for coherent manipulations of individual molecules.

The pathway of suppressing chemical reactions in lower dimensional traps has further been encouraged by theoretical proposals on many-body physics in such geometries. For example, a staggered arrangement of two-dimensional shallow optical lattice planes with repulsive interaction between dipolar molecules in the planes leads to a stable gas. In this configuration, adjacent molecules experience an attractive interaction and inter-layer pairing and chains are predicted to form in such arrangements [97].

Many new experiments are currently on the way to investigate molecules made of different alkaline combinations. For each experiment and each molecular species employed, it will be important to evaluate the stability and suitability of the gas for the study, in a three-dimensional shallow lattice, where collisions are not suppressed by repulsive dipole–dipole interactions. Another driving force for new experiments is to move towards species with larger mass ratios and hence larger electric dipole moment, e.g., LiCs. This is important to achieve strong interaction effects in spin–lattice type experiments.

First-generation experiments on molecules have dealt with the complexity of cooling a mixture and the technical challenges associated with the STIRAP transfer. As these techniques become more and more mature, new experiments that are underway or have recently been launched can take advantage of improved experimental technologies. A new generation of electric field electrodes inside glass cell vacuum chambers can deliver more homogeneous fields and can be driven to dynamically change the interaction in the gas and hence probe its time-dependent response. Further, existing technologies of quantum gas microscopes can be combined with new experiments on dipolar molecules to attain single site addressability in optical lattices. This is of particular interest in experiments that aim at coherently controlling the state of individual molecules, when used as quantum bits.

Concluding remarks

Ultracold heteronuclear molecules produced in a bottom-up experimental approach are suitable subjects to study the rich physics of dipolar quantum gases in various optical lattice geometries. Seminal experiments on KRb have stimulated broad activity with different molecular species. Such experiments on molecules are at the forefront of further developing the toolbox for controlling and studying quantum matter in its extreme forms.

10. Cold Rydberg gases

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Status

Rydberg atoms [98] with electrons excited to states of high principal quantum number n (usually $n > 10$) have many exaggerated properties compared to ground-state atoms, and the most fundamental one is their large dipole moments scaling as n^2, which result in high susceptibilities to external fields and strong long-range interactions between Rydberg atoms, even over macroscopic distances. In an ultracold and dense atomic sample, interactions between Rydberg atoms have energy exceeding that of thermal motion and act over distances longer than the typical inter-atomic separation. This gives rise to strongly correlated systems, such as ‘frozen’ Rydberg gases and Rydberg excitation blockades.

Cold Rydberg gases were first studied by investigating resonant energy transfer between Rydberg atoms excited from a laser-cooled atomic sample in a magneto-optical trap (MOT) [99]. The observed resonance broadening suggested a ‘frozen’ Rydberg gas picture, where the transfer process is no longer through two-body collisions as in thermal atomic gases, but rather through interacting simultaneously with many neighboring atoms, since the atoms are essentially stationary on the 1 μs timescale of a typical experiment.

One of the most important consequences of the strong long-range interaction between Rydberg atoms is the Rydberg excitation blockade [21] (see figure 15), that is, only one Rydberg excitation is allowed within a certain volume of a cold dense atomic sample and any further excitation is blocked due to the energy level shift by interaction. This excitation blockade has far-reaching implications and applications in many different research directions for cold Rydberg gases, including quantum information processing, quantum optics, and quantum simulation of strongly correlated many-body systems.

The first experimental evidence of Rydberg excitation blockades were found in laser-cooled atomic samples, and then in high-density near-degenerate atomic gases; recently, the Rydberg blockade was studied in detail in few-atom systems. All these are summarized in reference [22]. Recent experimental progress of cold Rydberg gases based on Rydberg blockades included making one Rydberg excitation over an entire BEC [100], observation of spatially ordered Rydberg excitation blockades in optical lattices [101], interaction enhanced imaging of Rydberg excitations [102], and nonlinear quantum optics with Rydberg gases [103].

