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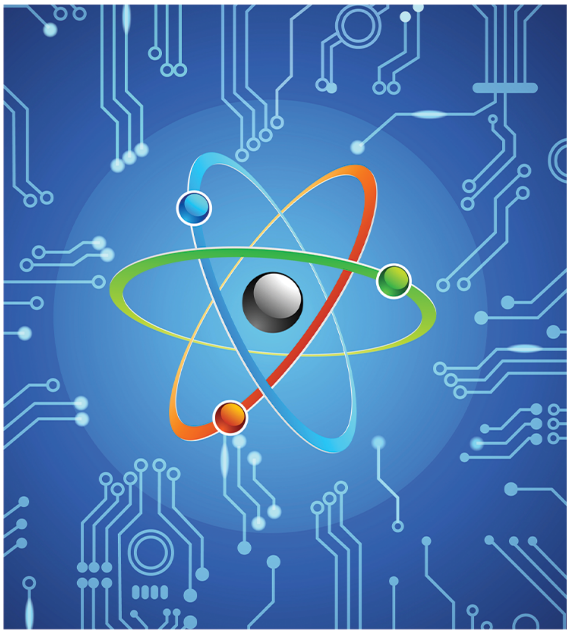

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Contents

Josephson junctions with fermionic superfluids: from one to many

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The Josephson effect is one of the most striking manifestations of a macroscopic system phase coherence. When two condensates are connected by a tunneling barrier, the wave functions overlapping below the barrier can get locked in phase and sustain a dissipationless super current through the junction. For sufficiently high barriers, the current depends sinusoidally on the relative phase between the two condensates and its maximum value, the critical current, depends on the intrinsic properties of the condensate. Josephson junctions are thus at the same time powerful probes of the phase coherence of a system and fundamental building block for atomtronics circuit, with well defined current-chemical potential and current-phase characteristics. In my talk I will present two realizations of an atomtronics circuit with Josephson junctions of fermionic superfluids of ultracold lithium-6. In a first experiment [1], we realize an array of Josephson junctions in a ring superfluid, a Josephson junction necklace. In such a multiply connected geometry, the phase difference across each junction is bounded to the phase winding of the condensate around the ring, giving rise to the counterintuitive stabilization of the current in the ring upon increasing the number of tunneling barriers. Secondly, I will report on an ongoing experiment on AC driving on a single junction with atomic Fermi superfluids. The periodic modulation of the current induces phase slips across the junction, which resonantly modifies the current-chemical potential characteristic. In particular we observe the emergence of a number of steps at constant non-zero chemical potential, resembling the Shapiro steps appearing in superconducting junctions coupled to an external electromagnetic field.

[1] L. Pezze' et al., Stabilizing persistent currents in an atomtronic Josephson junction necklace, accepted in Nature Communications.

Persistent current oscillations in a double-ring quantum gas

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Vorticity in closed quantum fluid circuits is known to arise in the form of persistent currents. In this work, we develop a method to engineer transport of the quantized vorticity between density-coupled ring-shaped atomic Bose-Einstein condensates in experimentally accessible regimes. Introducing a tunable weak link between the rings, we observe and characterize the controllable periodic transfer of the current and investigate the role of temperature on suppressing these oscillations via a range of complementary state-of-the-art numerical methods. Our setup paves the way for precision measurements of local acceleration and rotation

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Matter-wave interferometry of 2D Bose gases using a double-well potential for dressed atoms

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We form a precisely controllable double-well potential for quasi-2D Bose gases by dressing atoms with multiple RFs, in a magnetic quadrupole trap. After a time-of-flight expansion the two clouds overlap to produce interference fringes, from which we determine the local relative phase of the initial wave functions and vortex density. This is a powerful approach to investigate equilibrium and nonequilibrium many-body quantum systems via correlation functions and full-counting statistics. We probe the universal dynamics triggered by a quench from the superfluid to normal phase across the Berezinskii-Kosterlitz-Thouless critical point in a 2D Bose gas of rubidium atoms. By splitting a 2D gas into two, separated by a few microns, we suddenly halve the density to quench the system across the critical point. The subsequent relaxation dynamics are probed with matter-wave interferometry. We found that the time evolution of both the phase-correlation function and vortex density obeys universal scaling laws. This conclusion is interpreted by real-time renormalization group theory. Recent work on efficient loading atoms directly from optical molasses (MOT) into an RF-dressed trap to create a BEC will also be presented.

[1] S. Sunami et al., Universal scaling of the dynamic BKT transition in quenched 2D Bose gases. Science, 382, 443 (2023).

Two- and three-dimensional arrays of individual atoms: an introduction to potential implementations of atomtronics

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Through significant recent progress, regular registers of individual neutral atoms have established themselves as an auspicious platform for quantum technological applications. Hundreds of quantum bits (qubits) are available routinely. The marks of 1.000 qubits in 2D and 10.000 qubits in 3D have been passed recently, and 100 thousands of individual-atom quantum systems are within reach by extension of currently available technology. One-qubit gate operations are induced by electromagnetic fields and two-qubit gates are achieved by direct mutual interaction of neighboring atoms in highly-energetic internal states. With this contribution an impulse shall be given to extend this technological platform into the direction of ATOMTRONICS. I will discuss the physical principles and technological basis for quantum technology with neutral atoms cooled close to absolute zero temperature, held in vacuum, and trapped by light. I will present a scalable quantum information processing architecture based on advanced optical and quantum optical technologies. This platform is perfectly suited for applications in quantum simulation and quantum computing with individual atoms and atom ensembles. A proof of concept experiment has been performed to demonstrate the application of arrays of individual atoms in quantum sensing, and proposals towards ATOMTRONICS applications have been discussed.

