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Topological effects and synthetic gauge/magnetic fields for atoms and photons

Invited speakers:

Demetrios Christodoulides
Klaus Sengstock
Gennady Shvets
Michael Fleischhauer
Francesca Ferlaino
Gediminas Juzeliunas
Fabrice Gerbier
Alex Szameit
Darrick Chang
Mikael Rechtsman
Zhigang Chen
Thomas Pohl
Marcello Dalmonte
Thomas Gasenzer
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Contents

1 Introduction

The fields of ultracold atomic gases and optics and photonics are mutually entangled in many ways. The workshop aims to bring together scientists from the two communities to discuss the topics that are of great current interest in both fields.

These topics include synthetic gauge fields/synthetic magnetism for atoms and photons, physics of the Hall effect, topological phases and topological effects such as topological insulators, Weyl semimetals, and the manifestations of these phases in forms of topologically protected edge states. A flurry of papers is being published in most prestigious journals on these topics. It is our belief that both communities could benefit by having stronger links in understanding the methods from the other side, experimental difficulties, new possibilities and ideas.

The topics of mutual interest to optics and ultracold atomic gases have been flourishing in the past as well. Thus, the scope of the workshop goes beyond topological effects and synthetic gauge/magnetic fields.

The dynamics of a Bose-Einstein condensate (BEC), and the evolution of coherent light in nonlinear Kerr medium, are both described by the nonlinear Schrodinger equation (NLSE), referred to as the Gross-Pitaevskii equation in the BEC context. This analogy has opened the way for nonlinear atom optics with striking demonstrations of familiar nonlinear optics phenomena such as four wave mixing, superradiant Rayleigh scattering, matter-wave amplification, and matter-wave solitons. Solitons have had a special life and focus in both fields, from the most common bright solitons, to dark and discrete solitons. Their interaction with the uncondensed particles in BECs is related to incoherent solitons in optics. Strongly correlated systems such as one-dimensional strongly interacting 1D Bose gases have been realized with atoms, and there is great interest for producing them with photons, for example by employing coupled cavities. The list is much longer than the "conference scope text" should be.

The workshop topics are of natural interest and naturally occurring in condensed matter physics. For example, the gauge fields in graphene are extensively used to describe strained and stretched graphene, which has in fact been used in optical graphene as well. The condensed matter physicists are most welcomed to join the discussion.

This workshop is intended to bring together most distinguished scientists from the two communities, and also excellent scientists interested in the topics.

2 | Invited talks

Realizing Photonic Topological Insulators and Topological Anderson Insulators

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The discovery of topological insulators relying on spin-orbit coupling in condensed matter systems has created much interest in various fields, including in photonics. In two-dimensional electronic systems, topological insulators are insulating materials in the bulk, but conduct electric current on their edges such that the current is completely immune to scattering. However, demonstrating such effects in optics poses a major challenge because photons are bosons, which fundamentally do not exhibit fermionic spin-orbit interactions (i.e., Kramer's theorem). At microwave frequencies, topological insulators have been [1] in magneto-optic materials, relying on strong magnetic response to provide topological protection against backscattering - in the spirit of the quantum Hall effect. However, at optical frequencies the magneto-optic response is extremely weak, hence a photonic topological insulator would have to rely on some other property. Indeed, numerous theoretical proposals have been made for photonic topological insulators [2], but their first observation [3], made by our group, relied on a different idea: Floquet topological insulators [4]. Later that year, another group reported imaging of topological edge states in silicon photonics [5]. These experiments have generated much follow up, among them - as the arguably most intriguing one the area of *topological photonics* - our first experimental observation of topological Anderson insulators (predicted in [6]], where a system becomes topological only when disorder is introduced [7]. The purpose of this talk is to review these developments, discuss new conceptual ideas, and suggest applications.

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New Horizons in Topological Photonics: Quantum and non-Hermitian Effects

Rechtsman, Mikael C. (1); Lumer, Yaakov (2); Plotnik, Yonatan (2), Zeuner, Julia (3); Perez-Leija, Armando (3); Szameit, Alexander (3); and Segev, Mordechai (2)

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The notion of photonic topological protection was first put forward by Haldane and Raghu [1], and then realized by Soljačić [2] in the microwave regime using magneto-optic materials. Due to the inherently weak magneto-optic response at optical frequencies, a new mechanism was required to realize the topological protection of light: that of photonic Floquet topological insulators [3] (PFTI). In this paper, it was shown that light could travel along the edge of an evanescently coupled array of waveguides while truly suppressing any transverse backscattering. The field of topological photonics has since become a major research direction in many groups that study complex photonic structures, due to both its fundamental interest and is potential applications in overcoming fabrication imperfections to build more robust photonic devices. Indeed, the nonlinear properties of PFTIs have been studied [4,5], but two effects central to optics have yet to be introduced to topological photonics: that of non-Hermitian behavior, and quantum effects.

In the first part of my talk, I will show (both theoretically and experimentally) how in the most basic topological model (the Su-Schrieffer-Heeger dimer model), adding non-Hermiticity via dissipation allows the direct observation of a topological transition. This can be extracted from the bulk dynamics of the optical wavefunction alone (normally in topological systems, edge state information is required). In the second part of my talk, I will show how photonic quantum information can be protected in a PFTI. Topological insulators in electronic (i.e., solid-state systems) have shown promise for protecting qubits from decoherence - but photons interact with their environment very weakly and therefore are not under threat of decoherence. That said, photon entanglement characteristics are fragile and susceptible to scattering. In particular, NOON states [6,7] (which have applications in quantum lithography and sub-wavelength imaging) can be easily scattered and destroyed in a complex network. As I will show, photonic topological protection can overcome this scattering and preserve the "NOONity" of the quantum light.

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Long-range interactions of atoms and photons in photonic crystals

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Significant efforts have been made to interface cold atoms with micro- and nano-photonic systems in recent years. Originally, it was envisioned that the migration to these systems from free-space atomic ensemble or macroscopic cavity QED experiments could dramatically improve figures of merit and facilitate scalability in applications such as quantum information processing. However, there is a growing body of work pointing to an even more intriguing possibility, that nanophotonic systems can yield fundamentally new paradigms to manipulate quantum light-matter interactions, which do not have an obvious counterpart in macroscopic setups.

Here, we describe an example of such a new possibility, involving the investigation of quantum systems with long-range interactions. In particular, we show that atoms trapped near photonic crystals can become dressed by localized photonic "clouds" of tunable size [1]. This cloud behaves much like an external cavity, but one which follows the position of the atom. This dynamically induced cavity allows one to mediate and control long-range interactions between atoms. Interestingly, this phenomenon can in turn be leveraged to yield strong, long-range interactions between propagating photons. As an example, we show that this interaction can produce an effective binding between two spatially separated photons into a "molecule".

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Topological edge states and quantized transport in unitary and dissipative one-dimensional bosonic lattice models

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I discuss bosonic atoms in a one-dimensional superlattice potential with alternating tunneling rates t_1 and t_2 and with on-site [1] and non-local interactions [2]. This model is inversion symmetric and for purely on-site interactions it is the bosonic analogue of the Su-Schrieffer-Heeger model, which possesses topological properties in the half-filling Mott insulating (MI) phase. I introduce a many-body topological invariant, and discuss the emergence of edge states as well as a quantized topological transport in the bulk. Due to the absence of particle-hole symmetry the bulk-boundary correspondence, known from the fermionic model needs to be generalized. In the presence of non-local interactions topologically non-trivial phases with fractional filling are identified. Due to a degeneracy of the ground state for periodic boundary conditions specific topological excitations with fractional charge can occur in the bulk. For open boundary conditions topological edge states can transfrom into these topological excitations when changing the hopping amplitudes. Finally I discuss an open 1D superlattice model, described by a Lindblad master equation. This model is shown to have a quantized bulk transport, allowing for the definition of a topological invariant of the Liouvillian.