Meanwhile, a rising research direction, different from investigating the interactions between Rydberg atoms, is the experimental and theoretical studies of the interactions of Rydberg electrons with surrounding atoms [100] and among themselves [104].

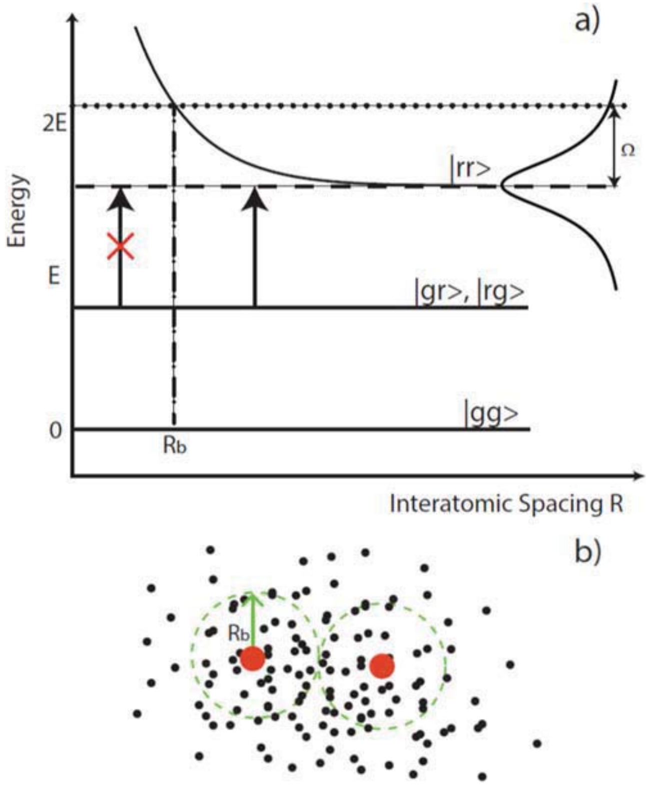

Figure 15. (a) The energy level shift (solid curve) of two interacting Rydberg atoms as a function of inter-atomic distance, where $|\mathbf{g}\rangle$ is the ground state, and $|\mathbf{r}\rangle$ the Rydberg state. Within the blockade radius R_b, defined by the excitation linewidth Ω (including laser linewidth and Rabi frequency), only one Rydberg excitation is allowed, and any further Rydberg excitation is forbidden. (b) An illustration of Rydberg excitation blockade. The small black dots are ground-state atoms, the red dots are Rydberg excitations, and the green circles indicate the blockade spheres, within which only one Rydberg excitation is possible.

Current and future challenges

While cold Rydberg gases offer many fascinating research opportunities, the main challenges lie in managing the complexity of such systems. Associated with the strong long-range interaction of Rydberg atoms is their large susceptibility to various perturbations from internal and external fields. Moreover, strong interactions comparable to the atomic energy intervals give rise to rich phases of Rydberg gases, but also bring about complicated dynamics, which lead to quick dephasing and even shortened lifetimes.

To take advantage of the scientific potential offered by cold Rydberg gases, careful studies of the parameter space over various parameters must be done to gain insight into all kinds of interaction and dephasing mechanisms, so that proper parameter windows can be chosen and feasible experimental schemes can be devised for applications along different directions. To access and investigate all these regimes, it is necessary to develop and combine techniques addressing three different issues: the preparation of ground-state atomic samples, the production and manipulation of Rydberg states, and the detection of Rydberg excitations.

Developing and improving the experimental abilities to control the linewidth, power, and pulse shape of excitation lasers, as well as the electric and magnetic fields present for atomic samples, will provide the capability of making precise and coherent Rydberg excitations of a high principal quantum number n (up to a few hundred) and a tunable blockade radius, and therefore allow well-defined access to different parameter regimes. Moreover, a key point to advance experiments on cold Rydberg gases is to explore efficient detections of Rydberg excitations through either field ionization, optical imaging, or photon detections. In addition the spectral resolution is of great importance for detection methods to have good spatial and temporal resolution, which can reveal details of the ultrafast dynamics of Rydberg gases. In addition, efforts have to be made, or even new methods have to be created, to combine the well-established experimental techniques of preparing ground-state atomic samples with that of Rydberg excitation and detection described above.

