

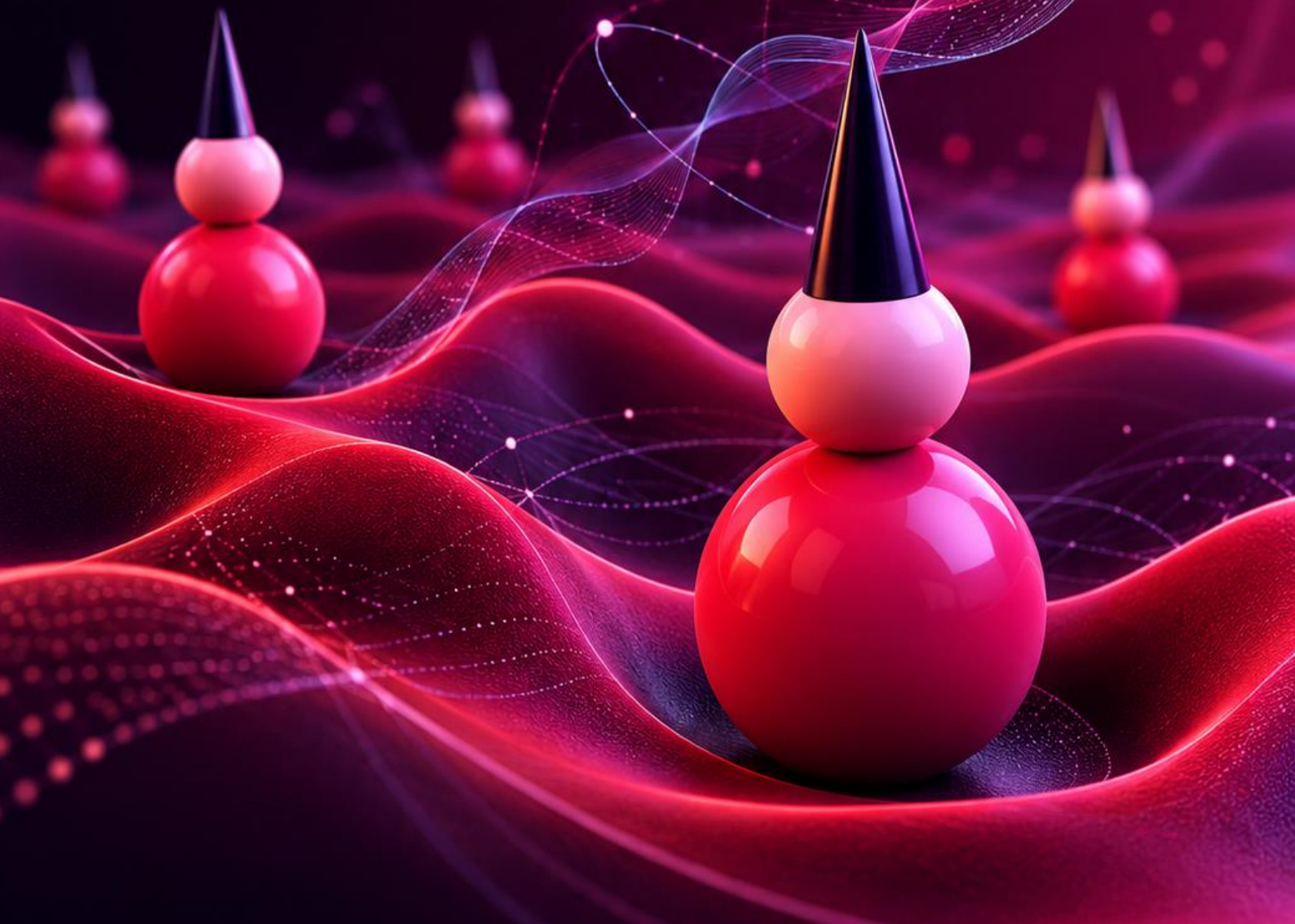
QUASIMODO 2026



International Workshop on

**Quantum Simulations with
Multicomponent Ultracold Atoms**

ABSTRACT BOOK



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The Rayleigh-Taylor instability in a binary quantum fluid

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Instabilities, where initially small fluctuations seed the formation of large-scale structures, govern the dynamics in wide variety of fluid flows. The Rayleigh-Taylor instability (RTI) is an iconic example that leads to the development of mushroom-shaped incursions when immiscible fluids are accelerated into each other. RTI drives structure formation throughout science and engineering including table-top oil and water mixtures; supernova explosions; and inertial confinement fusion. Despite its ubiquity, controlled laboratory RTI experiments are technically challenging.

Here we report the experimental observation of RTI in an initially phase separated binary superfluid consisting of a two-component Bose-Einstein condensate of Na^{23} atoms. We induce the RTI at the interface between these components using a magnetic gradient force (i.e. the Stern-Gerlach effect) to press the components together and observed the growth of mushroom-like structures. The interface becomes stable when the components are pulled apart, and we spectroscopically measure the dispersion relation of the “ripplon” interface modes.

Parity anomaly in a synthetic quantum Hall system of ultracold dysprosium atoms

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We realize a synthetic quantum Hall platform using ultracold dysprosium atoms, where a real spatial dimension is coupled to a synthetic dimension encoded in internal spin states. Raman-induced spin-orbit coupling generates a uniform artificial magnetic field, giving rise to Landau-level physics and chiral edge transport.

We focus here on the controlled realization of a topological phase transition driven by competing Raman and Bragg couplings. At the critical point, we observe robust half-quantization of the Hall response. We interpret this behavior in terms of a Dirac band touching and connect it to the parity anomaly of a single two-dimensional Dirac fermion.

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Keywords: *Quantum gases, topological systems, quantum Hall effect*

Photonic time crystals in Bose-Einstein condensates

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In this talk, we explore the physics of photonic time crystals. First, we demonstrate that Anderson localization can be observed in the temporal domain in photonic time crystals when a temporal disorder is introduced into the periodic modulation of the medium's refractive index [1]. Next, we show that a spatially homogeneous Bose-Einstein condensate with periodically modulated contact interactions serves as a platform for reproducing photonic time crystal physics [2].