Inertial effects in superfluid vortex dynamics

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In quantum matter, vortices are topological excitations characterized by quantized circulation of the velocity field. They are often modeled as funnel-like holes around which the quantum fluid exhibits a swirling flow. In this perspective, vortex cores are nothing more than empty regions where the superfluid density goes to zero.

In the last few years, this simple view has been challenged and it is now increasingly clear that, in many real systems, vortex cores are not that empty: thermal atoms, quasi-particle excitations, tracer atoms, just to name a few examples, can be commonly found in the cores of quantum vortices. These particles provide the vortex with an effective inertial mass.

In this talk, I will discuss the dynamics of two-dimensional point-like vortices whose cores are filled by massive particles. I will show that the introduction of core mass in the standard point-vortex model constitutes a singular perturbation, as it alters the order of the equations of motion. I will also discuss the new dynamical regimes that are unlocked by the presence of core mass. The simplest example is a single vortex within a rigid circular boundary, where a massless vortex can only precess uniformly. In contrast, the presence of a massive core can lead to small-amplitude radial oscillations, which are, in turn, clear signatures of the associated inertial effect.

I will also show that, as opposed to their massless counterpart, massive vortices can collide, resulting into vortex/antivortex annihilation processes or into the stabilization of doubly charged vortices. Eventually, I will discuss how the collective properties of a many-vortex system are modified by the presence of core mass. More specifically, I will show that the superfluid Kelvin-Helmholtz instability, governing the breakdown of regular vortex arrays, is mitigated by the inertial effects.

References

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Loss features and spin dependent scattering lengths in ultracold 162 Dy gases

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Dipolar gases such as erbium and dysprosium have a dense spectrum of resonant loss features associated with their strong anisotropic interaction potential. These resonances exhibit different behaviours with density and temperature, implying different microscopic properties. Here we present our quantitative study of the low-field (B ¡ 6G) loss features in ultracold thermal samples of 162Dy, revealing two- and three-body dominated loss processes [1]. We study their temperature dependence and detect a feature compatible with a previously unobserved d-wave Fano-Feshbach resonance. We also analyse the expansion of the dipolar Bose-Einstein condensate as a function of the magnetic field and interpret the changes in size near the resonances as a variation in the scattering length. This method, combined with spin-dependent light-shifts, allows us to extract the background scattering length of spin-polarised dysprosium samples in different Zeeman sublevels, namely —J, -J¿, —J, -J +1¿ and —J, -J +2—. We will present our preliminary results showing that the different background scattering lengths are all positive and of similar magnitude. Furthermore, we identify several spin-dependent Feshbach resonances, paving the way for the manipulation of spinor dipolar BECs.

Simulation of lattice systems with qubits

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Will present results on simulations of various algorithms to solve quantum many-body problems in lattice systems in a digital quantum computer. On the one hand I will tackle the nuclear structure problem within the nuclear shell model, where two-body terms connect in a highly non-regular way all the single-particle orbitals in the shell, similar to the molecular Hamiltonian. I will show how nuclear ground states can be simulated using the adapt-VQE algorithm run in qubits, and how a better understanding of nuclear entanglement within the nuclear shell model can aid in these simulations. On the other hand I will show simulations of adiabatic and diabatic evolutions to find ground and excited states and study dynamics in regular lattice systems such as 1D and 2D Fermi-Hubbard models with first neighbour tunnelings, also using a qubits simulator.

Cooper quartets design in interacting superconducting systems

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Quantum design of Cooper quartets in a double quantum dot system coupled to ordinary superconducting leads is presented as a novel platform for the study of an elusive many-body state of matter, that is at the basis of the phenomenon of charge-4e superconductivity. A fundamentally novel, maximally correlated ground state, in the form of a superposition of vacuum —0⟩ and four-electron state —4e⟩, emerges as a narrow resonance and it is promoted by an attractive interdot interaction. A novel phenomenology in the dissipationless transport regime is elucidated, that yields typical flux quantization in units of h/4e and manifests in non-local multi-terminal coherence and in two-Cooper pair transport properties mediated by the quartet ground state. The results open the way to the exploration of correlation effects and non-local coherence in hybrid superconducting devices, parity-protected quantum computing schemes and more generally, the work poses the basis for the design and simulation of novel correlated states of matter starting from ordinary ingredients available in a quantum solid state lab.

Solving Problems in Superfluid Rotation with Cavity Optomechanics

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Bose-Einstein Condensates (BECs) in ring potentials are a paradigm of quantum rotation, in which circulating states of atomic flow are spatially localized, able to carry high angular momentum, and persist for macroscopic lengths of time. An extensive amount of research activity, both experimental as well as theoretical, has addressed this platform. Among the topics investigated are superfluid hydrodynamics, atomtronics, matter wave interferometry, self-trapping, Berry phases, quantum computation, gyroscopy, rotation sensing, Josephson physics, gauge-fields, time crystals, topological excitations and cosmological simulations. In all the studies mentioned above, a fundamental question relates to the state of the rotation of the BEC. At present all existing states of detecting rotation in ring BECs are fully destructive of the condensate as they involve absorption imaging. Typically, they also involve time-off-flight expansion to account for optical resolution. In this work, we theoretically propose using the techniques of cavity optomechanics to sense ring BEC rotation with minimal destruction, in situ and in real time (Fig.1) [1]. Our approach exploits the availability of optical modes that carry orbital angular momentum (OAM). We present approximate analytical results for a few-mode quantum mechanical model as well as numerical simulations in a mean field treatment of the condensate and optical dynamics. We characterize the angular momentum content of persistent rotational eigenstates as well as superpositions, and bright solitons, both singly as well as pairwise in collision [2,3]. We show how rotating the optical lattice formed by the OAM-carrying modes allows us to minimally destructively measure the magnitude as well as sign of the condensate rotation [3]. Our work opens up new possibilities for sensing and manipulation of rotating matter waves, including a memory for OAM-carrying photons and detection of superfluid drag (Andreev-Bashkin effect).