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Controllable Photon Interactions in Atomic Rydberg Gases

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The combination of electromagnetically induced transparency (EIT) and strong interactions between atoms in highly excited states represents a promising route towards realizing few-photon nonlinearities in continuous space. The basic principle exploits the destruction of EIT for a dark-state polariton in response to the presence of another in its vicinity, thereby realizing strong and controllable refraction or absorption. A number of recent proof-of-principle experiments have demonstrated the high promise of this approach to implementing photonic quantum logic or studying many-body physics with photons. Yet, it turns out that a suppression of undesired losses typically requires conditions that are hard to realize and where other limiting factors diminish the fidelity of such potential applications.

In this talk, I will discuss an alternative approach that, instead of utilizing the destruction of EIT, is based on an interaction-induced switching between two kinds of dark-state polaritons featuring different propagation characteristics. Beyond boosting the fidelity of aforementioned applications this mechanism gives rise to unusual types of interactions that are of inherent chiral character, as will be demonstrated on a two-body level.

Magnetism with and without magnetism: Different regimes of magnetic-like interactions in quantum gases

Plenary talk

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The talk will address different regimes of magnetic interactions in ultracold quantum gases. The spin dependent contact interaction of ultracold atoms can lead to surprising collective behavior of e.g. fermionic atoms in optical lattices and in bulk [1,2]. Recently artifcial gauge fields even allowed to study magnetic like interactions for completely non-magnetic atoms [3] and to simulate strong external magnetic fields which eventually allow to realize high-B-field physics [4] like the Hofstadter butterfly.

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Artificial magnetic field and spin-orbit coupling for ultracold atoms

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In the initial part of the talk a background material will be presented on the artificial magnetic field and spin-orbit coupling (SOC) for ultracold atoms. Currently these are amongst the most active areas of research for ultracold atomic gases [1-4]. Subsequently we shall discuss some recent developments. One of the current challenges is to experimentally produce a two-dimensional (2D) SOC. Recently it was shown that a two-dimensional (2D) SOC of the Rashba or Dresselhaus type can be created for cold atoms without optical fields using pulsed magnetic field gradients [5,6]. The method relies on a properly chosen pulse sequence of inhomogeneous magnetic fields. Another recently suggested way to produce a two-dimensional spin-orbit coupling is to use a bilayer Bose-Einstein condensate. Here a combination of the Raman-induced one-dimensional SOC within individual layers and the laser-assisted interlayer tunneling makes the SOC effectively two-dimensional. An interplay among the inter-layer tunneling, Raman coupling, and intra-layer atom-atom interaction give rise to diverse ground-state configurations of the bilayer BEC [7,8]. We also discuss effects due to position-dependent SOC [9], as well as possibilities to simulate an artificial magnetic flux in optical lattices via an involvement of synthetic dimensions represented by the atomic internal degrees of freedom [10]. Such a semi-synthetic lattice has just been implement experimentally [11,12]. The semi-synthetic lattices exhibit a peculiar atom-atom interaction, long-range in the synthetic dimension and short-range in the ordinary dimension, so interesting many-body effects are expected.

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Exotic quantum criticality and dynamical gauge fields with Rydberg-dressed atoms

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Rydberg atoms in optical lattices offer tantalizing perspectives for the realization of exotic many-body states of matter, mostly due to the high degree of control in shaping interaction patters and the very favorable energy scales. In the first part of the talk, I'll present some recent results on the many-body physics of one-dimensional atoms dressed to Rydberg states. The soft-shoulder interactions of such systems give rise to unconventional critical scenarios, such as quantum liquids which do not satisfy Luttinger theorem [1] and emergent supersymmetric critical points [2], which could be observables in state-of-the-art settings.

In the second part of the talk, I will show how Rydberg atoms provide an ideal platform to realize various forms of frustrated quantum magnets whose low-energy physics is described by emergent *dynamical gauge fields* [3,4]. These gauge theories are akin to the ones commonly employed in particle physics, and naturally emerge in frustrated systems thanks to energy imposed constraints. I will briefly describe the main ingredients for the realization of such theories, and discuss a set of observables to probe their characteristic signatures.

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Exploring Dipolar Quantum Phenomena with Ultracold Erbium Atoms

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Given their strong magnetic moment and exotic electronic configuration, rare-earth atoms disclose a plethora of intriguing phenomena in ultracold quantum physics with dipole-dipole interaction. Here, we report on the first degenerate Fermi gas of erbium atoms, based on direct cooling of identical fermions via dipolar collisions [1]. We reveal universal scattering laws between identical dipolar fermions close to zero temperature [2], and we demonstrate the long-standing prediction of a deformed Fermi surface in dipolar gas [3]. Finally, we present the first experimental study of an extended Bose-Hubbard model using bosonic Er atoms in a three-dimensional optical lattice and we report on the first observation of nearest-neighbor interactions.

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Hofstadter optical lattice for ultracold Ytterbium atoms

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I will describe our experimental project aiming at the realization of a lattice for ultracold Ytterbium atoms including an effective magnetic field coupling to the atomic motion-the *Hofstadter optical lattice*. I will describe how such a lattice can be realized using geometric phases resulting from coherent atom-laser interactions, which mimick the Aharonov-Bohm phases experienced by charged particles moving in a magnetic field. Our specific experimental scheme uses an ultra-narrow optical transition (the “clock” transition) linking the ground state to a metastable excited state in bosonic Ytterbium. I will present the current status of the experiment, including preliminary spectroscopy experiments of Bose-Einstein condensates (BEC) on the clock transition and the observation of coherent Rabi oscillations between a BEC in the ground state and in the excited state.

Non-thermal fixed points: Universality, topology and turbulence

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Non-equilibrated many-body systems show much richer characteristics than those in equilibrium. There is the possibility for universal dynamics, showing up with the same properties in very different systems irrespective of their concrete building blocks. For example, superfluid turbulence in an ultracold atomic gas has the potential to show the same universal aspects as phenomena believed to have occured after the inflationary period of the early universe. This leads to the concept of non-thermal fixed points which lead beyond standard equilibrium universality. A selection of phenomena in bosonic matter wave and gauge-matter systems will be discussed, characterized by universal scaling behavior in space and time. This exhibits the close relation with quantum turbulence, the dynamics of topological defects, as well as magnetic and charge ordering phenomena. Our results open a path to explore a new class of universal far-from-equilibrium dynamics accessible in ultracold gas experiments and are important beyond the realm of these systems.