In this framework, the condensate acts as a time-varying medium which generates a momentum band structure for its own elementary excitations. We show that by tailoring the topological properties of the modulation protocol, it is possible to stabilize the system against condensate depletion.

Our results establish ultracold atomic gases as a versatile platform for investigating time-varying media, surpassing current experimental limitations in traditional photonic implementations.

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Multicomponent Ultracold Atoms and Spin Squeezing

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The generation of large-scale entangled states is a central objective of next-generation quantum technologies, with an immediate potential for applications. A particularly promising platform for this purpose is provided by multicomponent ultracold atomic gases composed of atoms with large internal spin degrees of freedom that are highly sensitive to external fields.

Spin squeezing represents one of the most mature and scalable approaches to quantum-enhanced sensing beyond the standard quantum limit, with applications in atomic clocks, magnetometry, and matter-wave interferometry. While the majority of previous studies have focused on effective spin-1/2 systems, higher-spin systems offer the possibility of generating stronger and more versatile resources. In particular, I will present our recent work [1] on scalable spin-squeezing generation in spinor Bose–Einstein condensates driven by the quadratic Zeeman effect. For spin-1 atomic species, such as Rubidium-87 and Sodium-23, the quadratic Zeeman term breaks the spin isotropy of contact interactions, thereby inducing spin-squeezing dynamics that display the same scaling behavior as the paradigmatic one-axis twisting model.

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Unconventional topological phases in some lattices

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I will present hidden multi-topological phases mediated by constrained inter-cell coupling [1] and the concept of sub-symmetry protected topological phases [2]. Topological phases of matter and their boundary states had great influence on condensed matter physics, photonics, and materials science. These topological phases are typically characterized by their energy bands through topological band theory. However, certain topological materials exist that do not fit within this framework, exhibiting unique boundary states that remain relatively obscure and under-researched.

In Ref. [1], we introduce a novel category of topological phases known as "multi-topological phases" (MTPs), which arise from constrained inter-cell coupling in lattice systems. We provide experimental evidence for these phases using a photonic platform. The MTPs display multiple sets of boundary states, each corresponding to a different topological invariant.

In Ref. [2], we introduce a concept of sub-symmetry (SubSy) protected topological phases; SubSy means that the symmetry (operator) equation holds only in part of the Hilbert space describing the system. Nevertheless, in some models topological boundary states are safeguarded by these weaker symmetries. This reframes our understanding of symmetry protected topological phases across various physical platforms.

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Exotic Quantum Statistics in Strongly Interacting 1D Bose Gases

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Exotic quantum statistics extend beyond the familiar dichotomy of bosons, which may occupy a single quantum state, and fermions, which must each occupy different ones. Between these extremes lie anyons, allowing particles to partially share one state, and fractional Fermi seas, where particles occupy several states.

My talk explores how strongly interacting 1D Bose gases provide a platform to realize unconventional statistics. I present the observation of emergent anyonic correlations induced by spin-charge separation, where a mobile impurity generates a system with a tunable statistical phase [1,2], providing a continuous transmutation from bosons through anyons to fermions, revealed through an asymmetric momentum-distribution and dynamical fermionization. I then report the realization of fractional Fermi seas [2,3,4]. These are many-body systems in which each particle occupies an integer number of states larger than 1. One might call the resulting statistics “super-fermionic”. For this, we drive our 1D Bose system via holonomy cycles into excited states. Friedel-like oscillations in the one-body correlations directly expose this exotic exclusion statistics.

Together, these results demonstrate a powerful and controllable route to exploring the full landscape of low-dimensional quantum statistics beyond the boson-fermion paradigm.

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Keywords: Quantum gases, quantum statistics, anyonization, fractional Fermi sea

Quantized soliton pumping through topological edge state instabilities

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Thouless pumping is an example for topologically protected, directed transport in linear systems [1,2, 3]. Recent advances have extended this concept to nonlinear systems, where paradigms of linear topology must be reconsidered and expanded [4, 5]. In this talk, I will present a nonlinear Rice-Mele model that demonstrates quantized transport of nonlinear kinks and solitons. By examining the topologically protected edge modes of the linearized model and combining it with methods from nonlinear dynamics, we predict instabilities in the nonlinear system. We characterize this effect similarly to linear pumps, highlighting that a standard topological index is insufficient to fully describe the phenomenon. Additionally, we show that by introducing multiple pumping parameters, the motion of the kink can be precisely controlled.

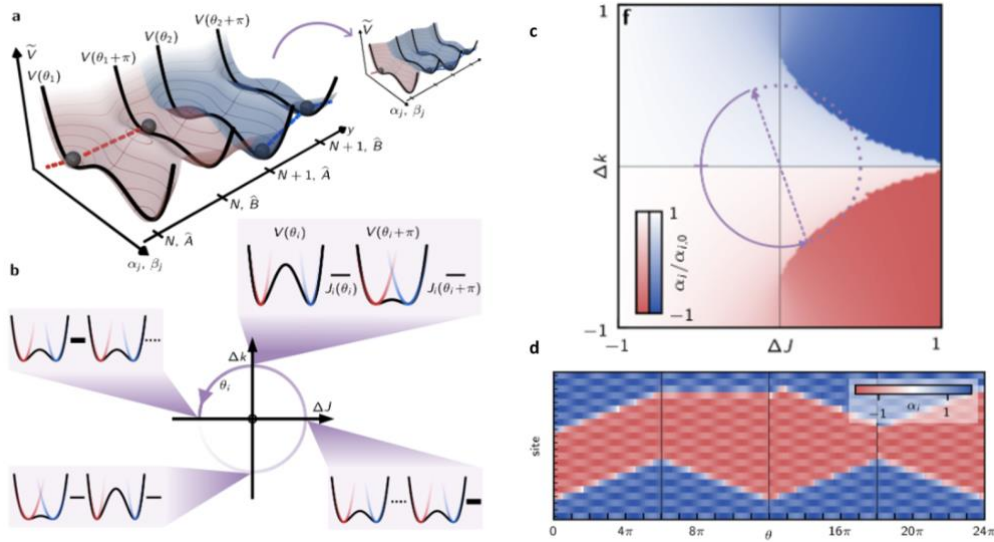


FIG. 1: Model. a, A chain of double-well systems. The black lines mark the on-site terms. Two distinct domains are indicated in blue and red. b, One unit cell of the discretized model throughout the pump cycle. c, Instability phase diagram. Red (Blue) regions correspond to parameters where the blue (red) domain is unstable. The purple circle marks the pump cycle performed in b. Parts of the pump cycle are never reached. d, Movement of domains while varying different pumping parameters.