Advances in science and technology to meet challenges

Many experimental advances in spectroscopy, imaging, and cooling and manipulation of individual atoms have been made to meet the challenges of studying cold Rydberg gases, and further developments are underway.

A very useful technique brought into studying cold Rydberg gases is the electromagnetically induced transparency (EIT) via a ladder configuration of a three-level scheme. Not only is EIT a very effective method for optical detection of Rydberg states, but it is also a good way to utilize the strong interactions between Rydberg atoms to generate high optical non-linearity at the single-photon level. Moreover, a non-destructive interaction enhanced imaging technique utilizing the Rydberg blockade effect via EIT has been proposed and realized to optically image Rydberg excitations [102]. Currently, experimental efforts are being made to advance this technique to resolve individual Rydberg excitations, which will make it possible to reveal, in real time, the full spatial and temporal correlations in the dynamics of Rydberg gases.

In addition by optical means, a technique is also being developed that allows imaging Rydberg excitations by spatially projecting ions from field ionization of Rydberg atoms onto microchannel plates (MCP) [105]. This technique can possibly be further advanced to image field-ionized Rydberg electrons. If successfully implemented, this will be a very unique tool to study the density-limited regime of Rydberg gases, where the size of the electronic wave-function becomes comparable to the distance between atoms and the delocalized electrons overlapping with each other over such large distances form a complete new many-body system, unavailable in conventional condensed matter systems.

Apart from detection techniques, advances are also required in preparing ensembles of ground-state atoms and in addressing individual atoms for Rydberg excitations. Two different approaches in such efforts are to scale up single-atom micro-traps to form an atom array and to directly load atoms into optical lattices or other lattice structures. In either approach, it is necessary to have deterministic loading and to further cool atoms down to the ground state of the trapping potential so that any irregularity in the position of the atoms is minimized to reduce the dephasing in the dynamics of the Rydberg gases.

Concluding remarks

Due to the strong long-range tunable interactions of Rydberg atoms and the superior controllability of ultracold atomic gases, cold Rydberg gases might become an ideal system for experimental investigations in quantum simulation, quantum information processing, and quantum optics. At the moment, cold Rydberg gases are still an emerging field where many experimental studies need to be performed to better understand this complex system, and new experimental techniques need to be developed to push further the frontier into totally unexplored regimes. Moreover, detailed and extensive theoretical studies are indispensable for advances in this field. With more and more physicists coming to work on the exciting topics of cold Rydberg gases, experimentally or theoretically, not only will the field flourish, producing many new results and generating new insights and applications, but also there exists the possibility to create physical systems that have not ever been available before for scientific investigation.

11. Stretching the boundaries of plasma physics with ultracold neutral plasmas

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Status

Plasmas are typically hot ionized gases—at temperatures of 1000 K or more, which are high enough for atomic or molecular collisions to lead to ionization. However, the boundaries of plasma physics have been stretched in the last decade by ultracold neutral plasmas (UCNPs), which have ion temperatures on the order of 1 K and tunable electron temperatures from 1–1000 K [23]. These unusual plasmas are created by photoionizing laser-cooled atomic gases, or in some cases by exciting molecules in a supersonic molecular beam [106].

Research on UNCPs began around 2000, and it grew out of interest in the dynamics of clouds of ultracold atoms excited to high-lying, strongly interacting Rydberg states (see section 10). The initial work was experimental, but it was quickly followed by a large body of theoretical and computational investigations. Experimentally, UCNPs are well diagnosed by charged-particle diagnostics and laser-induced fluorescence of the ions in the plasma [23]. Molecular dynamics simulations and a wide array of hydrodynamics, kinetic, and hybrid theoretical tools have also been applied to describe UCNPs.

Most research on UCNPs falls into one of three areas: exploration of a novel plasma system, leveraging particular properties of UCNPs to demonstrate or study phenomena found in traditional plasmas or explore potential applications, and the study of strongly coupled plasma physics.

