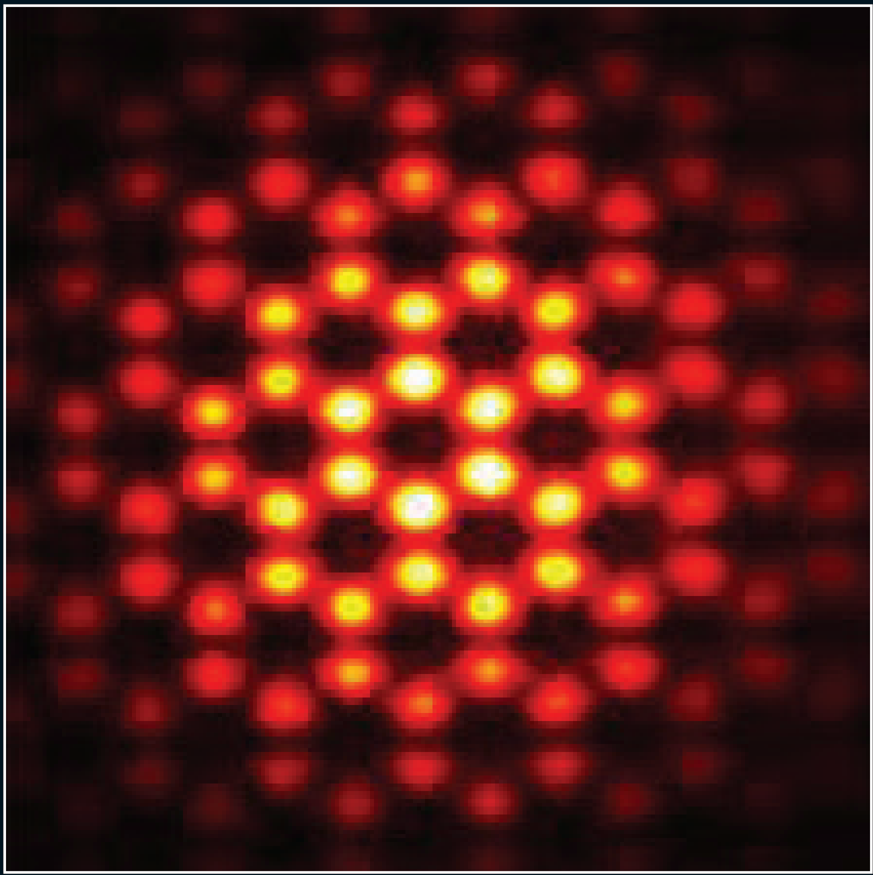
Programme and abstract book



Topical Research Meeting on Topological States in Strongly Interacting Light-Matter Systems

19–20 March 2018
De Vere Horwood Estate, Milton Keynes, UK

trm-tims2018.iopconfs.org

#IOPTIMS2018

IOP Institute of Physics

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09:30 (i) **Topological properties of cavity polaritons in 1D lattices**
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10:00 **Hybrid Nb-InGaAs 2DEG-Nb ballistic Josephson junctions for scalable topological quantum processing**
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10:20 **Topological properties of a dense atomic lattice gas**
Beatriz Olmos, University of Nottingham, UK

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11:10 (i) **Enhancement of polariton interactions using fractional quantum Hall states**
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17:10 (i) **On-chip microwave spectroscopy: The toolset to identify topological superconductivity**
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18:10 **Interacting topological insulators: The Su-Schrieffer-Heeger-Hubbard model for dopants in silicon**
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Eyre Suite

08:30 Registration (1911 Lounge)

09:00 (i) **Hybrid Dirac photons in topological orbital lattices**
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09:30 (i) **Superconducting quantum simulator for topological order and the Toric code**
Michael Hartmann, Heriot-Watt University, UK

10:00 **Quantum Spin Hall effect analog for vortices in an interacting bosonic quantum fluid**
Olivier Bleu, Institut Pascal, University Clermont Auvergne, France

10:20 **A novel platform for quantum optics and quantum information using topological insulator nanostructures**
Marie Rider, Imperial College London, UK

10:40 Coffee break (1911 Lounge)

11:10 (i) **The dispersive ultra-strong coupling regime between two bosonic fields and is applications**
Perola Milman, Université Paris Diderot, CNRS, France

