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EDITORIAL

Focus on atomtronics-enabled quantum technologies

Luigi Amico[1,2], Gerhard Birkl[3], Malcolm Boshier[4] and Leong-Chuan Kwek[2,5]

1 Dipartimento di Fisica e Astronomia, Università di Catania & CNR-MATIS-IMM & INFN-Laboratori Nazionali del Sud, INFN, Catania, Italy
2 Centre for Quantum Technologies, National University of Singapore, Singapore
3 Technische Universität Darmstadt, Germany
4 Los Alamos National Laboratory, United States of America
5 Institute of Advanced Studies and National Institute of Education, Nanyang Technological University, Singapore

Abstract

Atomtronics is an emerging field in quantum technology that promises to realize 'atomic circuit' architectures exploiting ultra-cold atoms manipulated in versatile micro-optical circuits generated by laser fields of different shapes and intensities or micro-magnetic circuits known as atom chips. Although devising new applications for computation and information transfer is a defining goal of the field, atomtronics wants to enlarge the scope of quantum simulators and to access new physical regimes with novel fundamental science. With this focus issue we want to survey the state of the art of atomtronics-enabled quantum technology. We collect articles on both conceptual and applicative aspects of the field for diverse exploitations, both to extend the scope of the existing atom-based quantum devices and to devise platforms for new routes to quantum technology.

1. Introduction

The pervasive importance of electronic devices, e.g. transistors, diodes, capacitors, inductors, integrated circuits, can be observed everywhere in our daily applications and usage. The key players in electronic devices are electrons and holes. Imagine circuitry in which the carriers are atoms instead of electrons and holes. The most evident features that result from such a design would be a reduced decoherence rate due to charge neutrality of the atomic currents, an ability to realize quantum devices with fermionic or bosonic carriers, and a tunable carrier–carrier interaction from weak-to-strong, from short-to-long range, from attractive-to-repulsive in type.

The rapid progress in quantum technology is spurring this dream to reality: atomtronics is an emerging field in physics that promises to realize those atomic circuit architectures exploiting ultra-cold atoms manipulated in versatile micro-optical circuits generated by laser fields of different shapes and intensities or by micro-magnetic circuits known as atom chips [1–4].

With the added value of a dissipation-less flowing atomic current, Atomtronics is expected to enhance the flexibility and the scope of cold-atom quantum technology. With the current know-how in the field, circuits with a lithographic precision can be realized. In principle, all aspects of mesoscopic physics and devices can also be explored. It is not just classical electronics which is targeted, but also atom-based spintronics and quantum electronic structures like Josephson-junction-based circuits (SQUID devices, etc.), quantum point contacts and impurity problems. Core devices for applications in quantum metrology, e.g., nano-scale amplifiers or precision sensors, can be designed and exploited. Finally, Atomtronics may also provide new solutions for the physical realization of quantum gates for quantum information protocols and hybrid quantum systems.

The goal of this focus issue in New Journal of Physics is to survey the state of the art of atomtronics-enabled quantum technology and, at the same time, to trigger new concepts and applications for the field. We covered both theoretical and experimental works. Like many collection of works, however, it is not meant to be comprehensive nor exhaustive. Readers are encouraged to look into the relevant literature cited in these papers for a more complete understanding.

In this introduction to the focus issue we group the articles in three sections: atomtronics quantum simulators, elements for atomtronics integrated circuits, and atomtronics device for sensing and computation.

2. Atomtronics quantum simulators

Quantum emulators or simulators have been one of the key goals of quantum technology [5–9]. The Atomtronics quantum technology of atomic currents flowing in closed architectures combined with carrier statistics that can be changed easily will ultimately enable a new platform of cold-atom quantum simulators. The object of the quantum simulation may be a notoriously hard problem in physics to be solved with classical logic, or it may provide insights on problems in different areas of physics, notably in quantum material science or high energy physics, that are still open. Atomtronics can address key issues, from fundamental concept of low-dimensional superfluidity in interacting quantum gases to the interplay of geometrical constraints, interactions and gauge potentials, to frustration effects, topological order, and edge state formation. Some examples have been addressed in recent studies in cold atomic samples, but here we are in the position to work with tunable boundary conditions, and capture physical conditions where flowing currents provide a way to actually characterize the system. The situation is comparable to developments in solid state physics: a fruitful avenue in that field is to study the (electronic) current in the system as a response to an external perturbation. The Atomtronics approach here is top-down: analyse the response of a quantum fluid to an external (artificial) gauge field to gain insight into the microscopic quantum dynamics. Finally, to achieve these goals, new ways to read out the state of the cold atom system are fostered.