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Bose-Fermi droplets at nonzero temperature

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We investigate the formation and dynamics of self-bound quantum Bose–Fermi droplets [1] at nonzero temperatures using numerical simulations. An attractive atomic Bose–Fermi mixture is described within a quantum hydrodynamic framework that incorporates beyond-mean-field corrections and thermal fluctuations, complemented by a simplified self-consistent Hartree–Fock model.

The properties of these droplets are analyzed as functions of the initial condensate fraction, total particle number, and interspecies interaction strength. To model finite-temperature states, we first determine the ground-state bosonic and fermionic densities in a spherically symmetric trap by solving coupled hydrodynamic equations in imaginary time. Thermal excitations are then introduced by gradually injecting energy into the system through controlled randomization of the amplitude and phase of the bosonic field, followed by real-time evolution. This procedure drives the mixture toward states close to thermal equilibrium with a reduced condensate fraction.

After the trapping potential is removed, we investigate the subsequent dynamics of the mixture under different boundary conditions [2]. In free space, absorbing boundaries induce evaporative cooling: excess atoms leave the system, the condensate fraction gradually approaches unity, and the droplet evolves toward a low-temperature self-bound state. In contrast, periodic boundary conditions describe a finite-volume system in which the droplet remains in equilibrium with a saturated bosonic and fermionic vapor. In this regime, the cooling process eventually saturates, and the condensate fraction stabilizes while the total particle number is conserved.

Our results provide insight into the finite-temperature properties of Bose–Fermi droplets and suggest experimentally accessible protocols for their realization and observation.

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Beyond Topological Insulators in Dipolar t-J Models

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In this talk I will discuss how dipolar fermionic atoms trapped in optical lattices can provide access to regimes beyond conventional Hubbard and t-J physics. In particular, I will show how the high degree of tunability of hopping, onsite interactions, and spin couplings allows for the realization of a rich variety of strongly correlated zero-temperature quantum phases, including a topological superconducting phase emerging from the interplay between strong interactions and anisotropic magnetic couplings [1]. In the second part, I will discuss how a similar setup can also stabilize conducting topological phases that appear purely as a finite-temperature effect, with no zero-temperature counterpart [2]

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From supersolids to anyons in bosonic mixtures with Raman couplings

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In this talk I will show how the interplay of Raman couplings with interactions gives rise to dress particles with tunable unusual properties both in the bulk and in optical lattices. In bulk mixtures, the dressed particle picture explains in simple terms existence and excitations of supersolid stripes [1] and the emergence of topological gauge theory for 1D anyons [2,3,4]. In optical lattice, the dressed particle picture explains the emergence of frustrated magnetism without geometric frustration [5] and provides a feasible route to the experimental realization many-body quantum phases of 1D and quasi-1D anyons.

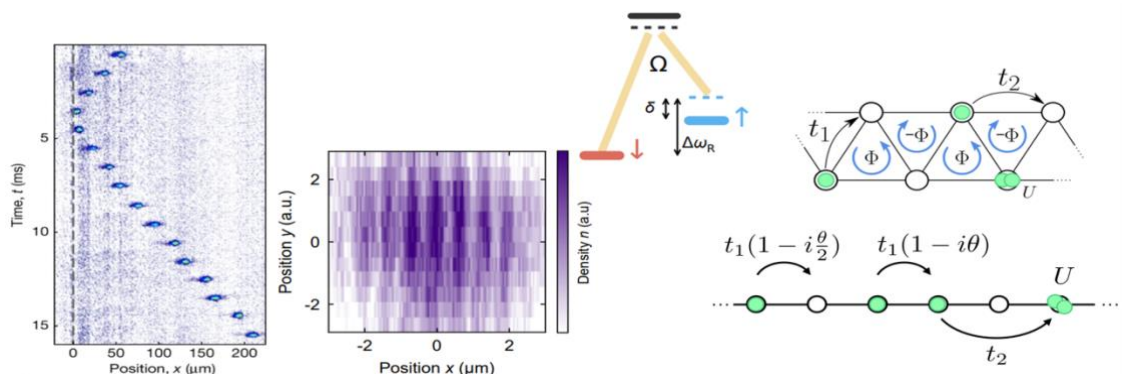


FIG. 1: A visual summary of the talk.

References

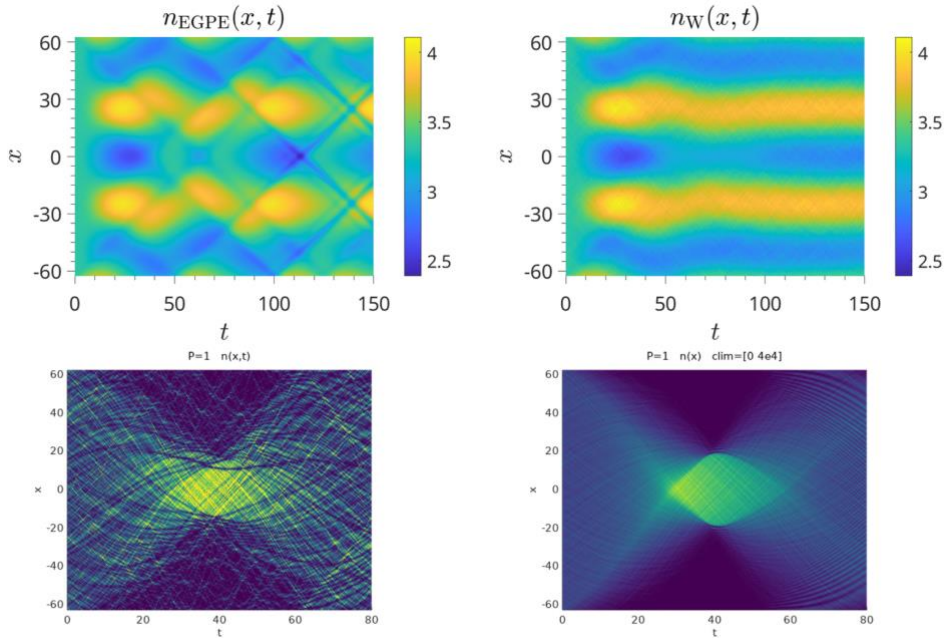
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Lee-Huang-Yang physics without a Lee-Huang-Yang term