11:40 (i) **Random access quantum information processors using multimode circuit quantum electrodynamics**
Srivatsan Chakram, University of Chicago, USA

12:10 Lunch, exhibition and posters (1911 Lounge)

14:00 (i) **2D polariton lattices designed for Dirac-cone and flatband dispersions: A versatile platform for topological photonics**
Sven Hofling, University of St Andrews, UK

14:30 (i) **Topological multi-terminal Josephson junctions**
Julia Meyer, University of Grenoble, France

15:00 **Optical chern insulators from conical refraction**
Robert Mc Guinness, Trinity College Dublin, Ireland

15:20 **Hybridization of bound states in a TSC/TI/TSC junction**
Konstantin Yavilberg, Ben-Gurion University of the Negev, Israel

15:40 Coffee break (1911 Lounge)

16:10 (i) **Double-sided coaxial circuit QED for quantum computing**
Peter Leek, University of Oxford, UK

16:40 **Analog quantum simulation of the Rabi model in the ultra-strong coupling regime**
Martin Weides, University of Glasgow, UK

17:00 **End of Meeting**

Poster programme
1911 Lounge

P1. Tuning across universalities with a driven open condensate
Alejandro Zamora, University College London, UK

P2. Searching for the KPZ phase in microcavity polaritons
Alexander Ferrier, University College London, UK

P3. Can coherently driven microcavity-polaritons be a superfluid?
Richard Juggins, University College London, UK

P4. Effecting spontaneous coherence in hybridised cavity-spin ensemble systems with incoherent driving
Rhonda Au Yeung, University of Surrey, UK

P5. Superconducting quantum circuits with Majorana fermions
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P6. Phases of driven dissipative atomic dipoles with nonlocal dissipation
Christopher Parmee, University of Cambridge, UK

P7. Tricritical behavior in the Chern-Simons-Ginzburg-Landau theory of Josephson junction arrays
Said Sakhi, American University of Sharjah, UAE

(i) Topological photonics: From integer to fractional quantum Hall effects with light

I Carusotto

INO-CNR BEC Center, Italy

In this talk I will outline the latest developments in the theoretical and experimental study of topological and magnetic effects in optical systems.

I will start by discussing optical analogs of the integer quantum Hall effect in a linear optical context. Experiments highlighting topologically protected edge states and the geometrical and topological properties of the bulk bands will be presented, with an eye towards new wave mechanics effect that stem from the Berry curvature seen as a momentum-space magnetic field.

I will then introduce the general idea of synthetic dimensions: by exploiting the mode index in multimode cavities as an extra degree of freedom, high ($d>3$) dimensional photonic systems may be realized using state-of-the-art photonic technology. Experimentally accessible consequences of higher topological invariants of high-dimensional bands will be presented.

I will conclude with a summary of the on-going developments in the direction of generating strongly correlated states of light in strongly nonlinear media, in particular fractional quantum Hall liquids of light.

(i) Topological properties of cavity polaritons in 1D lattices

J Bloch

CNRS/Université Paris Sud, France

Semiconductor microcavities appear today as a powerful platform for the generation of quantum fluids of light with imprinted topological properties. The strong confinement of both light and electronic excitations (excitons) in very small volumes gives rise to the formation of hybrid light-matter quasi-particles named cavity polaritons. Their photonic part allows for engineering of lattices of coupled resonators with peculiar topological properties, while their excitonic part gives rise to Kerr-like nonlinearities and to lasing through stimulated relaxation. Measuring photon leaking out from the cavity lattices allows direct visualization of the polariton band structure, their eigenmodes and potentially their edge states.

Two recent experiments illustrate the potential of this non-linear photonic platform. 1) We have fabricated a Fibonacci polariton quasi-crystal and evidenced a fractal band structure with distinct edge states. The winding number of these edge states, associated to topological invariants, could be directly measured by varying a structural parameter named phason [1]. 2) We have implemented a SSH topological chain of coupled micropillars and demonstrated lasing on a topological edge states. Because of its topological origin, the lasing mode presents strong robustness against perturbations [2].

By controlling the interplay between pump, on-site nonlinearity and dissipation, this photonic platform opens the way to the exploration of non-linear topological physics and in a near future quantum many body physics with light.