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SQUID-based metamaterials: Nonlinear dynamics, topology and quantum effects

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Superconducting metamaterials comprising rf Superconducting QUantum Interference Devices (SQUIDs) have been recently realized and investigated with respect to their tuneability, permeability, and dynamic multistability properties. These properties are a consequence of intrinsic nonlinearities due to the sensitivity of the superconducting state to external stimuli. SQUIDs, made of a superconducting ring interrupted by a Josephson junction, possess yet another source of nonlinearity, which makes them widely tuneable with an applied dc flux. A model SQUID metamaterial, based on electric equivalent circuits, is used in the weak coupling approximation to demonstrate the dc flux tuneability, dynamic multistability, and nonlinear transmission in SQUID metamaterials comprising nonhysteretic SQUIDs. The model equations reproduce the experimentally observed tuneability patterns and predict tuneability with the power of an applied ac magnetic field. Moreover, the results indicate the opening of nonlinear frequency bands for energy transmission through SQUID metamaterials, for sufficiently strong ac fields.

In addition to reviewing general dynamical properties of SQUID-based metamaterials [1,2] we will also discuss possible topological effects in graphene-like structures involving edge modes as well as pure quantum effects accessible at ultra low temperatures.

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Floquet-engineering topological and spin-dependent bands with ultracold fermions

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Periodically driven quantum systems, when observed on time-scales longer than one modulation period, can be described by effective Floquet Hamiltonians that show qualitatively new features. Using a magnetic field gradient, we apply an oscillating force to ultracold fermions in an optical lattice [1]. The resulting effective energy bands then become spin dependent, allowing for a tunable ratio of the effective mass (including negative values) for each internal state, which can be observed directly (Fig. 2.1a). The regime where one spin experiences a flat band and is completely localized whilst the other remains itinerant also becomes accessible.

In a honeycomb lattice, circular modulation of the entire lattice potential leads to the appearance of complex next-nearest neighbour tunnelling. This corresponds to a staggered magnetic flux in the lattice, allowing for the realisation of Haldane's model of a topological Chern insulator [2]. The transition between trivial and topologically non-trivial insulating regimes manifests as a gapless spectrum. By simultaneously breaking time-reversal symmetry and the inversion symmetry of the lattice, the transition can be mapped out using Bloch-Zener oscillations [3], see Fig. 2.1b. Furthermore, the non-zero overall Berry curvature leads to perpendicular drifts of an accelerated atomic cloud.

A crucial question for the extension of Floquet-engineering to interacting systems is whether periodic modulation creates excessive heating in the system. We identify regimes where this heating is minimal which paves the way for studying the interplay of topology and interactions or exotic spin-models.

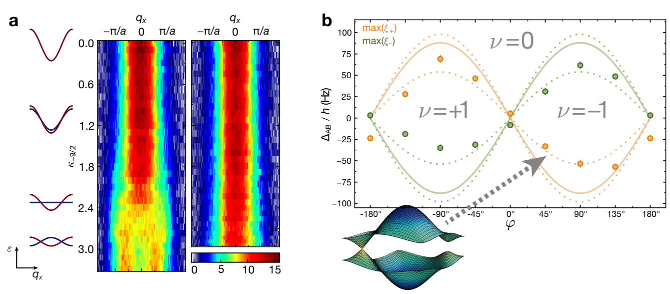

Figure 2.1: (a) Spin-dependent bands can directly be observed in the quasimomentum-distribution of two internal states. (b) Mapping out the topological transition (where the band becomes gapless) of Haldane's model.

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Bosonic Phases On The Haldane Honeycomb Lattice

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Recent experiments [1] in ultracold atoms have reported the implementation of artificial gauge fields in lattice systems. Motivated by such advances, we investigate the Haldane honeycomb lattice tight-binding model [2], for bosons with local interactions at the average filling of one boson per site. We analyze the ground state phase diagram and uncover three distinct phases: a uniform superfluid, a chiral superfluid and a plaquette Mott insulator with local current loops. Nearest-neighbor and next-nearest neighbor currents distinguish CSF from SF, and the phase transition between them is first order. We apply bosonic dynamical mean field theory and exact diagonalization to obtain the phase diagram, complementing numerics with calculations of excitation spectra in strong and weak coupling perturbation theory. The characteristic density fluctuations and excitation spectra can be probed in future experiments.

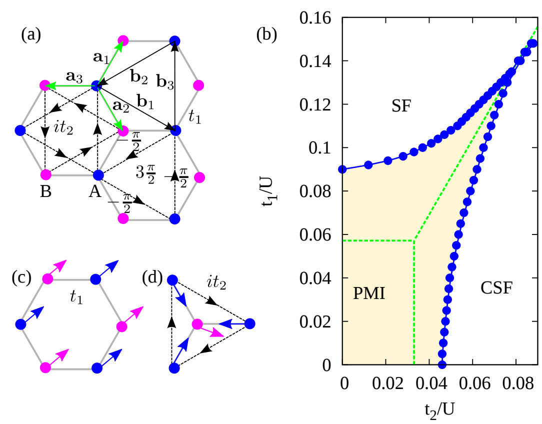

Figure 2.2: a) Lattice vectors and hopping integrals of the Haldane model. b) Phase diagram of the model at unit filling, containing plaquette Mott insulator (PMI), uniform superfluid (SF) and chiral superfluid (CSF) phases. c) Local condensate order parameter in the uniform superfluid; d) In CSF the condensate order parameters on sublattices A and B are determined up to a relative phase.

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Topological pumping in far-from-equilibrium periodically driven systems

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Periodically driven quantum systems, such as semiconductors subject to light and cold atoms in optical lattices, provide a novel and versatile platform for realizing topological phenomena. Among these are analogs of topological insulators and superconductors, attainable in static systems. However, some of these phenomena are unique to the periodically driven case. I will describe how the interplay between periodic driving, disorder, and interactions gives rise to new steady states exhibiting robust topological phenomena, with no analogues in static systems. Specifically, I will show that disordered two dimensional driven systems admit an “anomalous" phase with chiral edge states that coexist with a fully localized bulk. This phase serves as a basis for a new topologically protected, far-from-equilibrium transport phenomenon: quantized non-adiabatic charge pumping. I will make a comparison to interacting one dimensional driven systems, and show that despite the fact that they cannot support such a phenomenon, they do harbor current carrying states with excessively long life times.

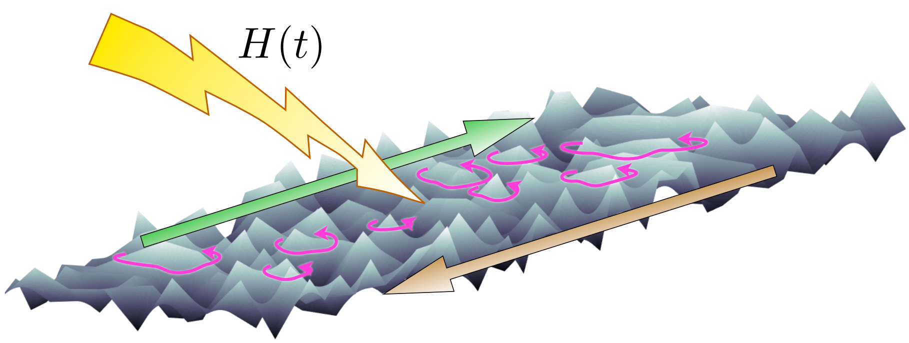

Figure 2.3: The anomalous Floquet-Anderson insulator (AFAI), in a disordered two-dimensional periodically-driven system with time-dependent Hamiltonian $H(t)$. In the AFAI phase all bulk states are localized, yet the system hosts chiral propagating edge states at all quasienergies. The nontrivial topology of the phase is characterized by a nonzero value of a new type of topological invariant, a winding number in terms of the time dependent unitary time evolution operator.