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Shapiro steps in driven atomic Josephson junctions

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We study driven atomic Josephson junctions realized by coupling two two-dimensional atomic clouds with a tunneling barrier. By moving the barrier at a constant velocity, dc and ac Josephson regimes are characterized by a zero and nonzero atomic density difference across the junction, respectively. Here, we monitor the dynamics resulting in the system when, in addition to the above constant velocity protocol, the position of the barrier is periodically driven. We demonstrate that the time-averaged particle imbalance features a plateau behavior that is the analog of Shapiro steps observed in driven superconducting Josephson junctions. The underlying dynamics reveals an intriguing interplay of the vortex and phonon excitations, where Shapiro steps are induced via suppression of vortex growth. We study the system with a classical-field dynamics method, and benchmark our findings with a driven circuit dynamics.

Shapiro Steps in a bosonic Josephson junction

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One paradigmatic example of quantum transport is the Josephson junction, which consists of two superconductors coupled by a weak link. Despite the obstacle between the two parts, they can support a supercurrent and phase coherence between them. Interesting is the relation between the current and phase, which is governed by the Josephson equations. This behavior is quite different from other conventional electronic devices. We experimentally investigate Bose-Einstein condensates coupled by a weak link in a bosonic Josephson junction. An analogue to the superconductor using a superfluid made from bosonic 87Rb atoms. The weak link is realized by a repulsive optical potential splitting the sample. Using a new time-dependent modulation scheme of the barrier we can look into the inverse ac Josephson effect and measure Shapiro steps in the current-voltage characteristic. In the case of cold atoms this corresponds to a velocity and chemical potential difference curve. One main aspect of this effect is, that it is able to create a potential difference solely based on the frequency of the modulation. Comparing to conventional superconductor theory, we find excellent agreement with the experimental data. By tuning different parameters of the protocol we characterize the height and width of the Shapiro steps in the system.

Subwavelength Superoscillatory Optical Tweezers

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Controlled trapping of individual atoms and their ensembles is of growing interest for quantum simulations of many body systems, quantum computing, optical clocks, and beyond. Here, we present trapping of single ultracold atom in an optical trap that can be continuously tuned from a standard Airy focus to a subwavelength hotspot smaller than the usual Abbe's diffraction limit. The hotspot was generated using the effect of superoscillations, by the precise interference of multiple free-space coherent waves. We characterized the superoscillatory optical trap by measuring the atom effective temperature, lifetime, and the trap frequency. We argue that superoscillatory trapping and continuous potential tuning offers not only a way to generate compact and tenable ensembles of trapped atoms for quantum simulators but will also be useful in single molecule quantum chemistry and the study of cooperative atom-photon interaction within subwavelength periodic arrays of quantum emitters. Preliminary results will be presented on this latter point.

Subwavelength Superoscillatory Optical Tweezers

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Quantum cryptography is traceable to the 1919 patent of Gilbert Vernam.[1] Elegantly adapted to the electromechanical communications infrastructure of his employer, the American Telephone and Telegraph company (AT&T), it uses the bitwise exclusive OR (XOR) of a binary message text, M, with a binary key, K, to produce a cyphertext, C = M XOR K. C could be sent over an insecure channel, and the message could be recovered from M = C XOR K. Quantum mechanics makes possible the secure generation of two copies of K. Claude Shannon of AT&T identified a set of conditions under which Vernam encryption would be secure, in the sense that no cryptanalytic attack on C alone could recover the message M.[2] This method was long used by the U.S. Government for its highest-security communications and may still be in use today. Communications among all the world's 7 billion smartphones and comparable numbers of other internet-enabled devices are secured by a public key infrastructure (PKI) that is based on the supposition that the prime factors of large integers are difficult to compute. This seemed a reasonable idea [3] until 1994, when Peter Shor showed that computational resources required for factoring an integer would grow as a polynomial function of the number of its digits if a quantum computer was used, rather than exponentially as is presumed to be the case for a classical computer.[4] About 10 years ago, the National Institute of Standards and Technology began a study of alternatives to current PKI that were not known to be susceptible to quantum cryptanalytic attack.[5] This has resulted in what is likely to be the most consequential response to the prospect of quantum computing to date.[6] The eventual retooling of PKI may take decades. I will discuss some prospects for the future. This presentation contains only public information and has not been reviewed or approved by any U.S. Government agency.

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High-Performance Atom Interferometry in Harmonic Traps

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Atom interferometry methods can be applied to a wide variety of sensing applications, including gravimetry, inertial navigation, atomic physics investigations, and potentially gravitational wave detection. Most applications use atoms in free fall, where perturbations to the atom's motion can be minimized. However, obtaining very high sensitivity requires long interrogation times, and in a terrestrial environment the resulting free fall distances can be inconveniently large. An alternative is to perform interferometry using atoms confined in a trap, where long interrogation times can be achieved in a small spatial volume. We have demonstrated a Sagnac interferometer using atoms confined in a magnetic time-orbiting potential trap. The atoms move in circular orbits through the trap, with radii up to 0.57 mm and interrogation times up to 0.6 s [1]. We implement two simultaneous counter-propagating interferometers, in which the Sagnac effect is differential, but most noise sources are common mode. Figure 1 shows the output signals of the two interferometers plotted against each other. The differential phase is determined from the eccentricity of the resulting ellipse.