[1] F. Baboux,et al., Phys. Rev. B 95, 161114(R) (2017) 2017
[2] P. St-Jean, et al., Nature Photonics 11, 651 (2017)

Hybrid Nb-InGaAs 2DEG-Nb ballistic Josephson junctions for scalable topological quantum processing

K Delfanazari[1], P Ma[1], T Yi[1], M Cao[1], R Puddy[1], Y Gul[2], I Farrer[3], H Joyce[1], D Ritchie[1], M Kelly[1] and C Smith[1]

[1]University of Cambridge, UK, [2]University College London, UK [3]University of Sheffield, UK

Here, we demonstrate an on-chip, integrated and scalable hybrid superconducting-semiconducting quantum circuit and discuss the coherent quantum transports in such system at temperature ranges between 35 mK and 800 mK [1]. Furthermore, we present the first experimental results on quantum interference effects in simply connected superconductor-2DEG junctions that lead to the observation of periodic magnetoconductance oscillations, analogous to Aharonov-Bohm interference effect in a small ring, in low orthogonal magnetic fields [2].

[1] K. Delfanazari, et al., Adv. Mater. 29, 1701836 (2017)
[2] K. Delfanazari, et al., Submitted (2018)

Topological properties of a dense atomic lattice gas

B Olmos[1], I Lesanovsky[1], J Minar[1], C Adams[2] and R Bettles[2]

[1]University of Nottingham, UK [2]Durham University, UK

We investigate the existence of topological phases in a dense two-dimensional atomic lattice gas. The coupling of the atoms to the radiation field gives rise to dissipation and a non-trivial coherent long-range exchange interaction whose form goes beyond a simple power-law. The far-field terms of the potential -- which are particularly relevant for atomic separations comparable to the atomic transition wavelength -- can give rise to energy spectra with one-sided divergences in the Brillouin zone. The long-ranged character of the interactions has another important consequence: it can break of the standard bulk-boundary relation in topological insulators. We show that topological properties such as the transport of an excitation along the edge of the lattice are robust with respect to the presence of lattice defects and dissipation. The latter is of particular relevance as dissipation and coherent interactions are inevitably connected in our setting.

(i) Enhancement of polariton interactions using fractional quantum Hall states

A Imamoglu, S Ravets and P Knuppel

ETH Zurich, Switzerland

Fractional quantum Hall states (FQHE) in two-dimensional electron systems (2DES) are topologically ordered states exhibiting long-range entanglement and anyonic quasi-particles. While transport measurements exclusively probe their chiral edge states associated, optical spectroscopy allow for investigation of the bulk properties.

In this talk, I will describe experiments where a GaAs 2DES is embedded inside a high quality-factor microcavity: the elementary optical excitations in such a system are polaritons that are dressed by density-wave excitations out of the FQHE ground-state, termed polaron-polaritons. We have studied linear and nonlinear optical properties of polaron-polaritons as a function of lowest Landau level filling factor. Remarkably, we have found that polariton-polariton interactions can be enhanced by more than an order of magnitude when the 2DES is tuned into FQHE states with filling factors $\nu=2/5$ and 2/3.

(i) Polariton polarization effects in 2D Lieb lattice and 1D topological zigzag chain of photonic microcavities

D Krizhanovskii

University of Sheffield, UK

Exciton-polaritons in microcavities have emerged as an attractive candidate for studying interacting bosons in lattice potentials. Giant nonlinearity and a small effective mass allow Bose-Einstein condensation at elevated temperatures, and the spatial, spectral and pseudospin (polarization) properties of the polaritons are directly accessible. The Lieb lattice is at the forefront of research into fundamental effects in condensed matter physics. The characteristic flat bands of the system allow high-Tc superconductivity, exotic ferromagnetism and a wealth of topological phases. 1D zizzag chain with alternating hopping coefficients permits emulation of the Su-Schrieffer-Heeger (SSH) model, which is an important paradigm of topological physics.

We optically load high-density polaritons into the 2D Lieb lattice, observing condensation into two separate flat bands associated with photonic “orbitals” of S- and P-like symmetries. Flat-band condensates reveal pseudospin textures due to an effective photonic spin-orbit coupling term, which arises from polarization sensitive polariton tunneling rate. Furthermore, strong interactions lead to a spatially inhomogeneous spectral fragmentation, showing the high sensitivity of flat-band particles to interactions.