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3 | Contributed talks

PT invariant Weyl semimetals in gauge symmetric systems

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Weyl semimetals typically appear in systems in which either time-reversal (T) or inversion (P) symmetry are broken. I will show that these topological states of matter can also arise in fermionic systems with gauge potentials preserving both T and P. I will discuss the role of the gauge symmetry in the formation of Weyl points for both Abelian and non-Abelian gauge potentials. Focusing on a $U(2)$ symmetric system in a cubic lattice, I will show that double-Weyl points and Fermi arcs appear as an effect of gauge invariance. A simultaneous breaking of both gauge and time-reversal symmetry brings the PT invariant system into a usual Weyl semimetal with inversion symmetry.

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Four dimensional quantum Hall effect with ultracold gases and photonics

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Recent experimental realization of the synthetic dimension in ultracold gases has opened a possibility of using ultracold gases to simulate physics of tight-binding models in a completely new way. Motivated by this development, we propose a realistic scheme to observe the four dimensional quantum Hall effect in ultracold gases, where the synthetic dimension plays the role of the fourth "spatial" dimension. We propose a minimal model which shows the four dimensional quantum Hall effect, and derive an expression for the Hall current in response to external electric and magnetic fields. In four dimensional systems, a topological index that appears in the Hall conductivity is the second Chern number, in contrast to the first Chern number in the two dimensional quantum Hall effect. We show that the second Chern number can be extracted through the measurement of the current or the center-of-mass drift in the four dimensional quantum Hall system [1].

We then discuss that a similar idea can also be employed to photonic systems to generate a synthetic dimension. We propose a scheme to generate a synthetic dimension in coupled photonic cavity arrays, and show how a synthetic magnetic field can be produced in the synthetic dimension. We also discuss how the four dimensional quantum Hall effect and the second Chern number can be observed in a driven-dissipative four dimensional photonic lattice with synthetic magnetic fields [2].

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Measurement of a Topological Edge Invariant in a Microwave Network

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We present a recently proposed class of two-dimensional photonic networks that exhibit topologically protected edge states. Formally, stationary states of such networks are equivalent to the Floquet states of a periodically driven lattice. We thus show that such photonic networks can exhibit topologically protected edge states even if all bands have zero Chern number, which is a characteristic property of Floquet band structures [1].

We also report on the experimental measurement of a topological invariant in such setup, consisting of the winding number of the reflection coefficient from one edge of the network [2]. The experiment can be regarded as a variant of a topological pump, with nonzero winding implying the existence of topologically protected edge states (see Fig. 3.1).

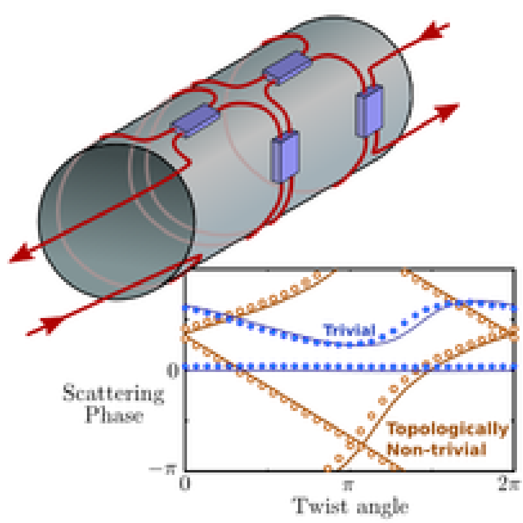

Figure 3.1: Left: Schematic of the topological pump setup which was used to measure the topological invariant of a 2D photonic network. Right: Arguments of the complex scattering matrix eigenvalues for the two-cell network, as the pumping parameter is tuned through 2π. The two eigenvalues having winding numbers ±1 corresponds to the bulk band structure being topologically nontrivial.

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General protocol to measure fragmentation in correlated BECs

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We propose a protocol based on the matter-wave interferometry for quantitative measurements of loss of coherence and fragmentation in ultra-cold atomic clouds. To quantify coherence and fragmentation we use the well-known and widely-used definition of condensation given by O. Penrose and L. Onsager [Phys. Rev. 104, 576 (1956)] in terms of eigenvalues of the reduced one-particle density matrix: When only one eigenvalue has a macroscopic occupation the system is condensed, when several - it is fragmented. This definition of condensation, in contrast to others is valid at zero temperature, for finite-N systems with general interparticle interactions in any dimension, i.e., in 2-3-D setups. It is also applicable for time-evolving systems, e.g., for non-stationary processes. To describe the protocol, first, we show Fig.1(a) how a coherent light-pulse applied to an initially-condensed solitonic system splits it into two matter-waves. The split system, as we have shown in PRL 106, 240401 (2011), inevitably becomes two-fold fragmented due to interparticle attractions, i.e., it develops correlations with time and loses the coherence - contrast the depicted many-body (MB) and mean-field (GP) results. Next, we show that by re-colliding the sub-clouds constituting the split density together, along with a simultaneous application of the same laser-pulse, one creates three matter-waves Fig.1(c) propagating with different momenta. We demonstrate Fig.1(b) that the number of atoms in the sub-cloud with zero-momentum is directly proportional to the occupation of the second natural orbital. This interferometric-based protocol to discriminate, probe, and measure the fragmentation is general and can be applied to ultra-cold systems with attractive, repulsive, short- and long-range interactions. We also would like to announce the release of the MCTDHB-Laboratory http://qdlab.org - a FREE-for-download, cross-platform (Mac-Win-Linux) solver of the many-boson Time-dependent Schrödinger equation with a simple graphical mouse-click front-end interface.

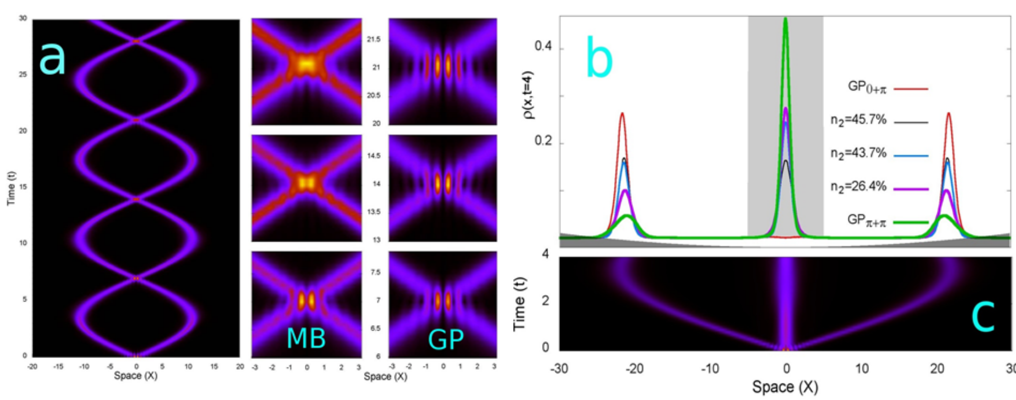

Figure 3.2: Illustrative numerical example of the protocol applied to the low-dimensional BEC with attractive inter-boson interaction.