We have explored the noise performance of the interferometer, and we observe significant run-to-run phase noise on the order of 1 radian. We are currently investigating the source of the short-term noise. However, we find the noise averages down as $1/\tau^{1/2}$ for averaging times τ up to at least 90 minutes. This indicates that the system has good long-term stability. The rotational accuracy of the measurement is 9 μrad/s for the data set shown in Fig. 1, and the rotational bias is stable to this accuracy over days.

Making best use of this type of interferometer requires the ability to model the motion of atoms in the trap accurately and efficiently, along with the consequent phase evolution. Direct solution of the Schrodinger equation is impractical on the time and length scales involved. A conventional alternative is the semiclassical approximation, in which trajectories are calculated as for a classical particle and the phase evaluated as the action on the classical path. The semi-classical approximation is exact for atoms in a harmonic potential, but realistic potentials are anharmonic to some degree, and it is not clear how this affects the accuracy of the semi-classical approximation. We have developed a new approximation method based on time-dependent perturbation theory using generalized coherent states. This can be used to determine the leading-order correction to the semi-classical approximation. We expect this approach will be useful for a variety of trapped atom interferometer applications.

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Angular momentum fractionalization in multi-component ultracold atomic circuits

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In this presentation, we will discuss our recent study on the behavior of persistent currents in multi-component bosonic and fermionic systems. Our research is primarily focused on the characterization of the persistent current behavior at different interaction regimes. In addition, we build a comprehensive understanding of the states that correspond to the fractionalized angular momenta per particle of the system. The readout of interference patterns is also analyzed through time-of-flight expansion to gain deeper insights into the inner mechanism behind fractionalization and its manifestation in these interferograms, focusing on the limits of zero and strong interactions. Our research findings are significant because they can provide valuable information about the phenomena of angular momentum fractionalization in multi-component ultracold atomic systems. This study can bring new avenues in the field expanding the interests of current states beyond the single component Bose gases or the recently observed persistent current in two-component fermionic systems.

Interaction-enhanced chiral currents in atomic synthetic structures

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Experimental platforms of ultracold fermionic atoms trapped in optical lattices are a powerful tool to realize and investigate the properties of novel quantum systems, where the relevant energy scales of the system can be artificially tuned. In particular, exploiting electronic and nuclear properties of alkaline-earth-like atoms (such as ^{173}Yb or ^{87}Sr), it is possible to realize controllable multicomponent Hubbard-like models, characterized by more than the usual two spin states, where the “flavor” index is provided by the nuclear state of the atom. In recent experiments, alkaline-earth-like atoms loaded in optical lattices and coupled to external Raman laser beams have been used to realize synthetic ladders where one of the dimensions is not spatial, but it is provided by the Raman-coupled nuclear states. Tuning the phase gradient of the Raman processes along the real dimensions, it is possible to realize artificial gauge fields piercing the ladder, resulting in persistent spin-dependent currents in the low-temperature thermal states of the system (i.e. in a chiral behavior).

In the present talk, after reviewing some details of the experimental implementation and introducing relevant theoretical methods for the simulation of interacting fermionic systems (such as Dynamical Mean Field Theory), we investigate how the spin-dependent chiral currents are affected by the local interparticle repulsion, showing a remarkable enhancement close to the Mott transition and a slow decay moving deep in the insulating regime. We motivate this result by unveiling the quasi-particle nature of the interaction-driven insulator and we strengthen its generality by showing results for different geometries (including $(2+1)$-dimensional structures with different number of flavors).

A Floquet-Rydberg quantum simulator for confinement in Z2 gauge theories

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Recent advances in the field of quantum technologies have opened up the road for the realization of small-scale quantum simulators of lattice gauge theories which, among other goals, aim at improving our understanding on the non-perturbative mechanisms underlying the confinement of quarks. In this work, considering periodically-driven arrays of Rydberg atoms in a tweezer ladder geometry, we devise a scalable Floquet scheme for the quantum simulation of the real-time dynamics in a Z2 LGT. Resorting to an external magnetic field to tune the angular dependence of the Rydberg dipolar interactions, and by a suitable tuning of the driving parameters, we manage to suppress the main gauge-violating terms and show that an observation of gauge-invariant confinement dynamics in the Floquet-Rydberg setup is at reach of current experimental techniques. Depending on the lattice size, we present a thorough numerical test of the validity of this scheme using either exact diagonalization or matrix-product-state algorithms for the periodically-modulated real-time dynamics.

The surprisingly rich physics of the time-modulated quantum pendulum

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In classical mechanics, a pendulum whose parameters are modulated in time provides a standard example for introducing classical chaos, with the emergence of mixed or fully chaotic stroboscopic phase spaces. In quantum physics, although the Schrödinger equation is fully linear, the same Hamiltonian offers the possibility of studying the wave localization effect and chaos-assisted tunneling [1]. We will detail our recent results in this direction. Using quantum control techniques to drive the pendulum appropriately [2] and quantum tomography to certify the generation of the desired quantum state [3], we have recently extended the accessible physics in this

system by demonstrating the production of squeezed states and matter wave transport with a quantum ratchet [4], performing qubit-based quantum computations, carrying out various quantum simulations based on Floquet Hamiltonian engineering including the generation of a synthetic and tunable cristal [5] and by observing multiple matterwave interference effect related to strong (Anderson) localization.

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Resonance Cascades as a Tool of Quantum Number Theory

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In this presentation, we consider situations where the existence of a contiguous cascade of quantum resonant transitions is predicated on the validity of a particular statement in number theory. As a case study, we look at the following trivial statement: ”Any power of 3 is an integer.” Consequently, we ”test” this statement in a numerical experiment where we demonstrate an un-impeded upward mobility along an equidistant, log(3)-spaced subsequence of the energy levels of a potential with a log-natural spectrum, under a frequency log(3) time-periodic perturbation. With the knowledge gained in this project, we consider similar schemes aimed at two more number-theoretical statements: ”Any product of two sums of two squares of integers is a sum of two squares of integers” (this one can be proven using the Diophantus-Brahmagupta-Fibonacci identity) and ”Any even is a sum of two primes” (i.e. the Goldbach conjecture, still unproven) (Fig. 1). The empirical relevance of all three projects is ensured by the current experimental progress in creating cold-atomic potentials with a tailored quantum spectrum, in the laboratory of Donatella Cassettari (U of St. Andrews).