UCNPs represent a new type of plasma because of their small size, low temperatures, and creation method. Much attention has focused on the properties and dynamics of these systems, such as understanding the expansion of the plasma into surrounding vacuum, evolution of the ion and electron temperatures, and the creation of Rydberg atoms in the plasma through three-body recombination.

One of the most distinguishing features of UCNPs is the exquisite control and knowledge of the initial plasma conditions, such as the initial density distribution and temperatures of ions and electrons. This has made UCNPs an ideal platform for exploring topics from traditional plasma physics, such as collective modes, the effects of electric and magnetic fields on plasma dynamics, and hydrodynamic and kinetic regimes of plasma behavior. UCNPs display interesting variations on the traditional themes, such as the nature of ion acoustic waves and electron plasma oscillations. They also provide a powerful new window into open problems in plasma physics, such as the crossover regime from hydrodynamic to kinetic behavior.

One of the main drivers of interest in UCNPs is the fact that they enable the study of strongly coupled plasma physics. Strong coupling arises in many fields of physics including plasma, atomic, condensed matter, and nuclear/particle interactions, and it is associated with phase transitions and the establishment of spatial correlations of particles [107]. For example, these topics are of interest in many-body systems of ultracold molecules (section 9) and Rydberg gases (section 10). Plasmas are strongly coupled when the Coulomb interaction energy between neighboring particles exceeds the thermal energy, characterized by the Coulomb coupling parameter, $\Gamma \geqslant 1$, where $\Gamma = e^2/4\pi\varepsilon_0 a k_B T$. Here, T is the temperature and a is the Wigner–Seitz radius, $a = [3/(4\pi n)]^{1/3}$ for density n. Ions in UCNPs equilibrate with $\Gamma \sim 2$–4. Electrons are limited by three-body recombination to $\Gamma < 0.2$ [23].

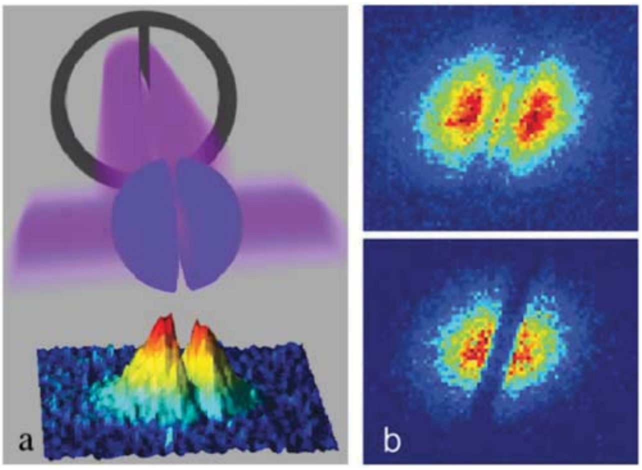

Figure 16. Ultracold neutral plasma creation and imaging. (a) Ultracold neutral plasmas are typically created by photoionizing laser-cooled atoms. Here, strontium atoms are ionized by a laser that passes through an intensity mask to create two plasma hemispheres that expand into each other. A sheet of light resonant with ions in the plasma excites fluorescence, which is imaged with a CCD camera. (b) Spatially, temporally, and spectrally resolved images record plasma dynamics such as the excitation of density waves.

UCNP ions are strongly coupled at very low density because of their low temperature. This leads to slower plasma timescales compared to solid-density plasmas and allows detailed study of the dynamics. This has enabled discovery of phenomena that occur during equilibration of strongly coupled systems, such as disorder-induced heating and kinetic energy oscillations [23], and has been exploited to study the breakdown of Landau–Spitzer theory for collisional equilibration rates [108].

The field continues to expand into new areas. UCNPs are now also created with femtosecond lasers in atomic beams [109], and from molecules in a supersonic molecular beam [106]. The latter introduces molecular processes such as dissociative recombination. The potential use of UCNPs as sources for bright electron and ion beams, such as in focused ion beam machines [110], is also an active area of research.