A Thouless Quantum Pump with Ultracold Bosonic Atoms in an Optical Superlattice

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Thouless introduced the concept of a topological charge pump [1] that would enable robust transport of charge through an adiabatic cyclic evolution of the underlying Hamiltonian. In contrast to classical transport, the transported charge was shown to be quantized and purely determined by the topology of the pump cycle, making it robust to perturbations [1, 2]. On a fundamental level, the quantized charge transport can be connected to a topological invariant, the Chern number, first introduced in the context of the integer quantum Hall effect [3, 4]. A Thouless quantum pump may therefore be regarded as a 'dynamical' version of the integer quantum Hall effect. Here, we report on the realization of such a topological charge pump using ultracold bosonic atoms that form a Mott insulator in a dynamically controlled optical superlattice potential. By taking in-situ images of the atom cloud, we observe a quantized deflection per pump cycle. We reveal the genuine quantum nature of the pump by showing that, in contrast to ground state particles, a counterintuitive reversed deflection occurs when particles are prepared in the first excited band. Furthermore, we were able to directly demonstrate that the system undergoes a controlled topological phase transition in higher bands when tuning the superlattice parameters.

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Edge-induced Bloch oscillations and ordinary conductivity in the presence of a gauge field

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We consider the dynamics of a quantum particle in a finite along the x-direction square lattice in the presence of a normal to the lattice plane 'magnetic' field and an in-plane 'electric' field aligned with the y-axis. For a vanishing magnetic field this dynamics would be common Bloch oscillations where the particle oscillates in the y-direction with an amplitude inverse proportional to the electric field. We show that a non-zero magnetic field crucially modifies this dynamics. Namely, the new Bloch oscillations consist of time intervals where the particle moves with constant velocity in the x-direction intermitted by intervals where it is accelerated or decelerated along the lattice edges. Next we address this dynamics in the presence of an inelastic scattering process. We show that the system enters a steady regime with the stationary current which is not uniform across the sample: for a weak electric field (linear response regime) it is localized at the lattice edge while for a strong field it extends inside the sample. A semi-analytical method for calculating the stationary current is presented.

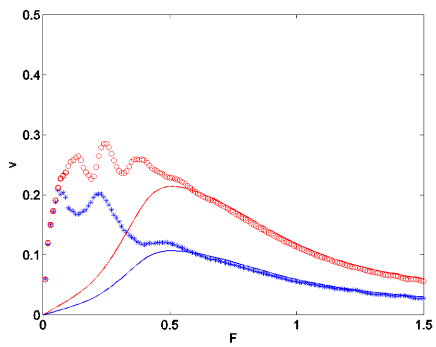

Figure 3.3: Total stationary current as the function of an electric field for two samples of different width. In the linear response regime the current is due to the edge states and, hence, is independent of the sample width.

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Schwinger pair production with ultracold atoms

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We consider a system of ultracold atoms in an optical lattice as a quantum simulator for electron-positron pair production in quantum electrodynamics (QED). For a setup in one spatial dimension, we investigate the nonequilibrium phenomenon of pair production including the backreaction leading to plasma oscillations. Unlike previous investigations on quantum link models, we focus on the infinite-dimensional Hilbert space of QED and show that it may be well approximated by experiments employing Bose-Einstein condensates interacting with fermionic atoms. The calculations based on functional integral techniques give a unique access to the physical parameters required to realize the QED phenomena in a cold atom experiment. In particular, we use our approach to consider quantum link models in a yet unexplored parameter regime and give bounds for their ability to capture essential features of the physics. The results suggest a paradigmatic change towards realizations using coherent many-body states rather than single atoms for quantum simulations of high-energy particle physics phenomena.

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Experimental study of 2D Anderson localization with an atomic kicked rotor

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Dimension 2 is expected to be the lower critical dimension for Anderson localization in a time-reversal-invariant disordered quantum system [1]. Quantitative experimental study of 2D Anderson localization has been considered for a long time, and still is a real defy. Using an atomic quasiperiodically kicked rotor, equivalent to a two-dimensional Anderson-like model [2], we experimentally study Anderson localization in dimension 2 (see Fig. 3.4) and we observe a localized wavefunction dynamics [3]. We also show that the localization length depends exponentially on the disorder strength and is in quantitative aggreement with the predictions of the self-consistent theory of 2D Anderson localization.

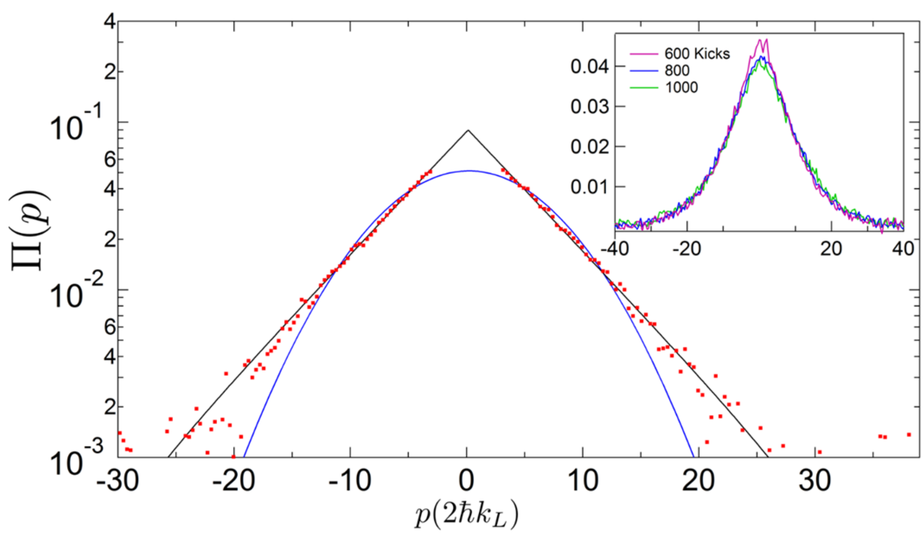

Figure 3.4: Signatures of the 2D Anderson localization. The wings of the wavefunction (logarithmic scale) measured at 200 kicks already show the double exponential shape characteristic for the localization. Inset: velocity distributions for 600, 800 and 1000 kicks, showing that the dynamics of wavefuncthion is frozen for these timescales.

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Synthetic field-induced charge density waves

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The recent experimental discovery of charge density wave (CDW) on graphene sheets in intercalated graphite compound CaC6 (see Fig. 1) [1] has drawn a lot of attention in physical community. Most importantly, the inability to explain the origin of such charge modulation via standard Fermi surface nesting mechanism, obviously implies the necessity to introduce new concepts in understanding the physics of density waves. Here, we propose a model in which we utilize lattice deformation-induced synthetic magnetic field, which influences electron dynamics via magnetic breakdown mechanism, to explain the onset of electron density modulation. The physical properties of graphene are significantly changed in CaC6 compound which is formed by intercalation of graphite with Ca atoms that form a hexagonal superlattice between graphene sheets. Also, they push the carbon sheets to 35% larger distance and dope them with 0.2 electrons per carbon atom, resulting in finite Fermi surface. The observed CDW appears along the underlying Ca ion lines and has period in perpendicular direction equal to three times that of the Ca superlattice, without measured displacement of carbon lattice. Taking all counted, the nesting mechanism to induce a CDW instability is ruled out. However, the observed density wave periodicity relates Fermi surfaces exactly to slightly overlapping position, having the new lattice unit cell $3\sqrt{3}a \times \sqrt{3}a \quad R30^\circ$ (a is a carbon-carbon distance). Earlier, we proposed a mechanism by which the density wave can be induced by magnetic breakdown, that lowers total energy of the system in such configuration, due to an external magnetic field [2]. Here, a slight, spontaneous, inplane deformation of carbon lattice creates a perpendicular synthetic magnetic field that can be large (few dozens Tesla). Electron tunneling assisted by that field (magnetic breakdown) connects closed electron orbits [3] thus delocalizing electron motion and lowering its energy. The onset of density wave is a result of energy balance between electron condensate energy decrease due to the tunneling, and elastic energy "paid" to create the self-consistent synthetic magnetic field that assists the tunneling.