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Beyond-mean field contributions such as the Lee-Huang-Yang correction are crucial for a number of phenomena of current interest in ultracold quantum physics such as Bose-Bose quantum droplets or supersolids. They are usually incorporated in the celebrated extended GPE (EGPE) in a quasi-empirical manner by inserting terms coming from the equation of state of a uniform gas into nonuniform equations. The underlying process, however, is quantum fluctuations in the field. We demonstrate how to naturally generate the LHY physics and corrections directly from fluctuations present in the field using a truncated Wigner representation with no LHY term. Evolving the field subsequently with the bare GPE of the truncated Wigner method allows one to access dynamical quantum effects beyond the reach of the EGPE. Such as: correlations, coherence decay, single realisations, and the onset of quantum fluctuation effects with growing interaction strength. We find that evolution can deviate significantly from both the plain GPE and the EGPE. In particular, as interaction grows, many of the interference effects predicted by the coherent EGPE theory are found to be suppressed, and the EGPE offers no improvement over the plain GPE compared to the full Wigner model [1]. With appropriate care we have also been able to create 1d Bose-Bose droplets stable under the truncated Wigner GPE evolution in the absence of a trap.



Top row: evolution of a uniform Bose gas after a periodic potential is turned on. EGPE on left, more complete truncated Wigner dynamics on right. Bottom row: evolution of a single Wigner realization after a harmonic potential is turned on. higher interaction on left, lower on right.

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Bridging analog simulation and digital computation in dynamic optical lattices

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Optical lattices provide a highly scalable platform with naturally fermionic constituents, making them an ideal architecture for simulating classically intractable quantum systems. The standard paradigm for analog quantum simulation in these platforms typically proceeds via global state preparation, followed by Hamiltonian evolution and readout. However, this approach faces bottlenecks, most notably the limitations imposed by finite temperature during state preparation and the inherent difficulty of implementing error correction.

To address these challenges, we have realised high-fidelity gate and shuttle operations for fermionic potassium atoms trapped in a dynamic optical lattice structure [1]. Crucially, these operations benefit from geometric protection, rendering them robust against technical noise. By leveraging these digital gate operations, we demonstrate the configurable preparation of strongly correlated initial states [2], effectively bridging the gap between digital quantum circuits and analog Hamiltonian evolution. Going further, I will outline a roadmap towards realising a fully universal neutral-atom quantum processor, alongside a discussion of the outstanding challenges on the path to fault tolerance.

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Keywords: quantum simulation, quantum computation, optical lattices

Exploring supersolid dynamics with spin-orbit-coupled quantum gases

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Ultracold atoms are a powerful tool for the analogue simulation of quantum many-body phenomena. In our experiment in ICFO (Spain), we employ Bose-Einstein condensates with spin-orbit coupling, where the internal state of the atoms is linked to their momentum through optical coupling. This alters the single-particle dispersion relation and thus provides a flexible experimental platform to engineer synthetic quantum systems.

In my talk I will show how we have exploited the interplay of the dispersion relation with the tunable interactions in potassium to realize a robust supersolid stripe phase. Supersolidity is an exotic phase of matter that spontaneously breaks both gauge and translation symmetry, thus combining the frictionless flow of a superfluid and the crystalline structure of a solid.

Using a matter-wave magnification technique, we have achieved in-situ imaging of this phase. By observing its collective modes, we have revealed the peculiar dynamics of the supersolid: it hosts both superfluid and crystal excitations. In particular, we demonstrate that the system has a compressible crystalline structure, thereby settling an ongoing debate on the properties of supersolidity in spin-orbit-coupled condensates and establishing them as a platform to investigate supersolid dynamics.

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Multicomponent Ultracold Atoms in Non-Abelian Gauge Fields

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The celebrated spin-orbit interaction can be interpreted as the occurrence of a (static) non-Abelian gauge field, with $SU(2)$ as the underlying symmetry. In this talk, I will first review our work on this phenomenon, exploring the dynamics of strontium ultracold atoms in an artificial gauge field [1]. The latter is generated thanks to resonant laser on a multicomponent tripod scheme as presented in Fig.1. Then, we extend the concept of internal-external state coupling to higher internal symmetry, exploring features beyond the established spin-orbit regime using artificial $SU(3)$ non-Abelian gauge fields. We demonstrate the inherent all-state connectivity of $SU(3)$ systems by performing targeted geometric transformations. Then, we investigate color-orbit coupling, an extension of $SU(2)$ spin-orbit coupling to $SU(3)$ systems [2]. We reveal a rich dynamical interplay between three distinct oscillation frequencies, which possesses interesting analogies with neutrino oscillations and quark mixing mechanisms. Finally, placing ourselves in the point of view of the internal dynamics, $SU(d)$ geometric transformations can be view a qudit gates useful for future quantum computing [3]. Here, we will present our most recent results on a qutrit Hahn echo [4].