- *Coherent superposition of current flows in an atomtronic quantum interference device*, Aghamalyan *et al* [10].
- *Entanglement and violation of classical inequalities in the Hawking radiation of flowing atom condensates*, de Nova *et al* [11].
- *Quantum simulation of conductivity plateaux and fractional quantum Hall effect using ultracold atoms*, Barberàn *et al* [12].
- *Bandwidth-resonant Floquet states in honeycomb optical lattices*, Quelle *et al* [13].
- *Chaos and two-level dynamics of the atomtronic quantum interference device*, Arwas and Cohen [14].
- *Spin–orbit-coupled Bose–Einstein-condensed atoms confined in annular potentials*, Karabulut *et al* [15].
- *Quasi-molecular bosonic complexes-a pathway to SQUID with controlled sensitivity*, Safavi-Naini *et al* [16].
- *Robustness of discrete semifluxons in closed Bose–Hubbard chains*, Gallemì *et al* [17].
- *Holographic optical traps for atom-based topological Kondo devices*, Buccheri *et al* [18].
- *Vortex dynamics in superfluids governed by an interacting gauge theory*, Butera *et al* [19].

3. Elements for atomtronics integrated circuits

One of the most important goals of Atomtronics is to conceive radically new types of quantum device exploiting phase coherence and persistent currents in optical circuits or rf-guides. Elementary circuit elements (ring condensates, matter-wave beam splitters, matter wave guides etc.) have been already constructed, with the next step being to assemble them in atomtronic circuits with complex architectures. So far, tunnel couplings have been the suggested basic mechanism for coupling the circuit elements. Given the feature of the phase coherence in the system, such coupling relies on the Josephson effect.

- *Integrated coherent matter wave circuits*, Ryu and Boshier [20].
- *Atom transistor from the point of view of nonequilibrium dynamics*, Zhang *et al* [21].
- *Resonant wavepackets and shock waves in an atomtronic SQUID*, Wang *et al* [22].
- *Stability and dispersion relations of three-dimensional solitary waves in trapped Bose–Einstein condensates*, Mateo and Brand [23].
- *Transport of ultracold atoms between concentric traps* via *spatial adiabatic passage*, Polo *et al* [24].
- *Principles of an atomtronic transistor*, Caliga *et al* [25].
- *Transport dynamics of ultracold atoms in a triple-well transistor-like potential*, Caliga *et al* [25].
- *Versatile electric fields for the manipulation of ultracold NaK molecules*, Gempel *et al* [26].

- *Suppression and enhancement of decoherence in an atomic Josephson junction*, Japha *et al* [27].
- *Realizing and optimizing an atomtronic SQUID*, Mathey and Mathey [28].

4. Atomtronics devices for sensing and computation

High precision interferometric sensors using matter waves promise a considerable gain in sensitivity compared with the existing solutions (for rotation sensing, in particular, the gain over the light based technology, can be up to $\sim 10^{10}$, for equal enclosed areas and equal particle flux) [29]. Since Bose–Einstein condensates are governed by a nonlinear dynamics, Atomtronics sensors can be based on solitary waves. A special type of interferometric sensor is the atomtronic quantum interference device (AQUID) the atomic counterpart of the SQUID. The AQUID effective dynamics are those of a qubit, so the device may provide a new physical implementation for quantum computation with reduced decoherence. For such devices, the working point is set by applying synthetic magnetic fields/physical steering of the condensate which can induce quantum phase slips. Quantum gates, however, can be also realized through atom-solidstate hybrid schemes.

- *Coherent quantum phase slip in two-component bosonic atomtronic circuits*, Gallemì *et al* [30].
- *Minimally destructive, Doppler measurement of a quantized flow in a ring-shaped Bose–Einstein condensate*, Kumar *et al* [31].
- *Engineering dark solitary waves in ring-trap Bose–Einstein condensates*, Gallucci and Proukakis [32].
- *Comparative simulations of Fresnel holography methods for atomic waveguides*, Henderson *et al* [33].
- *Bose–Einstein condensation in large time-averaged optical ring potentials*, Bell *et al* [34].
- *Addressed qubit manipulation in radio-frequency dressed lattices*, Sinuco-Leòn and Garraway [35].
- *An atomtronic flux qubit: a ring lattice of Bose–Einstein condensates interrupted by three weak links*, Aghamalyan *et al* [36].
- *Matter-wave interferometers using TAAP rings*, Navez *et al* [37].

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