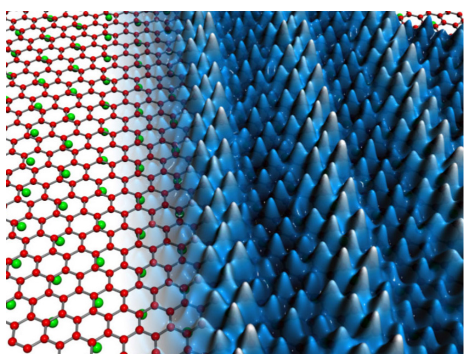

Figure 3.5: Charge density wave on the graphene sheet at the surface of intercalated graphite compound CaC6. [1]

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Cavity Optomechanics with Ultra Cold Atoms in Synthetic Gauge Field

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In this talk we discuss the properties of ultra cold atoms in synthetic abelian and non-abelian gauge field placed inside a single mode Fabry-Perot cavity. Due to strong atom-photon coupling the resultant phases of ultra cold atoms in such ambiance shows interesting features. As specific cases we shall consider the cavity optomechanics of ultra cold fermionic atoms placed in a synthetic magnetic field (abelian) [1] and the cavity induced phase-diagram of spin-orbit coupled ultra cold bosonic atoms (non-abelian case) [2]. We particularly emshasize how the bistable features in the transmission spectrum from the cavity can be used to detect the interesting properties of ultra cold atoms in such cavity (Fig. 3.6). We shall also explain how the cavity induced quantum optical lattice can create a number of interesting magnetic phases (Fig. 2). The talk is primarily based on the references mentioned below.

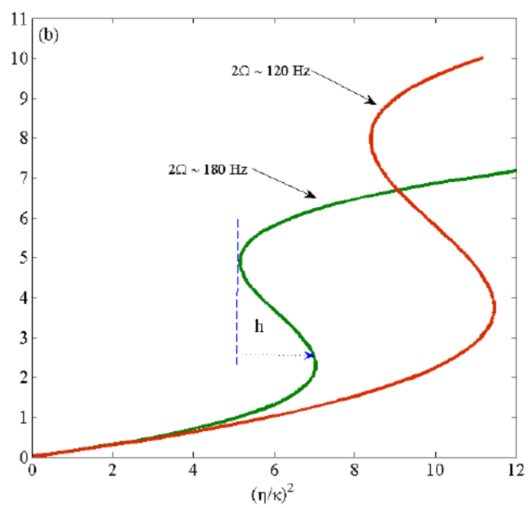

Figure 3.6: Cavity Transmission Spectrum for certain magnetic phases for Spin-Orbit coupled Bosonic Atoms in a Cavity

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Quantum simulation of conductivity plateaux and fractional quantum Hall effect using ultracold atoms

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We analyze the role of impurities in the fractional quantum Hall effect using a highly controllable system of ultracold atoms. We investigate the mechanism responsible for the formation of plateaux in the resistivity/conductivity as a function of the applied magnetic field in the lowest Landau level regime. To this aim, we consider an impurity immersed in a small cloud of an ultracold quantum Bose gas subjected to an artificial magnetic field. We consider scenarios corresponding to experimentally realistic systems with gauge fields induced either by rotation or by appropriately designed laser fields. Systems of this kind are adequate to simulate quantum Hall effects in ultracold atom setups. We use exact diagonalization for few atoms and, to emulate transport equations, we analyze the time evolution of the system under a periodic perturbation. We provide a theoretical proposal to detect the up-to-now elusive presence of strongly correlated states related to fractional filling factors in the context of ultracold atoms. We analyze the conditions under which these strongly correlated states are associated with the presence of the resistivity/conductivity plateaux. Our main result is the presence of a plateau in a region, where the transfer between localized and non-localized particles takes place, as a necessary condition to maintain a constant value of the resistivity/conductivity as the magneticfield increases.

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4 | Posters

Nonlinear quantum optics in graphene

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We show that graphene possesses a strong nonlinear optical response in the form of multiplasmon absorption, with exciting implications in classical and quantum nonlinear optics [1]. Specifically, we predict that graphene nanoribbons can be used as saturable absorbers with low saturation intensity in the far-infrared and terahertz spectrum. Moreover, we predict that the extreme localization of plasmon fields in graphene nanodisks leads to such a strong two-plasmon absorption that it becomes nearly impossible to excite a second quantized plasmon in the system. This plasmon blockade effect would cause the nanodisk to behave essentially like a quantum two-level system, which is observable in its resonance fluorescence spectrum, see Fig. 4.1.

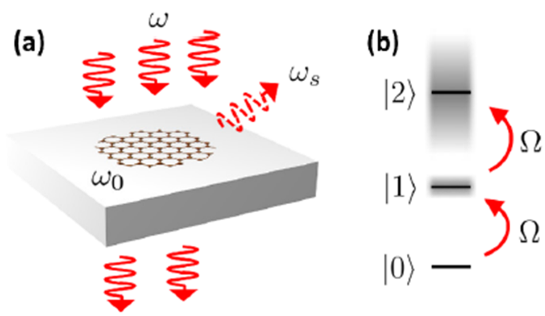

Figure 4.1: (a) Resonance fluorescence of a graphene nanodisk. (b) Quantized plasmon energy levels in a disk. Two-plasmon absorption induces a huge linewidth of a doubly excited state |2>, which makes it extremely difficult to populate this state and effectively turns the disk into a two-level system.

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Weyl points in three-dimensional optical lattices: synthetic magnetic monopoles in momentum space

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We show that Hamiltonians with Weyl points can be realized for ultracold atoms using laser-assisted tunneling in three-dimensional (3D) optical lattices. Weyl points are synthetic magnetic monopoles that exhibit a robust, 3D linear dispersion. They are associated with many interesting topological states of matter, such as Weyl semimetals and chiral Weyl fermions. However, Weyl points have yet to be experimentally observed in any system. We show that this elusive goal is well-within experimental reach with an extension of the techniques recently used to obtain the Harper Hamiltonian [1].

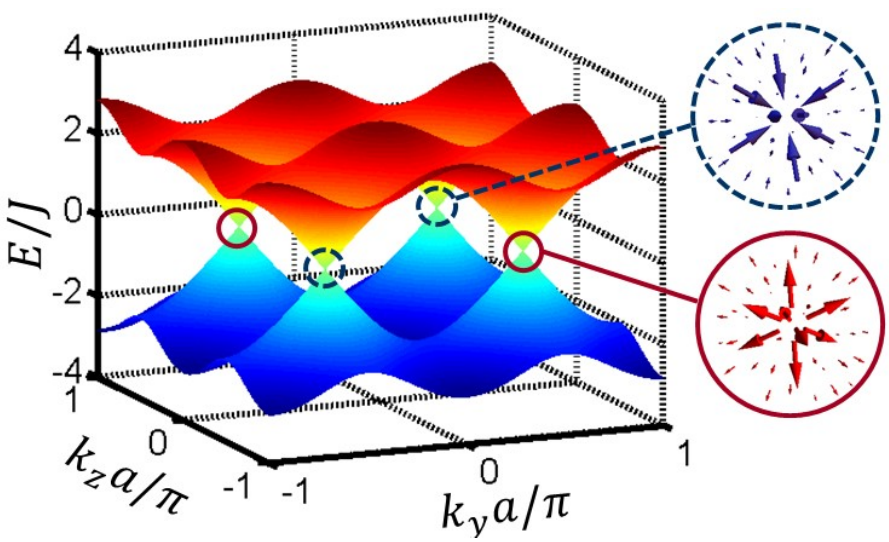

Figure 4.2: Energy spectrum in the $k_x = 0$ plane of the Brillouin zone, showing linear dispersion in the proximity of the four Weyl points. The insets show the Berry curvature of two Weyl points, demonstrating that they are synthetic magnetic monopoles in momentum space.