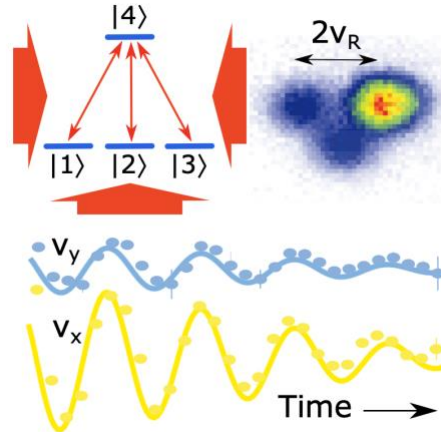


FIG. 1: (Left) Tripod scheme used to generate two dark states and underlying $SU(2)$ dynamics. (Right) Typical discrete momentum distribution after interacting with the $SU(2)$ non-Abelian gauge field. (Lower) spin-momentum dynamics in $SU(2)$ non-Abelian gauge field.

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Spinor bosons in an optical cavity

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The richness of possible ground states of spinor bosons placed in an external lattice and a cavity is revealed. We discuss the simplest case when the external lattice nodes coincide with the antinodes of the cavity field. We analyze the problem within the grand-canonical mean-field approach, considering both the homogeneous system and the nonhomogeneous case with a harmonic trapping potential. Due to the spin degree of freedom, in the homogeneous case we treat the system in a twofold manner: we impose the physically relevant total-magnetization constraint, while also discussing the minimization landscape for the full unconstrained problem. In the latter, by combining analytical arguments with numerical calculations based on the Gutzwiller ansatz, we show that the system exhibits two types of magnetic phases: an antiferromagnetic Mott insulator (AFM) and a ferromagnetic density wave (FDW). In addition, three distinct supersolid phases emerge, characterized by different patterns of spin and density imbalances. In case of the zero total magnetization, only two of the three supersolid regimes survive, and the FDW phases are replaced by NOON density waves (NDW). These new ground states present density-modulated quantum superpositions of the underlying spin components of bosons. We also present the exphase diagram of the trapped system, which is directly relevant for future experiments.

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Keywords: spinor bosons, optical cavity, Gutzwiller approximation

Chiral dynamics of interacting bosons in flux-frustrated lattices

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Recent experimental results on neutral atoms in synthetic gauge fields have shown remarkable advances in presence of interactions. We discuss interacting bosonic atoms in dimerized optical lattices subjected to time-reversal preserving π -flux that induces frustration and competing time-reversal broken ground states. We show the existence of vortex superfluid and insulating phases and the appearance of a chiral Higgs mode near criticality. We discuss the extension of this framework to three-dimensional models with exotic loop current patterns.

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Keywords: gauge fields, quantum phases, optical lattices

Simulating cavity QED with spin-orbit coupled Bose-Einstein condensates revisited

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Simulating cavity quantum electrodynamics in synthetic platforms offers a promising route to exploring light–matter interactions without real photons, while enabling the transfer of cavity-based techniques to other systems. Among such platforms, Bose–Einstein condensates with synthetic spin–orbit coupling provide a controllable setting where internal and motional degrees of freedom become coupled, mimicking aspects of cavity quantum electrodynamics. In this work, we critically assess the extent to which spin–orbit coupled Bose–Einstein condensates can emulate cavity quantum electrodynamics phenomena, with a focus on squeezing and entanglement generation.

We show that spin–orbit coupled Bose–Einstein condensates can faithfully reproduce the physics of a single atom coupled to a quantized field—realizing an analog of the quantum Rabi model—but inherently fail to capture genuine collective effects characteristic of the Dicke model, such as cavity-mediated many-body entanglement.

Our results clarify both the potential and the fundamental limitations of spin–orbit coupled Bose–Einstein condensates as analog quantum simulators of cavity quantum electrodynamics, offering guidance for future strategies to generate and control non-classical states of matter in photon-free, highly tunable platforms.

Correlated impurities in ultracold gases: Non-equilibrium dynamics and applications to thermometry

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We theoretically investigate the correlated decoherence dynamics of two mobile impurities trapped within a gas of ultracold fermionic atoms [1]. By using a mean-field approximation we self-consistently describe the effect of impurity-gas collisions on impurity motion, while decoherence of the impurities internal state is computed exactly within a functional determinant approach. At equilibrium, we find that the impurities undergo bath-induced localization as the impurity-gas interaction strength is increased.

We then study the nonequilibrium dynamics induced by a sudden change of the impurities' internal state, which can be experimentally probed by using a Ramsey interferometry scheme [2]. Our theoretical approach allows us to investigate the effect of impurity motion on decoherence dynamics, finding strong deviations from the universal behavior associated with Anderson's orthogonality catastrophe when the mass imbalance between impurity and gas atoms is small. Finally, we show that mobile impurities can be used as thermometers of their environment, and that bath-mediated correlations can be beneficial for thermometric performance at low temperatures, even in the presence of nontrivial impurity motion. Our results showcase the interesting open quantum dynamics of mobile impurities dephasing in a common environment, and how they can help to provide more precise temperature estimates of ultracold fermionic mixtures.

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POSTERS N1

Fermionic magic resources in disordered quantum spin chains

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Fermionic non-Gaussianity quantifies a quantum state's deviation from a classically tractable free-fermionic description, constituting a necessary resource for computational quantum advantage. Here we use fermionic antifatness (FAF) to measure this deviation across ergodic and many-body localized (MBL) regimes. We focus on the paradigmatic disordered spin-1/2 XXZ chain and its impurity variant with local interactions. Across highly excited eigenstates, FAF evolves from typical state behavior at weak disorder to strongly suppressed values deep in the MBL regime, with volume-law scaling in the XXZ chain and an area-law bound in the impurity setting. Rare long-range catlike eigenstates exhibit a pronounced enhancement of FAF, making it a sensitive diagnostic of mechanisms proposed to destabilize MBL. Starting from product states, we find that in the MBL regime FAF grows slowly in time, approaching saturation via a power-law relaxation. Overall, our results show that MBL suppresses fermionic non-Gaussianity, and the associated complexity beyond free fermions, while ergodicity restores it, motivating explorations of fermionic non-Gaussianity in other ergodicity-breaking phenomena.