What concerns 1D polariton lattices experimentally, measurement of photonic topological invariants and demonstration of topological 0D edge modes in zigzag chains has been reported. Here, we realize a novel four-component version of SSH model featuring the polarization effects due to polarisation dependent polariton tunnelling and TE-TM splitting of the photonic modes. We develop a generalized tight binding description of our system and take polarization-resolved spectroscopic measurements to delineate the contributions of the two effects on the spatial and spectral profiles of topological edge states.

Static and dynamic lattices for microcavity polaritons

P Santos, A Kuznetsov, P Helgers, J Buller, K Biermann and A Tahraoui

Paul-Drude-Institut für Festkörperelektronik, Germany

Microcavity exciton-polaritons (MPs) are quasi-particles resulting from the strong coupling between photons in a microcavity (MC) and quantum well (QW) excitons embedded in it. Due to their hybrid matter/light character, MPs have a low effective mass and, therefore, de Broglie wavelengths reaching several mu. The realization of quantum functionalities with MPs requires the control of the energy and spatial overlap of the wave functions of single MPs trapped in potentials with precisely controlled shape and size. The long de Broglie wavelengths make it possible to control MPs and form MP lattices using mm-sized potentials. In this talk, we demonstrate the confinement of MPs in traps with effective lateral sizes down to 1 μm produced by patterning the active region of the (Al,Ga)As MC in between two molecular beam epitaxy (MBE) growth runs. We correlate structural information about the lateral interfaces of the patterned areas with the energy and wave functions of confined MP states obtained by spatially resolved optical spectroscopic. We show that sharpness of the lateral trap interfaces is limited by the anisotropic overgrowth process to a minimum width of approx. 1 mu. The structuring method is suitable for the fabrication of lattices of proximal traps with negligible site disorder and supporting hybridization between adjacent lattice sites. In such arrays, the wave function of MP condensates extends over several lattice sites. Finally, we show that the lattice potentials can be modulated by electrically generated surface acoustic waves, which allows for the dynamic control of the lattice potential.

(i) Topological states in the strong-coupling limit

K Le Hur

Ecole Polytechnique and CNRS, France

In this presentation, we discuss our progress on topological states in several directions bridging between materials, circuit QED, Josephson junctions and ultra-cold atom systems. Specific recent examples of interest to us in the “strong-coupling limit” are related to quantum Hall physics of bosons close to a Mott phase [1], the Su-Schrieffer-Heeger [2] and quantum spin models [3]. We address in more details a superconducting box to engineer Z2 Kitaev quantum spin liquids and many-body Majorana states with some applications in codes [4]. Light-matter systems and time-dependent protocols allow to implement and probe novel topological states.

[1] Alexandru Petrescu, Marie Piraud, Guillaume Roux, I. P. McCulloch, Karyn Le Hur, Phys. Rev. B 96, 014524 (2017)
[2] Tal Goren, Kirill Plekhanov, Félicien Appas, Karyn Le Hur, Phys. Rev. B 97, 041106 (2018).
[3] Kirill Plekhanov, Ivana Vasić, Alexandru Petrescu Rajbir Nirwan, Guillaume Roux, Walter Hofstetter, Karyn Le Hur arXiv:1707.07037
[4] Fan Yang, Loïc Henriet, Ariane Soret, Karyn Le Hur, arXiv:1801.05698