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The Harper-Hofstadter Hamiltonian and conical diffraction in photonic lattices with grating assisted tunneling

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We present a grating assisted tunneling scheme for tunable synthetic magnetic fields in photonic lattices [1]. Grating assisted tunneling is inspired with laser assisted tunneling in ultracold atomic systems theoretically proposed in Refs. [2,3], subsequently developed to experimentally realize Harper-Hofstadter Hamiltonian [4,5]. The synthetic fields emerge from the nontrivial phases of the resulting tunneling matrix elements. The scheme is straightforward to implement at optical frequencies in optically induced one- and two-dimensional dielectric photonic lattices. We propose implementation of the Harper-Hofstadter Hamiltonian in these photonic lattices [1]. As a signature of the synthetic magnetic fields, we demonstrate conical diffraction patterns in particular realization of these lattices, which possess Dirac points in k-space. We compare the light propagation in the realistic (continous) systems with the evolution in discrete models representing the Harper-Hofstadter Hamiltonian, and obtain excellent agreement (see Fig. 4.3).

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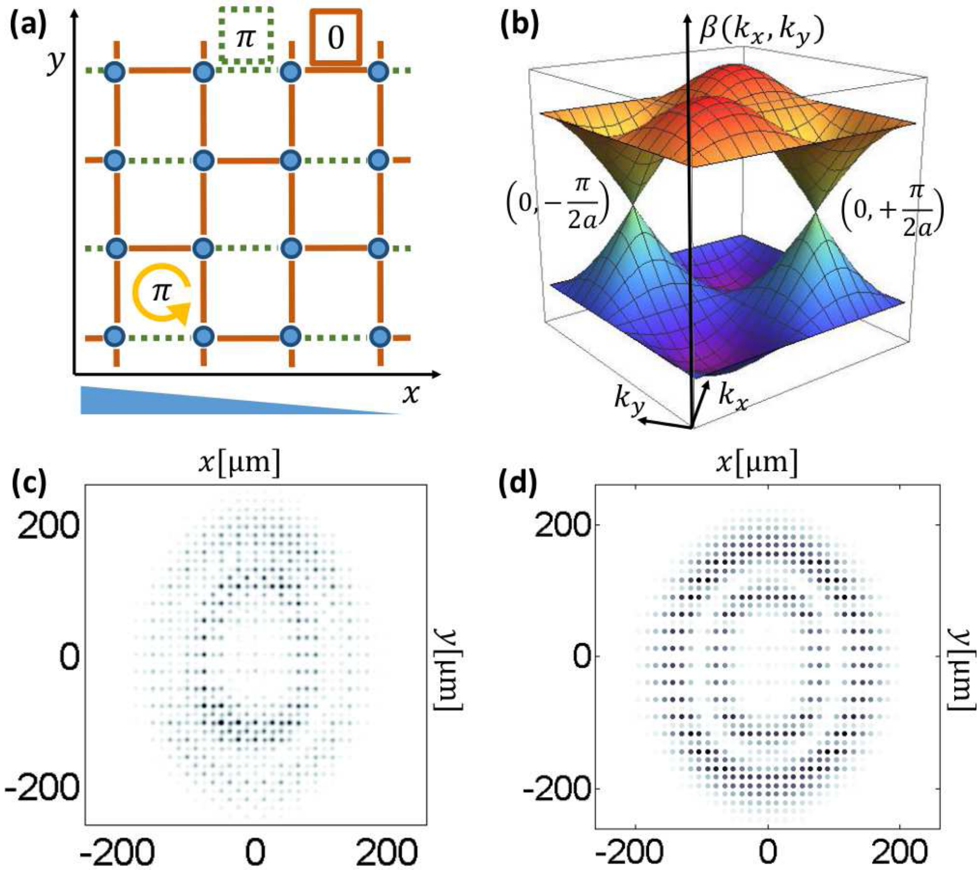

Figure 4.3: Grating assisted tunneling and conical diffraction in a square photonic lattice. (a) Sketch of the 2D lattice with grating assisted tunneling along the x direction. The resulting nontrivial hopping phases π and 0 are denoted with dashed and solid lines, respectively. A wavepacket that makes one loop around the plaquette accumulates the phase π. (b) The lattice possesses two 2D Dirac cones at $(k_x, k_y) = (0, \pm\pi/2a)$ in the dispersion $\beta(k_x, k_y)$, where β is the propagation constant. (c) Intensity of a beam, which initially excites modes in the vicinity of the Dirac points, after propagation for $z = 162$ mm. The intensity has two concentric rings corresponding to conical diffraction pattern. (d) Simulation of the diffraction pattern in the discrete model corresponding to the lattice in (a), which also exhibits conical diffraction.

TA second generation setup for experiments with ultracold lanthanide atoms

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In recent years experiments with ultracold samples of lanthanide atoms moved into the focus of the community, as their large magnetic moments, e.g. $7\mu_B$ for Erbium or $10\mu_B$ for Dysprosium, allow for the investigation of the long-range, anisotropic magnetic dipole-dipole interaction. Recently, the impact of this interaction on the Bose-Hubbard dynamics has been observed in our group for the first time ([1], see contribution by S. Baier). Here, we present a second generation setup for experiments with multiple species of lanthanides, namely Erbium and Dysprosium, enabled by the close resemblance in the properties of both elements. We give a detailed overview over the setup as well as a short outlook on the planned experiments with mixtures of both species as well as with optical lattices, including single-site imaging. For example, quantum magnetism could be studied in our experiments at the single atom level. Therefore, many interesting phases of matter, such as antiferromagnetism, high-temperature superconductivity, and frustrated spin system, can be investigated in a controlled environment. In addition, because of the long range interaction, it becomes possible to cool atoms in optical lattices to realize some interesting phases, like antiferromagnetism, which can be destroyed by thermal fuctuations. Furthermore, the third pillar of our experimental setup is based on the fact, that lanthanide atoms, with their complex level structure, represent an interesting starting position for Rydberg physics in the ultracold regime. Unlike the alkali or alkaline earth metals, where only electrons from a s-state can be excited to a Rydberg state, for lanthanides also electrons from the open anisotropic 4f-shell can be addressed. Thus, s-,p-,d-,f- or h-Rydberg states can be excited with a simple two-photon excitation scheme either via a broad- or a narrow-line transition in the first excitation step.