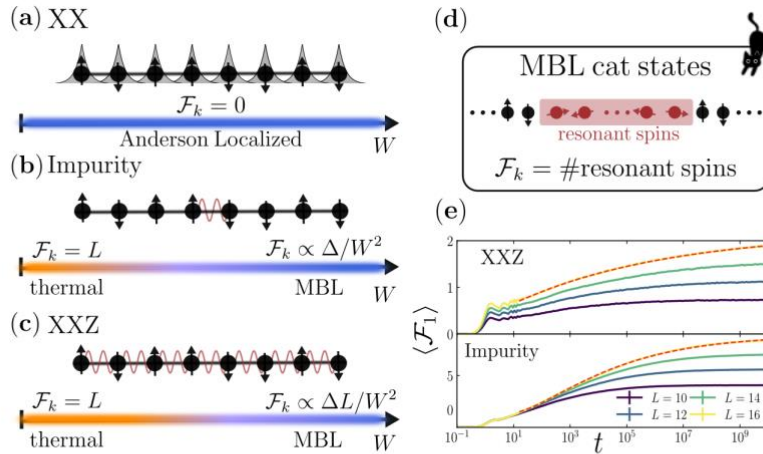


Figure 1: *Summary of results.* (a) The disordered XX chain is Anderson localized and fermionic Gaussian, with vanishing FAF. (b,c) Adding interactions ($\Delta \neq 0$) generates fermionic magic: in the MBL regime, FAF obeys area-law scaling in the impurity model (b) and volume-law scaling in the XXZ chain (c). (d) Rare cat-like eigenstates strongly enhance FAF, with \mathcal{F}_k capturing the number of resonant spins. (e) Starting from a product state, FAF grows slowly and saturates via power-law relaxation in both models.

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POSTERS N2

How Hydrodynamics Dictates Quantum Scrambling: The Scrooge Ensemble

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Macroscopic conserved charges strictly constrain microscopic quantum scrambling. We demonstrate that time-evolved states in ergodic $U(1)$ symmetric disordered models act as typical states drawn from an instantaneous Scrooge ensemble $\rho(t)$ -an ensemble that maximizes randomness subject to local charge profiles. Analytical predictions from this framework excellently match exact unitary evolution, revealing that the complex growth of entanglement and participation entropies is fundamentally slaved to underlying linear hydrodynamics. Consequently, macroscopic transport directly dictates the dynamical scaling of quantum state complexity

POSTERS N3

Time-quasi-crystals from periodic driving

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Discrete time crystals - phases of matter exhibiting a robust subharmonic response in observables, stabilised by many-body interactions - have swiftly become a well-established platform in which to observe condensed matter phenomena in the time domain. In analogy to quasi-crystalline solids, time-quasi-crystals represent an aperiodic but ordered extension of this idea, which have recently been realised in experiment. Most of the existing proposals of time-quasi-crystal consist of two-tone driving by a pair of incommensurate frequencies to impose quasiperiodic order in the time domain.

In this work, we present a model of coupled clock chains, i.e., chains of short-ranged-interacting 'qudits', which displays an enlarged subharmonic response under single-frequency driving. In the limit of larger clock dimensions, this approaches a time-quasi-crystal. Clock chains have recently attracted a great deal of attention as an interesting theoretical platform. In part, this is due to the observation of Z_N ordered phases (Rydberg crystals) in experiments with Rydberg atom arrays, whose phase boundary bears a resemblance to that of the Z_N symmetric quantum chiral clock chain. On the other hand, they are of interest from the perspective of quantum computing implementations, since the elementary excitations of this model in the topologically ordered phase are Abelian parafermions, which can allow for realization of Universal Quantum Computation with fewer additional operations than comparable systems of qubits.

Our model represents a system in which time-quasi-crystalline order can arise due to the intrinsic Hilbert-space structure leading to incommensurate responses to a periodic drive, rather than from the active imposition of incommensurate frequencies on the system by aperiodic driving.

Keywords: Discrete time crystals, quasicrystals, symmetry breaking, Floquet phases of matter

POSTERS N4

Magnetic phases for two component bosons in the cavity

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As experimental trapping of ultracold spinor bosonic gases in high-finesse optical cavities continues to advance, there is a growing need for theoretical studies of the corresponding extended Bose–Hubbard models with two-component bosons. We analyze the system within mean-field theory in the grand-canonical ensemble. The homogeneous system hosts two insulating magnetic phases: an anti ferromagnet (AFM) and a spin density wave (SDW). When tunneling is introduced, these phases become surrounded by a superfluid phase and three distinct supersolid phases, distinguished by different patterns of spin and density imbalances between odd and even sites. Finally, we include a harmonic trapping potential with a fixed magnetization constraint in our simulations, which allows us to obtain the full phase diagram directly relevant for experiments, revealing plethora of different phases that could be observed in a trap.

Keywords: cavity QED, spinor bosons, optical lattices, extended Bose-Hubbard, quantum magnetism

POSTERS N5

Enhancement of work extraction in many-body quantum batteries using one-dimensional ultracold atoms

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Over the past decade, quantum batteries have shown the potential to surpass their classical counterparts in terms of energy storage and charging power by harnessing quantum effects such as correlations and entanglement among battery cells [1], and are therefore considered important components of future quantum technologies [2]. In this work, we study the charging performance of a many-body bosonic quantum battery driven by a one-dimensional harmonic-oscillator charger, focusing on how many-body effects and intra-species interactions influence the energy-transfer dynamics. By tuning the charger frequency, the available transferable energy can be increased and the system can reach a resonance condition where perfect energy transfer and maximal extractable work are achieved. In the weak-coupling limit, the battery–charger dynamics are well captured by an effective two-level model, which accurately predicts the maximum stored work, ergotropy, and optimal charging time. In this regime, many-body batteries exhibit enhanced charging and ergotropic power, reduced quantum speed limits, and comparable or lower irreversible work relative to single-particle batteries. We further examine the role of intra-species interactions: repulsive interactions suppress performance, whereas attractive interactions can significantly enhance it, with both types of interactions generating additional resonance peaks.

Our results show that particle number and interaction control provide powerful tools for designing fast, efficient, and scalable quantum batteries, and point toward feasible experimental implementation in ultracold-atom platforms.