In collaboration with Oleksandr Marchukov, Andrea Trombettoni,Giuseppe Mussardo, and Donatella Cassettari.

Ultracold dipolar bosons trapped in a 3-well atomtronic circuit

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The atomtronics field studies the wide set of characteristic features of quantum gases, such as entanglement, transistor-like properties and persistent currents; and capitalizes on them to develop quantum devices [1]. Triple well potentials have gained interest due to their simplicity but rich phenomenology [2,3]. The fully connected triangular shape arrangement provides the smallest system to feature angular momentum with superfluid phase. In our investigation, we analyze the behavior of a small ensemble of dipolar bosons confined in this minimal system, with a focus on in-plane dipole orientation across multiple configurations. The system is described by an extended Bose-Hubbard Hamiltonian. We investigate ground state properties for a wide range of on-site interaction and dipolar interaction strengths. We find that the system shows very rich phenomena as we vary the polarization angle, e.g. the entanglement between sites depends on the dipole direction. Moreover, we characterize the system studying the coherence properties and find that dipolar interactions maintain the condensed state with little depletion in the studied range of dipole strengths, which could be an advantage to sustain superfluid currents. We underscore the prospective utility of dipolar interaction as a facilitative mechanism for manipulating entanglement within the system.

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Braiding of Majorana fermions in a (p+ip) Fermi superfluid:some issues.

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Most of the discussion in the literature of the Majorana fermions (M.F.'s) believed to exist in so-called p+ip Fermi superfluids, and in particular of their possible application in topological quantum computing (TQC) has analysed the problem using the familiar Bogoliubov-de Gennes (mean-field) formalism, which conserves total electron number only mod 2. We ask:Suppose that we require that electron number be conserved, period, at all stages of the calculation, then what are the consequences for the characteristic properties of M.F.'s, in particular for their (physical) braiding statistics? While we do not give a definitive answer to this question, our considerations suggest that these consequences could be enough to destroy the possibility of using these excitations for TQC, and certainly indicate that the problem merits further consideration.

Atomic interferometry and spatial adiabatic passage of ultracold atoms in optical tweezers

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The recent emerging technology of trapping single atoms in optical tweezers and controlling their position opens the door for exciting applications in quantum computation, simulation, and sensing. In this talk, I will present an experiment demonstrating spatial adiabatic transport of atoms between three tweezers, through precise control of coherent tunneling. I will then explain how such adiabatic processes can be harnessed to implement spin-independent atomic beam splitters, which are key elements in atomic interferometry. I will present a proposal for a new guided atomic interferometry based on optical tweezers. The new interferometer allows for long probing time, sub-micrometer positioning accuracy, and utmost flexibility in shaping the atomic trajectory. We also highlight the advantage of using fermionic atoms to obtain single-atom occupation of vibrational states and to eliminate mean-field shifts. Additionally, we detail two adiabatic splitting and recombining schemes with two or three tweezers that are robust to experimental imperfections and work simultaneously with many vibrational states. This property allows for multi-atom interferometry in a single run. We discuss two applications well-suited for the unique capabilities of the tweezer interferometer: the measurement of gravitational forces and the study of Casimir-Polder forces between atoms and surfaces. I will also discuss how tweezer-based atomic interferometry can be extended to perform clock interferometry. Such experiments can explore the quantum twin paradox and test, for the first time, the evolution of quantum coherence in the context of gravitational time dilation.

Hall effect in atomic ladder systems

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We consider a two-leg ladder of ultracold fermionic or bosonic atoms in an artificial gauge field. Using a bosonization approach retaining the band curvature terms, we calculate the Hall imbalance (density difference between the two legs of the ladder) induced by a longitudinal current. In the case of the bosonic ladder, we distinguish the Meissner phase at low flux from the vortex phase at higher flux. In the former, the imbalance is proportional to the flux, while in the latter, the imbalance decreases with flux. In the fermionic ladder at low flux,we also obtain an imbalance proportional to the flux. By adding a potential difference between the legs, we can cancel the imbalance. This allows to define the Hall conductance of the ladder system. We discuss the relation of Hall conductance with the dependence of stiffness on atomic density.

Many-body quantum heat engines based on free-fermion systems

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We study the thermodynamics of free-fermion systems coupled to quantum thermal baths within a Markovian approximation. In particular, we construct a four-stroke quantum Otto engine by alternately coupling such kind of systems to two reservoirs at different temperatures and operating adiabatic switches of some Hamiltonian parameters, followed by isochoric transformations. We show that the engine can operate in four different modes; in particular it can act as a heat engine and as a refrigerator, with thermodynamic performances that are affected by the possible presence of quantum criticality in the model. We also discuss the effects of non perfect thermalization with the baths and of adiabatic processes which are executed in a finite width of time.

Excitation currents in Rydberg atom ring networks

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Highly excited Rydberg atoms are a powerful platform for quantum simulation and information processing. Here, I will discuss atomic ring networks to study chiral currents of Rydberg excitations. I will first present a protocol in which the currents are controlled by a phase pattern imprinted via a Raman scheme. Depending on the interplay between the Rabi coupling of Rydberg states and the dipole-dipole atom interaction, the current shows markedly different features. Secondly, I will discuss a Quantum Optimal Control protocol to create excitation currents in Rydberg atom ring shaped networks. Besides those ones with single winding number, superposition of quantum current states characterized by more winding numbers can be obtained. The single current states are eigenstates of the current operator that therefore can define an observable that remains persistent at any time. In the case of superpositions of different winding numbers, the features of the excitations dynamics reflects the nature of current states, a fact that in principle can be used to characterize the nature of the flow experimentally without the need of accessing high order correlators.