Single-photon ps-correlations of exciton-polariton emission in acoustic lattices

A Kuznetsov, K Biermann and P Santos

Paul-Drude-Institut für Festkörperelektronik, Germany

Microcavity (MC) exciton-polaritons (MPs) are bosonic quasi-particles resulting from the strong coupling between the MC photons and quantum wells excitons. Being light-mass composite bosons, characterized by de Broigle-wavelength of several µm, EPs may undergo Bose–Einstein-like condensation (BEC). Lattices of interacting quantum-confined MPs have been suggested for all-optical circuitry and quantum-applications. Such lattices may be created by µm-scale static lateral-modulation of the MC thickness [1] or by periodic acoustic strain modulation [2]. Details of interactions in such arrays are difficult to address due to the extremely short time-scale, limited by MC photon lifetime to ps-range. In the present work we investigate the dynamics of exciton-polariton condensates (EP) in tunable square lattices formed by interference of two orthogonal surface acoustic waves in a GaAs-based microcavity, Fig. 1(a). These lattices support gap soliton (GS) MPs BEC-condensates at high symmetry M-points of the lattice, which emit angularly separated narrow light beams, Fig. 1(b,c). Their time-traces show acoustic modulation of the intensity and wave function of GS, Fig. 1(d). One interesting question is, whether the photons emitted as GS beams are correlated in time. Despite originating from the same optical-pump state the emission of the GS from different M-points is uncorrelated, as evidence by the second order single-photon cross-correlation value $g^{(2)} = 1$ down to 10 ps. The time-resolved photoluminescence technique may be straightforwardly applied for studies of dynamics and correlations in arbitrary lattices both in momentum- and real-space.

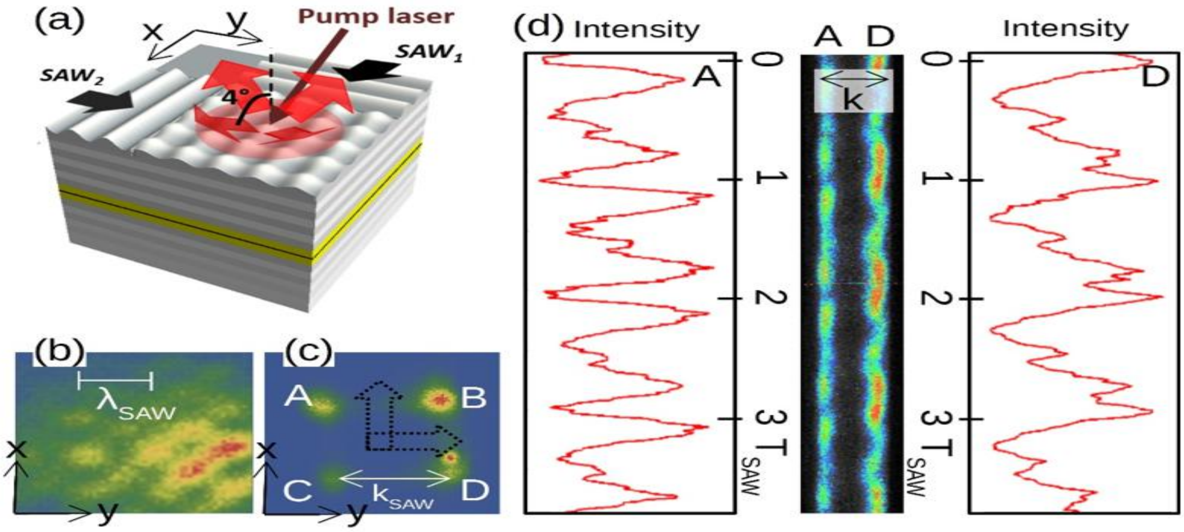

Fig. 1. (a) A schematic of an exciton-polariton (MPs) microcavity (MC). Alternating gray layers at the bottom and top are distributed Bragg reflectors (DBRs). Sandwiched between the DBRs is the cavity spacer with embedded quantum wells (in black). SAW_1 and SAW_2 designate orthogonal surface acoustic waves (SAWs) forming a square potential lattice. Excitation of EPs condensate is carried out close to the condensation threshold in the optical parametric oscillator configuration, represented by a dark-brown arrow. The four red arrows designate emission of MPs gap-solitons (GS). (b) Time-integrated real-space image of GS emission, showing square lattice due to SAWs. The blurred spots are separated by $\lambda_{SAW}/\sqrt{2}$, where $\lambda_{SAW} \approx 8$ μm is the SAW wavelength. (c) Time integrated momentum-space image of GS emission. The small size of the spots (A, B, C and D) corresponds to the narrow angular distribution of emission. The dashed black arrows indicate the SAW propagation directions. k_{SAW} designates the magnitude of SAW wavevector. (d) Middle panel: accumulated streak camera image of 50000 single sweeps of the A-D pair of GS spots in (c); time resolution ≈ 10 ps. Right and left panels show intensity profiles along the time axis in periods of the SAW ($T_{SAW} \approx 2.7$ ns). SAW-induced modulation of the emission of A and D spots of MPs GS is clearly seen.