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Keywords: quantum battery, ultracold atoms, two-component system, many-body effects

POSTERS N6

Geometry and Fluctuations: Exploring 3D Bose-Einstein Condensates in Anisotropic Traps

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This study investigates the interplay between confinement geometry and the thermal fluctuations of a Bose-Einstein condensate (BEC). Utilizing Hybrid Sampling - a novel Monte Carlo-based simulation method developed by the authors - we analyze interacting Bose gases within both canonical and microcanonical frameworks in a 3D anisotropic harmonic potential. We demonstrate that the trap's aspect ratio serves as a critical tuning parameter for particle number ensemble fluctuations. Notably, our results reveal a geometric transition in fluctuation behavior: while interactions typically suppress fluctuations in isotropic systems, high levels of anisotropy lead to a significant enhancement of maximal fluctuations.

Keywords: BEC, statistical quantum mechanics, Monte Carlo methods, interacting Bose gases, trapped systems

POSTERS N7

Spin Dynamics in the Strongly Interacting Mott Regime of SU(d)

Fermi-Hubbard Systems

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I will discuss how the dynamics of spin-full fermionic atoms in optical lattices in a deep Mott regime is significantly dependent on the atomic spin s . The atomic spin could be any spin-like internal degree of freedom, in particular, the nuclear spin. Dynamics of fermionic atoms (eg.: Sr-87, Rb-85, Yt-173) in optical lattices in the simplest framework is given by Fermi-Hubbard model, consisting of nearest neighbor tunneling and on-site repulsion. In case when repulsion term is way stronger than tunneling term in the Hamiltonian, the system originally prepared in a state with one atom in each site, will evolve preserving single site occupation. An effective model for this evolution is given by Spin-Exchange (SE) Hamiltonian, consisting of effective nearest neighbor interaction and spin exchange processes. The best studied case is the one for atomic spin $s = 1/2$. It is however very peculiar case, since for $s = 1/2$ SE model is just identical with isotropic Heisenberg model (nearest neighbors spin interaction). The full SE model for arbitrary s is way richer than Heisenberg, what reveals in a larger degeneracy of SE eigenstates. The different, broader set of eigenstates qualitatively changes the spin dynamics of SE system when $s \geq 1$ is considered.

In [1] we show how to derive a broader class of SE model eigenstates. By using these eigenstates, I analytical compute effective spin dynamics of SE system subjected to weak spin coupling to external light. My analytical results are supported by exact numerical simulations. I also propose a possibly simply feasible experimental test to determine the effect of the larger degeneracy of SE model with respect to Heisenberg, to be performed on systems like Strontium-87 in an optical lattice.

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Keywords: Large spin fermions, Fermi-Hubbard model in deep Mott, collective spin dynamics

POSTERS N8

Nonstabilizerness in quantum-enhanced metrological protocols

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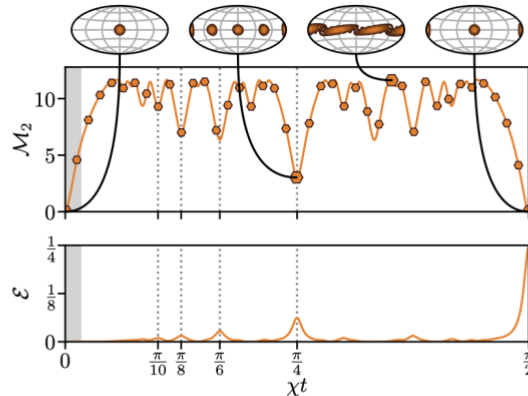
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Nonstabilizerness (colloquially “*magic*”) characterizes genuinely quantum (beyond-Clifford) operations necessary for preparation of quantum states and can be measured by stabilizer Renyi entropy (SRE). For permutationally symmetric states, we show that the SRE depends, for sufficiently large systems, only on a constant number of expectation values of collective spin operators. This compact description is leveraged for analysis of spin-squeezing protocols, which inherently generate nonstabilizerness. Under one-axis twisting (OAT), the generation of optimal squeezing is accompanied by a logarithmic divergence of SRE with system size. Continued time evolution under OAT produces metrologically useful so-called kitten states, that is, superpositions of rotated Greenberger-Horne-Zeilinger states, that feature many-body Bell correlations but exhibit a smaller, system-size-independent SRE that decreases with increasing Bell-correlation strength.

Our results reveal connections between nonstabilizerness, multipartite correlations, and quantum metrology and provide a practical route to quantify nonstabilizerness in experiments for precision sensing.



Dynamics of SRE, \mathcal{M}_2 (upper panel), and many-body Bell correlator, \mathcal{E} (lower panel), during OAT dynamics in the time scale $t \leq \pi/2$ for $N = 100$. Markers indicate exact numerical SRE calculations, while solid lines show the value of \mathcal{M}_2 calculated with our compact formula. Insets show the corresponding Husimi functions at marked times. Shaded areas correspond to the spin-squeezing time scale while dashed lines correspond to times at which kitten states are generated.

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POSTERS N9

Optical creation of soliton lattices and localised vortices in multicomponent Bose–Einstein condensates

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We present a widely accessible and experimentally realisable technique for the controlled creation of dark-bright solitons and soliton lattices in atomic Bose–Einstein condensates (BECs). The method is based on preparing the condensate in a dark state of a Λ -coupled three-level system [1]. Numerical simulations reveal that individual dark-bright solitons created through this scheme can survive over experimentally accessible timescales, even when the coupling laser fields are switched off [2]. Meanwhile, the fate of soliton lattices upon the quench of the fields depends on the scattering lengths: the lattice is found to persist on timescales comparable to the condensate lifetime only when the scattering lengths are all equal.

The present dark-state-based technique also opens up new avenues for exploring unconventional vortices in two-component BECs. Using light beams with orbital angular momentum [3], we theoretically show how to create a stable, pinned vortex configuration, where the rotating component is confined to the region surrounded by the second, non-rotating component [4]. The atoms constituting this vortex can be localised in volumes much smaller than the volume occupied by the second component.