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Characterizing cold atomic clouds using Rydberg excitation

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In recent years, Rydberg atoms have been used as qubits for quantum computing and simulation as well as sensing. In this talk I will demonstrate that they can also be useful for characterizing cold atomic clouds. Specifically, I will show results on measuring the oscillation frequency and ac Stark shift of rubidium atoms in a dipole trap, and spatially resolved measurements of the temperature of an atomic cloud using Rydberg Doppler broadening thermometry.

Atomic soliton transmission and induced collapse in the scattering from a narrow barrier

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We report systematic numerical simulations of the collision of a quasi one-dimensional bright matter-wave soliton made of Bose-condensed alkali-metal atoms through a narrow potential barrier by using the three-dimensional Gross-Pitaevskii equation. In this way, we determine how the transmission coefficient depends on the soliton impact velocity and the barrier height. Quite remarkably, we also obtain the regions of parameters where there is the collapse of the bright soliton induced by the collision. We compare these three-dimensional results with the ones obtained by three different one-dimensional nonlinear Schrödinger equations. We find that a specifically modified one-dimensional nonpolynomial Schrödinger equation is able to capture all the main features of the three-dimensional findings. In particular, this simplified but very effective one-dimensional model takes into account the transverse width dynamics of the soliton with an ordinary differential equation coupled to the partial differential equation of the axial wavefunction of the Bose-Einstein condensate.

Fast transport and splitting of spin-orbit-coupled spin-1 Bose-Einstein condensates

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In this talk, we present the dynamics of tunable spin-orbit-coupled spin-1 Bose-Einstein condensates confined within a harmonic trap, focusing on rapid transport, spin manipulation, and splitting dynamics. Using shortcuts to adiabaticity, we design time-dependent trap trajectorie and spin-orbit-coupling strength to facilitate fast transport with simultaneous spin flip. Additionally, we showcase the creation of spin-dependent coherent states via engineering the spin-orbit-coupling strength. Through numerical simulations, we elucidate non-adiabatic transport and associated spin dynamics, contrasting them with simple scenarios characterized by constant spin-orbit coupling and trap velocity. Furthermore, we discuss the nonlinear effect induced by atomic interactions using the Gross-Pitaevskii equation, highlighting the stability and feasibility of the proposed protocols for the state-of-the-art experiments with cold atoms.

Mimicking the Su-Schrieffer-Heeger model with a lattice of rings

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Over the last decades, the study of topological insulators has become one of the most active fields in condensed matter physics. One of the main features of these exotic systems is the existence of a bulk-boundary correspondence, which correlates the non-trivial topological indices of the bulk energy bands with the presence of robust edge modes. At the single-particle level, topological phases are well understood and can be systematically classified in terms of their symmetries and dimensionality. However, many questions regarding the characterization of interacting topological systems remain open. We investigate [1] a system of one or two bosons with contact interactions in a one dimensional lattice of rings with alternating distances. This geometry mimics the Su–Schrieffer–Heeger (SSH) model [2], which was initially proposed to describe solitons in polyacetylene, and was latter revealed as the simplest instance of a topological insulator. The two-particle SSH model with on-site interactions was previously studied in [3]. Here, we consider that each local potential has eigenstates with orbital angular momentum (OAM) l with winding numbers ±l. The particles are loaded into the states with l = 1 providing each site of the lattice with two internal states. At the single-particle level, the two circulation states within each site lead to two decoupled Su-Schrieffer-Heeger lattices with correlated topological phases. We characterize the topological configuration of these lattices in terms of the alternating distances, as well as their single-particle spectrum and topologically protected edge states. Secondly, we add on-site interactions for the two-boson case, which lead to the appearance of multiple bound states and edge bound states. We investigate the doublon bands in terms of a strong-link model and we analyze the resulting subspaces using perturbation theory in the limit of strong interactions. All analytical results are benchmarked against exact diagonalization simulations.

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Superfluidity and Sound Propagation in Disordered Bose gases

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Superfluidity describes the ability of quantum matter to support frictionless flows and plays a fundamental role in many transport phenomena as well as in technological applications. Thus, it is crucial to achieve a good understanding of the robustness of superfluid properties to external perturbations. This presentation covers theoretical and numerical results on the impact of speckle disorder on the superfluidity and sound propagation of an ultracold Bose gas. A key insight is that disorder reduces the speed of sound and introduces damping of sound modes at all wave lengths above the disorder correlation length. Adopting a hydrodynamic approach elucidates connections to relevant equilibrium quantities like compressibility and superfluid fraction. While hydrodynamics becomes inappropriate for strong one-dimensional disorder, it remains accurate in the two-dimensional setting and can be exploited to extract the superfluid fraction even in regimes where other methods, e.g., based on Leggett's bounds, become imprecise. The predicted effects are well within the reach of state-of-the-art cold-atom experiments and carry over to more general disorder potentials.

Observation of continuous and discrete time crystals

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Discrete (DTCs) and continuous (CTCs) time crystals are dynamical many-body states, showing robust self-sustained oscillations, emerging via spontaneous breaking of discrete or continuous time translation symmetry, respectively. DTCs are periodically driven systems that oscillate with a subharmonic of the drive, while CTCs are driven continuously and oscillate with a system inherent frequency. I will show experimental realizations of continuous and discrete time crystals in Bose-Einstein condensates of rubidium atoms strongly coupled to a high finesse optical cavity. I will discuss how these two dynamical many-body phases are connected via a subharmonic injection locking process.