[1] R.I.Kaitouni et al., *Phys.Rev.B*, **74**, 1–8(2006)
[2] E.A.Cerda-Méndez et al., *Phys.Rev.Lett.*, **105**, 116402(2010)

Topological phases in the non-Hermitian Su-Schrieffer-Heeger model

S Lieu

Imperial College London

We address the conditions required for a Z topological classification in the most general form of the non-Hermitian Su-Schrieffer-Heeger (SSH) model. Any chirally symmetric SSH model will possess a “conjugated-pseudo-Hermiticity” which we show is responsible for a quantized “complex” Berry phase. Consequently, we provide an example where the complex Berry phase of a band is used as a quantized invariant to predict the existence of gapless edge modes in a non-Hermitian model. The chirally broken, PT-symmetric model is studied; we suggest an explanation for why the topological invariant is a global property of the Hamiltonian. A geometrical picture is provided by examining eigenvector evolution on the Bloch sphere. We justify our analysis numerically and discuss relevant applications.

(i) Synthetic spin orbit interaction for Majorana devices

T Kontos

CNRS/ENS, France

In this talk, I will show how we combine superconducting contacts with a magnetic texture proximal to a carbon nanotube. We demonstrate a large synthetic spin orbit interaction which deeply modifies the induced superconducting correlations in the carbon nanotube. We also observe a zero bias conductance peak which is the hallmark of Majorana zero modes. Our findings could be used for advanced experiments, including microwave spectroscopy and braiding operations.

(i) Driven nonlinear cavities for quantum computation and simulations

S Puri

Yale University, USA

Kerr-nonlinear cavities are characterized by photon-photon interactions and display rich physics when the nonlinearity is stronger than the dissipation. For example, they are useful for realizing nonclassical states of light and quantum simulations of many-body systems. Progress in superconducting circuits has led to development of Josephson junctions and microwave cavities with long lifetimes. As a result, it is possible to achieve strong Kerr nonlinearities in a superconducting platform. In this talk, I will introduce a novel device based on a pumped Kerr nonlinear cavity which allows realization of a stabilized photonic cat state. These photonic cat states are important for understanding the role of decoherence in macroscopic systems, in precision measurements and hardware-efficient quantum computation. Moreover, I will also discuss how a network of such driven nonlinear cavities can be used for simulations of frustrated spin systems. The continuous variable nature of the states in the large Hilbert space of the cavity provides new opportunities for exploring quantum phase transitions in many-body systems.

(i) On-chip microwave spectroscopy: The toolset to identify topological superconductivity

A Geresdi

QuTech, Delft University of Technology, The Netherlands

Narrow gap semiconductors, such as InAs and InSb have become the most studied platform of topological superconductivity and Majorana zero modes (MZMs) due to their strong spin-orbit coupling, large Landé g-factor and the possibility of inducing superconductivity with highly transparent Ohmic contacts to bulk superconductors.

We utilize a superconducting tunnel junction as an on-chip microwave generator to investigate the essential building blocks of prospective topological quantum bits. By exploiting the AC Josephson effect, we map the excitations of nanowire Josephson junctions up to 90 GHz bounded by the superconducting gap of the generator. With this technique, we show the presence of gate-tunable Andreev bound states in a ballistic semiconductor channel for the first time, and demonstrate how an external magnetic field influences the spectrum in the presence of strong spin-orbit coupling, relevant for the search of Majorana bound states. In addition, we demonstrate that the microwave generator has a profound influence on the poisoning dynamics of Cooper-pair transistors made of InAs nanowires, the atomic building blocks of braiding and fusion schemes.