We also show that the vortex position can be changed dynamically by moving the laser beams, provided the beams' movement speed remains below the speed of sound. This allows us to use the localised vortex to stir the second component, and to determine the superfluid flow's critical velocity.

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POSTERS N10

Pair and chiral superfluidity in subwavelength triangular ladders

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Spontaneously symmetry-broken (SSB) phases are ubiquitous in nature, ranging from crystalline order to superfluidity and superconductivity, and their controlled realization remains a central goal in the field of quantum simulation. Ultracold atomic systems provide an exceptionally clean and tunable platform for exploring such collective phenomena. A paradigmatic example of SSB is superconductivity, where fermions form Cooper pairs that condense into a phase-coherent macroscopic state. Understanding how pairing and phase coherence arise in lattice systems with engineered interactions is therefore of fundamental interest.

In this work we demonstrate that coupling ultracold atoms in a particular tripod scheme realizes a frustrated, non-standard Bose–Hubbard model with strong pair hopping and density-induced tunneling. Starting from the dark-state Wannier basis, we derive the extended Bose-Hubbard Hamiltonian. We then use density matrix renormalization group (DMRG) calculations to map out the many-body phase diagram. We find that interaction-driven pair tunneling stabilizes a robust pair superfluid, characterized by power-law decay of pair correlations and gapped single-particle excitations. Additionally, a chiral superfluid arises from frustration induced by competing nearest neighbour (NN) and next-nearest neighbour (NNN) tunnelings. Finally, by mapping the strong-pairing regime onto an effective XXZ spin model, we provide analytic insight into the origin of these phases and their phase boundaries.

Our theoretical results establish subwavelength state-dependent lattices as a versatile route to realizing pairing, frustration, and unconventional superfluidity with ultracold atoms.

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Keywords: Quantum many-body physics, DMRG, geometric frustration, ultracold atoms

POSTERS N11

Spin-Orbit Coupling of Optical Vector Vortices in Coherently Prepared Media

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We investigate the propagation of an optical vector vortex weakly interacting with a coherently prepared atomic medium (phaseonium) in a three-level Λ configuration. The vector beam consists of vortex pulse pairs with right- and left-circular polarizations, corresponding to opposite spin angular momentum (SAM), and carrying opposite orbital angular momentum (OAM) charges $\pm l$. We show that during the propagation of the vortex pairs, analytically obtained in the linear regime, the medium inherits the topology of the vortex pair, mapping the OAM onto a spatially structured atomic coherence. This mapping produces $2|l|$ -fold azimuthal transparency structures that reshape the beam intensity from a ring into a petal-like pattern. The OAM-structured atomic coherence induces a corresponding optical anisotropy within the medium, which feeds back into the propagating vector beam, resulting in optical spin-orbit coupling manifested as SAM exchange, rotation, and evolution of polarization textures. Depending on the initial ground-state population of the phaseonium, the polarization state evolves between left-circular, linear, and right-circular polarizations. The work has been published in Ref.[1].

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POSTERS N12

Aharonov-Casher Chern bands for ultracold dark state atoms

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The Λ scheme of atom–light coupling enables the creation of synthetic magnetic fields that act on ultracold atoms adiabatically following the dark state [1–6]. However, it is problematic to produce a uniform magnetic field needed for forming flat Landau-like energy bands. Recently, it was noticed that a flat lowest energy band can be created for the adiabatic motion of valence band holes in condensed matter bilayer systems [7] or for the adiabatic motion of ultracold atoms in laser fields [6] if the synthetic magnetic field and geometric scalar potential obey the Aharonov-Casher (AC) condition [8]. Here we present a general framework for realizing the Aharonov–Casher (AC) condition for dark-state atoms using superpositions of plane waves [9]. We show that configurations involving three, four, and six plane waves can generate smooth nonstaggered synthetic magnetic fields obeying the AC condition, whereas deviations from perfect tuning additionally produce narrow magnetic flux tubes with opposite sign. We demonstrate the emergence of topological bands with nearly ideal Landau-level behavior needed for simulating the fractional Quantum Hall effect with ultracold atoms.

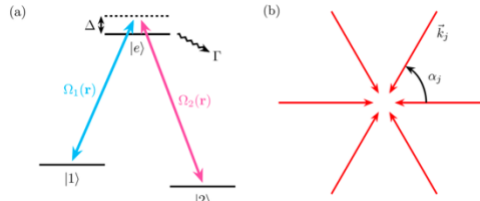


FIG. 1: (a) The Λ scheme of the atom-light coupling. (b) N laser fields making by Rabi frequencies Ω_1 and Ω_2 .

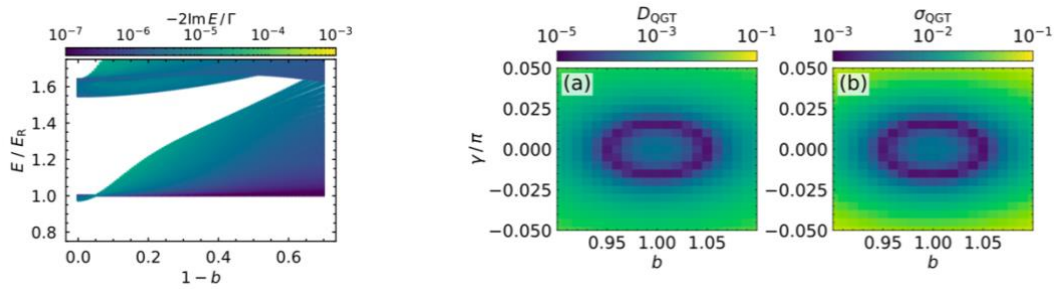


FIG. 2: LEFT. Bulk energy spectrum vs the amplitude imbalance $1-b$ for the square ($N = 4$) configuration with the phase imbalance $\gamma = 0$, $\Omega_0 = 2000ER$, $\Delta = 2000ER$, and $\Gamma = 1000ER$. Colors indicate the decay rate $-2\text{Im } E/\Gamma$. RIGHT. The corresponding quantum geometry of the lowest energy band [9].

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ABSTRACT BOOK