Instabilities of matter waves in optical lattices under floquet driving

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Ultracold atoms held in optical lattice potentials have emerged as promising candidates for quantum simulators and quantum computation. In particular, Floquet engineering, manipulating the system's properties by applying a periodic driving, plays a crucial role in generating artificial gauge fields and exotic topological phases. However, driving-induced heating and the growth of phonon modes limit its applications in interacting many-body systems. In this work we study the stability of a driven Bose-Hubbard model over a wide range of driving frequencies. At high frequencies the response of the system is chiefly governed by parametric resonances, while at low frequencies modulational instabilities, similar to those seen in static systems, become important. At intermediate driving frequencies an interesting competition between the two types of instabilities will occur. We experimentally confirm the presence of these instabilities, in both untilted [1] and tilted [2] lattices, and probe their properties. Our results allow us to predict stable and unstable parameter regions for the minimization of heating in future applications of Floquet engineering.

A review: basic fractional nonlinear-wave models and solitons

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FILE

Gas-to-soliton transition of attractive bosons on the surface of a sphere

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Atomtronics primarily focuses on studying atomic physics in linear configurations or in curved geometries such as rings. There are no theoretical limitations to extending these analyses to 2D curved geometries like the surface of a sphere. In this presentation, I will discuss our recent study of bosons on the spherical surface with zero-range attractive interactions [1]. The main result of the paper is the observation of a first-order transition from a weakly-attractive uniform state to a soliton as the radius is increased. Two particularly interesting aspects emerge from our study: a) the 1D counterpart of the sphere (i.e. the ring) displays a second-order transition [2], and b) we predict the possibility to create macroscopic superpositions between uniform and solitonic states for a relatively large number of particles (10 ¡ N ¡ 20). Our work demonstrates how by confining a quantum gas in a tunable curved geometry one can control the few- to many-body physics of the system. In perspective, extensions of this study could both lead to technological applications as well as consolidating the fundamental study of quantum systems in curved spatial domains [3].

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Holographic Realization of the Prime Number Quantum Potential

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I plan to start the seminar by presenting a discussion of the experimental realization with holographic techniques of the prime number quantum potential, defined as the potential entering the single-particle Schrödinger Hamiltonian with eigenvalues given by the first N prime numbers. We also implemented the potential having as eigenvalues the first lucky numbers, a sequence of integers generated by a different sieve than the familiar Eratosthenes's sieve used for the primes. Further possible implementations are also considered. In the final part I will discuss how to possibly apply these potentials to the Goldbach conjecture and factorization algorithms.

Shortcuts to Adiabaticity for Bose-Einstein Condensates in Anisotropic Traps

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We engineer shortcut paths to achieve adiabatic evolution for an interacting Bose-Einstein condensate confined in generalized 3D harmonic traps. Experiments in quantum gas systems, such as cooling of the gas, relies on adiabatic transformations of the tuneable parameters: the trap frequencies and the interaction strength between the atoms. While tuning, our method enables a faster and reliable transfer between the initial and final quantum states, suppressing the undesirable excitations at the same time. The technique is robust even against large structural changes in the harmonic confinement from 3D to cylindrical shapes. We analyze the system in a wide range of interaction strengths and find perfect fidelity values. Finally, we also apply the technique in a fully isentropic engine to boost the efficiency and power output of the cycle.

Charging interacting quantum batteries using STIRAP

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Quantum technologies need a quantum energy initiative [1], in the sense that we should develop new strategies and devices able to store quantum energy for further use in consumption hubs in quantum devices. In this send, one possibility is to create quantum batteries [2], systems that can store and transfer energy in an efficient way by taking advantage of quantum mechanical effects [3]. We study a system with three single-particle internal energy states populated with N particles. We also consider an interaction between particles in the same internal state. Our model starts with a configuration where all the particles are in the lowest single-particle state and tries to charge to the second excited state using a STIRAP protocol [4]. We explore the charge at the end of the procedure and find different behaviors depending on the number of particles, the external coupling of the STIRAP, and the interaction strength. We show that in this kind of battery, the interaction develops a crucial role in the charging process. We have developed a simplified two-mode model that captures the diabatic behavior and reproduces the exact time-dependent numerical simulations. This provides a deeper understanding of the charging procedure.

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Rydberg Atomtronic Devices

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Atomtronics realises circuits through the guidance of neutral ultra-cold atoms. However, a recent proposal in the field of atomtronics has been the integration of Rydberg atoms, whereby instead of transporting matter, the established flow is of Rydberg excitations. We take advantage of the blockade and anti-blockade phenomena, resulting from the large dipole moments of such atoms, to prevent or facilitate the flow of excitations throughout networks of Rydberg atoms. In our work, we capitalise on these ideas along with the use of specific atom detunings, in order to create a toolbox of Atomtronics devices. We first formulate a method to control the flow of excitations through a Rydberg network which is enabled via a gate atom to either block or facilitate the transport of excitation in analogy to a switch. Second, we generate non-reciprocal flow by using the conditions of the anti-blockade and manipulation of the geometry of a Rydberg network. By adjusting the gate atom's detuning and position, we enable flow to only propagate in one direction and become blocked in the reverse. Lastly, we devise Rydberg networks to conduct logical decisions. Employing the anti-blockade mechanism we create a classical AND gate and a NOT gate, whereby combining both, we produce a universal logic gate set.