(i) Topology and adiabatic limit in slowly driven quantum systems

B Seradjeh and M Rodriguez-Vega

Indiana University – Bloomington, USA

A periodically-driven quantum system can exhibit essentially non-equilibrium, Floquet topological phases. The topological indices of these phases can be tuned by drive parameters, such as the frequency, the amplitude, or the shape of the drive. While this behavior is well-understood for fast drives within high-frequency approximations, the situation under a slow drive remains largely unexplored. To understand this regime, we have studied the low-frequency dynamics of prototypical driven one-dimensional models, including the driven Su-Schrieffer-Heeger and Kitaev models, of Floquet topological insulators and superconductors. We find that at low frequencies, the Floquet topological indices not only remain nonzero, but fluctuate. Over a small frequency range, these fluctuations have a universal Gaussian distribution with a width that grows as inverse-square-root of the drive frequency. We explain this universal behavior by revealing a diffusive structure in the winding numbers of the Floquet-Bloch evolution operator, and confirm our results numerically. Thus, we argue that the adiabatic limit of Floquet topological phases is highly structured, with universal fluctuations persisting down to very low frequencies.

Interacting topological insulators: The Su-Schrieffer-Heeger-Hubbard model for dopants in silicon

N Le[1], A Fisher[2] and E Ginossar[1]

[1]University of Surrey, UK [2]University College London, UK

We study the effect of short-range and long-range interactions on the Su-Schrieffer-Heeger (SSH) model. Such interactions are expected for a realization of the model with dopants in silicon. We study the addition energy spectrum and the spatial extent of the bulk and edge states in the non-trivial phase at various strength of interaction. When the Hubbard-U is increased, we observe an anti-crossing of the addition energy levels and the edge states are filled at quarter-filling instead of half-filling which is the case for the non-interacting SSH model. Entanglement entropy and spin correlation of the edges and bulk states are computed for revealing how their properties change across the topological phase transition in the presence of the interactions. Possible experimental realizations based on quantum dots and dopants are discussed, with an emphasis on identifying the edge states by transport measurement.

(i) Hybrid Dirac photons in topological orbital lattices

A Amo

PhLAM - CNRS - Université de Lille, France

The recent discovery of new types of Dirac dispersions in condensed matter physics has open the box of "Dirac engineering": the manipulation of the transport and magnetic properties of electrons by heterostructuring materials with different types of Dirac cones. Here we use orbital polariton lattices to take this idea into the photonic realm [1, 2]. By tailoring the local photonic hoppings we realise experimentally different types of Dirac cones combining zero, finite and infinite effective masses for photons. This hybrid Dirac cones are related to topological phase transitions in the photonic lattice, characterised by different winding numbers.

These results provide a new route to the manipulation of photon transport on a chip, and open the door to study the physics of Lifshitz transitions, including the recently proposed implementation of black hole analogues in Dirac materials [3].

[1] T. Jacqmin *et al.*, Direct Observation of Dirac Cones and a Flatband in a Honeycomb Lattice for Polaritons. *Phys. Rev. Lett.* **112**, 116402 (2014)

[2] M. Milićević *et al.*, Orbital Edge States in a Photonic Honeycomb Lattice. *Phys. Rev. Lett.* **118**, 107403 (2017)

[3] G. E. Volovik, Black hole and hawking radiation by type-II Weyl fermions. *JETP Lett.* **104**, 645–648 (2016)

(i) Superconducting quantum simulator for topological order and the Toric code

M Hartmann[1], M Sameti[1], A Potocnik[2], D Browne[3], A Wallraff[2] and M Sameti[1]

[1]Heriot-Watt University, UK [2]ETH Zurich, Switzerland [3]University College London, UK

Topological order is now being established as a central criterion for characterizing and classifying ground states of condensed matter systems and complements categorizations based on symmetries. Fractional quantum Hall systems and quantum spin liquids are receiving substantial interest because of their intriguing quantum correlations, their exotic excitations and prospects for protecting stored quantum information against errors.

In this talk I will discuss our recent approach for implementing the Hamiltonian of the central model of this class of systems, the Toric Code, in lattices of superconducting circuits. The four-body interactions, which lie at its heart, are in our concept realised via Superconducting Quantum Interference Devices (SQUIDs) driven by a suitably oscillating flux bias. All physical qubits can be individually controlled and strings of operators acting on them, including the stabilizers, can be read out via a capacitive coupling to common transmission line resonators. The architecture we propose thus provides a versatile quantum simulator for topological order and lattice gauge theories.