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Trapping atoms in the evanescent field of laser written waveguides

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We analyze evanescent fields of laser written waveguides and show that they can be used to trap atoms close to the surface of an integrated optical atom chip. In contrast to subwavelength nanofibres it is generally not possible to create a stable trapping potential using only the fundamental modes. This is why we create a stable trapping potential by using two different laser colors, such that the waveguide supports two modes for the blue detuned laser, while for the red detuned light the waveguide has only a single mode. In particular, we study such a two-color trap for Cesium atoms, and calculate both the potential and losses for the set of parameters that are within experimental reach. We also optimize system parameters in order to minimize trap losses due to photon scattering and tunneling to the surface.

Experimental Demonstration of a Synthetic Lorentz Force by Using Radiation Pressure

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Synthetic magnetism plays an important role in the development of controllable quantum emulators. The first implementation of synthetic magnetism used the analogy between the Lorentz force and the Coriolis force [1]. Methods based on laser-atom interaction employ the analogy between the Berry phase in atomic systems, and the Aharonov-Bohm phase for charged particles [2].

We experimentally demonstrate a synthetic Lorentz force for cold atomic gases, based on radiation pressure and the Doppler effect, as proposed in Ref. [3]. We demonstrate this force in two different ways. The first way is by measuring the dependence of the transverse radiation pressure force on the velocity of a cold atomic cloud [4]. This is done by observing the motion of its center of mass, Fig. 4.4. The transverse synthetic Lorentz force is perpendicular to the velocity, and it is zero for a cloud at rest. The second way we demonstrate this force is by observing the free expansion of the cold atomic cloud. While expanding the cloud starts to rotate. The cloud is made rotationally asymmetric which enables the detection of the rotation by observing the change in shape of the cloud.

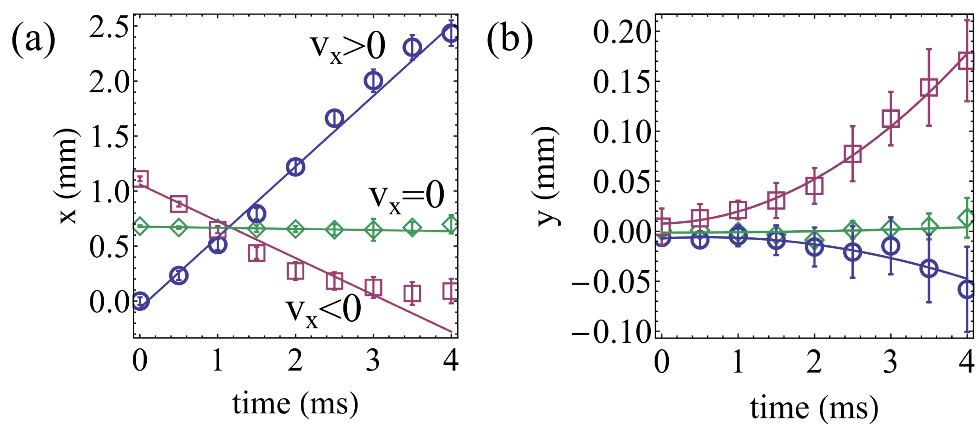

Figure 4.4: The trajectories of the CM of the atomic cloud in the presence of the synthetic Lorentz force. (a) $x(t)$, and (b) $y(t)$ for three different initial velocities.

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Universality in molecular halo clusters

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I will present the study [1] of weakly bound dimers and trimers with a radius extending well into the classically forbidden region, performed with the goal to test the predicted universality of quantum halo states. The focus were molecules consisting of T↓, D↓, ^{3}He, ^{4}He and alkali atoms, where interaction between particles is much better known than in the case of nuclei, which are traditional examples of quantum halos. The exploration of realistic systems was supplemented by model calculations in order to analyze how low-energy properties depend on the interaction potential. The use of variational and diffusion Monte Carlo methods enabled very precise calculation of both size and binding energy of the trimers. For the first time, we were able to establish both the more convenient scaling variables and the universal line which dimer and trimer halo states follow. Finally, we were able to observe, and determine when, universal line of tango trimers departs from the Borromean one.

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Momentum-space artificial magnetic field in the trapped Harper-Hofstadter model

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The Harper-Hofstadter model is a two-dimensional lattice model with a perpendicular magnetic field. The model has attracted much attention from various communities due to its topologically nontrivial bands; in particular in ultracold gases and photonic systems, the model has been recently experimentally realized. Here we theoretically show that the Harper-Hofstadter model in the presence of an external harmonic trap can be understood as a particle moving in momentum space in the presence of the momentum-space magnetic field [1,2]. The "kinetic energy" in momentum space is given by the external trap, and the artificial magnetic field in momentum space is given by the Berry curvature. The location of the external trap in real space sets the boundary condition in the magnetic Brillouin zone. By changing the location of the external trap, one obtains the Laughlin's gedankenexperiment of quantum Hall effect in momentum space. We show that the model exhibits Landau levels in momentum space, or the model is described by the Harper-Hofstadter model in momentum space, depending on the system parameters.

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Collective Modes of Dipolar Fermi Gas from Collisionless to Hydrodynamic Regime

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We study the low-lying collective excitations of a Fermi gas at zero temperature confined to a triaxial harmonic trap, featuring the anisotropic long-range dipole-dipole interaction. In order to analyze the collective modes of this system, we follow Ref. [1] and solve analytically the underlying Boltzmann-Vlasov equation by using the relaxation-time approximation and by performing a suitable rescaling of the equilibrium distribution [2]. The resulting ordinary differential equations for the dynamics of the scaling parameters are linearized around equilibrium in order to determine both eigenvectors and eigenfrequencies of the collective modes. Due to the smallness of the dipolar interaction strength, the collisionless regime corresponds to the case of a noninteracting Fermi gas, i.e., the three low-lying modes represent one-dimensional cloud elongations along only one of the respective trap directions [3, 4]. In contrast to that, we get in the hydrodynamic regime the usual breathing, quadrupole, and radial quadrupole mode, where the cloud elongations are truly three- and two-dimensional, respectivley [5, 6]. We investigate in detail how the eigenvectors change when decreasing the relaxation time all the way from the collisionless to the hydrodynamic regime. We also analyze the quench dynamics, which is induced by a sudden rotation of the polarization of the atomic magnetic moments by 90°, and show that it can be understood by a superposition of the low-lying collective modes. These analytical and numerical calculations are relevant for understanding quantitatively the current Innsbruck experiment with ultracold fermionic erbium atoms, which interact via their magnetic dipole moments [7].

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Extended Bose-Hubbard Models with Ultracold Magnetic Atoms

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Strongly magnetic atoms are an ideal systems to study many-body quantum phenomena with anisotropic interactions. Here, we report on the first observation of the manifestation of magnetic dipolar interaction in extended Bose-Hubbard (eBH) dynamics by studying an ultracold gas of Er atoms in a three-dimensional optical lattice [1]. We drive the superfluid-to-Mott-insulator (SF-to-MI) quantum phase transition in presence of the anisotropic and long-range dipole-dipole interaction (DDI) and demonstrate that the dipolar interaction can favor the SF or the MI phase depending on the orientation of the atomic dipoles. In a combined experimental and theoretical work, we show that the system is well described by the individual terms of the eBH Hamiltonian. This includes the onsite interaction, which, additional to the well-know isotropic contact interaction, can be tuned with the DDI by changing the dipole orientation and the shape of the onsite Wannier functions. We find for the first time the presence of the nearest-neighbor interaction between two adjacent particles, and report on the density-assisted tunneling term, revealing itself in the angle dependence of the critical point in the SF-to-MI transition.

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