Exploring Quantum Criticality in a 4D Quantum disordered system

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Phase transitions are prevalent throughout physics, spanning thermal phenomena like water boiling to magnetic transitions in solids. Quantum phase transitions, particularly intriguing, occur at temperatures near absolute zero and are driven by quantum fluctuations rather than thermal ones. The strength of the fluctuations is very sensitive to dimensionality, which determines the existence and nature of phase transitions. For many systems there exists a certain upper critical dimension (UCD) above which mean-field theories accurately describe the properties of the phase transitions. Previously observed experimentally in 3D, the Anderson metal-insulator transition [1]; is an example of quantum phase transition for which the UCD has been controversial. While its UCD has been predicted to be equal to four by the so-called self-consistent theory, numerical simulations indicate that this is not the case, at least up to dimension six – hinting the possibility that the UCD be in fact infinite.

In this work, using an ultracold atom quantum simulator to engineer synthetic dimensions, we experimentally observe and study the Anderson transition in four dimensions. Our system is an atomic kicked rotor [2]; of dilute potassium atoms, submitted to a quasi-periodically modulated pulsed laser standing wave used to engineer both synthetic dimensions and disorder [3]. Varying the experimental parameters, we are able to observe the Anderson localization-delocalization phase transition in dimension four. We precisely locate the critical point using a model-independent analysis based only on the existence of a scale-invariant behavior at criticality. We then characterize the universal dynamics in the vicinity of the phase transition, and measure the values of the critical exponents, proving the non-mean-field character of the Anderson transition in 4D. The measured exponents are shown to be in agreement with Wegner's scaling law in dimension four. This work marks the first observation and characterization of the Anderson transition in four dimensions. We believe that our experimental study of transport phenomena in high dimension, with a highly controlled ultracold atomic system would be of great interest to the audience of Atomtronics conferences.

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Experiments in ultracold spin mixtures of Na atoms

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A mixture of ultracold atoms in two different hyperfine states, with the possibility of engineering the coupling between the states and the density profiles, can serve as an interesting platform for designing spintronic circuits. I will present an overview of some of the last results obtained in our laboratory in Trento [1], in which we employ mixtures of Bose-Einstein condensed Na atoms in two different internal states. Depending on the states involved, the system can either be miscible or immiscible. Here I will focus on the results obtained with an immiscible mixture in the presence of a coherent coupling between the two states, provided by an external radiation field. This radiation acts as an effective magnetic field and allows to drive a phase transition analogous to the para- to ferromagnetic transition in the Ising model [2]. In particular, the presence of two equally energetic ground states allows for the formation of extended domains with opposite magnetization. The interface separating these domains is the least energetic excitation in a ferromagnet, called a domain wall, and can be deterministically created and controlled in our experiment thanks to the applied radiation field. In the hysteresis region of the para- to ferromagnetic phase diagram, where for small change of the parameters one of the two states becomes metastable and the other the absolute ground state, we investigated the spontaneous decay dynamics from the metastable many-body state to the absolute ground state, through the observation of macroscopic spin bubbles [3] and found connections with the false vacuum decay description in quantum field theory.

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Emergent topological properties in Kronig -Penney type models.

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Ultracold systems offer a clean testbed for realizing different quantum models, which are challenging to implement with condensed matter systems. Experimental advancement in cold atom physics allows the creation of subwavelength [1,2] nanoscale potentials where atoms can strongly interact. This potential will enable us to realize the Kronig –Penney model and its variations. Introducing a lattice shift in this potential resulted in nontrivial topology and topologically protected edge states[3]. Developing control strategies for such systems is of fundamental interest in quantum technologies that rely on the robustness of states. In this work, we analyze the topological properties of 1d potential, which resembles the Kronig Penney model, which supports topological edge states. We have studied the many body quench between trivial and nontrivial regimes and see the deviations in expected orthogonality catastrophe[4]. To better understand the effect of the edge states in the quench dynamics, we also examine the work probability distribution[5].

Differential Mach-Zehnder Interferometry With Trapped BECs

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Trapped atom interferometers are important tools for the measurement of forces with high spatial resolution. Here we report on the realization of Mach-Zehnder interferometers (MZI) with Bose-Einstein condensates (BEC) of 39K optically trapped in an horizzontal array of double-well potentials (DWs)[1]. Each DW represents an independent MZI which can work simultaneously with the other ones. Having more than one correlated interferometer is useful, since it's possible to cancel out the effect of common sources of noise acting on the system via differential analysis and realize a trapped atom gradiometer. This allows to measure differential forces acting on the two sensors with high spatial resolution even inn presence of strong noise. In our system we can load the BEC in up to three DWs spatially separated by 10 um, with a mean number of atoms per DW of few thousands and 5 um spacing between left and right modes. To demonstrate the functioning of our sensor, we impose a well known harmonic potential on the system and we show that the interferometric differential phase evolves linearly as a function of the interrogation time as expected. Thanks to a broad Feshbach resonance, we can finely tune the two body scattering length to zero and cancel two body interactions, reaching coherence time of few hundreds ms. In the future we will investigate the possibility to operate several interferometers simultaneously and measure higher orders of the Taylor expansion of the external potential acting on the atoms. In addition we are planning to generate number squeezed states in our system introducing repulsive interactions. Exploiting non classic states at the interferometer's input will allow us to enhance the sensitivity of our sensor beyond the standard quantum limit.

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The Lieb excitations and topological flat mode of spectral function of Tonks-Girardeau gas in Kronig-Penney potential

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Lieb excitations are fundamental to the understanding of the low energy behaviour of many-body quantum gas. Here we study the spectral function of a Tonks-Girardeau gas in a finite sized Kronig-Penney potential and show that the Lieb-I and Lieb-II excitations can become gapped as a function of the barrier height. Moreover, we reveal the existence of a topological flat mode near the Fermi energy and at zero momentum. Through scaling analysis, we determine the divergent behaviour of spectral function. Our results provide a significant reference for the observation of the gapped Lieb excitations and the topological flat mode of quantum gases in subwavelength optical lattice potentials.