UCNP research has broader impact because of the importance of strong coupling in non-neutral plasmas, dusty plasmas, laser-produced high energy density plasmas, and astrophysical environments [111]. This also connects UCNP research to liquid physics and soft condensed matter, in which statistical mechanics models of strongly coupled systems are also important [107]. Similar plasma creation and expansion dynamics are observed in nanoplasmas created by ionization of clusters [112].

Current and future challenges

The greatest challenge in UCNP research is the pursuit of more strongly coupled plasmas. Essentially independent of initial experimental conditions, UCNP ions equilibrate with Coulomb coupling parameter $\Gamma \sim 2$–4, just barely in the liquid-like regime. Particle dynamics change significantly at $\Gamma = 30$ when caging effects set in. Near $\Gamma = 200$, Coulomb systems undergo a first-order phase transition to a solid state. Access to stronger coupling would allow study of collisions, transport, and collective modes across a wide variety of coupling strengths deep into the liquid regime. Theory is difficult for strongly coupled plasmas, so experimental studies are needed.

Many schemes have been proposed to increase the coupling in UCNPs. The limitation in Coulomb coupling arises because of the large potential energy inherent in the random spatial distribution of ions just after plasma creation [114]. Schemes to increase Γ either involve removing ion energy after plasma creation, such as through laser cooling the ions, or pre-correlating the positions of atoms or molecules before ionization to reduce the initial potential energy, such as using an effect called the ‘Rydberg blockade’ (section 10) to create regularly spaced Rydberg atoms that are then ionized, ionizing atoms in an optical lattice or quantum degenerate Fermi gas, or relying on molecular processes to remove closely spaced pairs of ions in a plasma created from molecules [106].

Phenomena in strongly coupled plasmas that are sensitive to correlations between particles, such as collision rates, transport, and the liquid–solid phase transition, are not captured by hydrodynamic models or tractable kinetic treatments. Full molecular dynamics simulations are required to model these systems. UCNPs have attracted significant interest from computational plasma physicists because modeling UCNPs presents a great challenge for current computational resources. Excellent diagnostics allow detailed comparison of numerical and experimental results.

There are many other frontiers of current and future UCNP research. Experimental investigations of transport and collisional processes in UCNPs are still relatively new, as are studies of molecular UCNPs. The use of UCNPs for bright electron and ion beams could potentially improve the resolution for applications using charged particles for imaging and nanomachining. Plasmas created from multiple atomic species with differing masses are being considered, and these should introduce new collective modes and alter the plasma dynamics. On the theory front, there are efforts to adapt kinetic theories to describe the effects of strong coupling in UCNPs. There is also great opportunity to connect UCNP research more strongly to mainstream plasma physics by leveraging the unique characteristics of UCNPs for further study of collective modes, instabilities, and kinetic and hydrodynamic bulk plasma phenomena.

Advances in science and technology to meet challenges

Continued progress in the field will proceed in tandem with developments in many areas. Greater computational power and techniques will improve plasma modeling, which will drive greater scientific understanding and open new questions. Each potential path towards stronger coupling presents its own technical challenges, although they seem surmountable. Improved and less expensive laser sources are bringing laser cooling of plasma ions into reach. The Rydberg blockade effect, gases in optical lattices, and quantum degenerate Fermi gases have never been demonstrated for samples large enough to produce a plasma that could be easily studied with current diagnostics.

Molecular plasmas have opened new opportunities and in many ways simplify creation of UCNPs by circumventing the need for laser cooling. If a molecular system could be found that allowed for optical imaging of the ions, this would allow *in situ* probing of the resulting plasma. Larger plasmas, in terms of physical size and number of particles, would be valuable for applications in charged-particle beams. This would also slow down the plasma expansion, which would allow improved measurement of collisional and transport phenomena.

Concluding remarks

It is difficult to capture all the current trends in UCNP physics in a short paper, and it is impossible to predict the future directions the field will take. But with the continued interplay between experiment, theory, and simulation, it is clear that one should expect many more fundamental discoveries and even some practical applications to come.

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