Quantum Spin Hall effect analog for vortices in an interacting bosonic quantum fluid

D Solnyshkov, O Bleu and G Malpuech

University Clermont Auvergne, France

Topologically protected pseudospin transport, analogous to the quantum spin Hall effect, cannot be strictly implemented for photons and in general bosons because of the lack of pseudospins protected by Time-Reversal symmetry. We show [1] that the required protection can be provided by the real-space topological excitation of an interacting quantum fluid: a quantum vortex. We consider a Bose-Einstein condensate at the Gamma point of the Brillouin zone of a quantum valley Hall system based on two staggered honeycomb lattices. We demonstrate the existence of a coupling between the winding number of a vortex and the valley of the bulk Bloch band. This leads to chiral vortex propagation on each side of the zigzag interface between two regions of inverted staggering. The topological protection provided by the vortex winding prevents valley pseudospin mixing and resonant backscattering on one side the interface. It makes of the valley Chern number a meaningful topological index, and allows a truly topologically protected valley pseudospin transport, contrary to the interface states of the non-interacting Hamiltonian.

This configuration can be seen as a quantum spin Hall effect analog, but where the role of spin is played by the winding of the vortices. Our results illustrate the unique behaviour of bosonic quantum fluids located in topologically non-trivial periodic structures.

It can apply to polariton condensates in recently fabricated polariton honeycomb lattices, atomic BECs in optical lattices and other interacting quantum fluids.

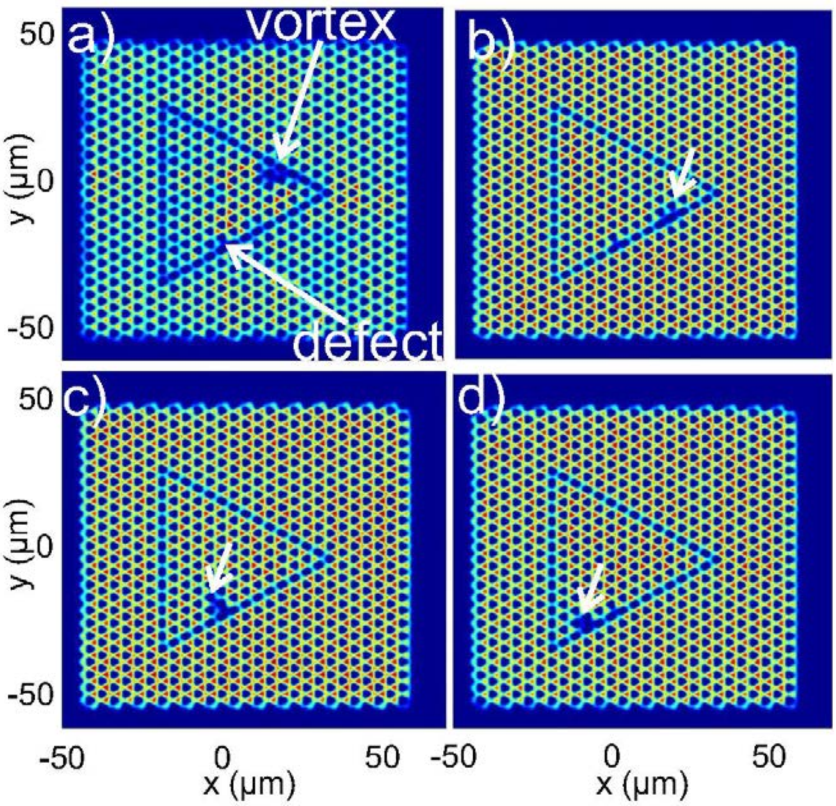

Figure 1. Snapshots of vortex propagation along the interface

[1] O. Bleu et al, arXiv:1709.01830 (2017)

A novel platform for quantum optics and quantum information using topological insulator nanostructures

M Rider, V Giannini, P Haynes and D Lee

Imperial College London, UK

Topological insulators (TIs) are a distinctive class of materials, which are insulating in the bulk but support topologically protected conducting surface states. Since their discovery, most work on these materials has focused on their electronic properties, whilst their interaction with electromagnetic fields has largely been untouched. In small topological insulator nanoparticles (TINP) such as those studied by Siroki et al [1], the dispersion relation of the topological surface states is no longer continuous but discretized. By studying the optical transition properties between these states we explore their use as a lasing system and for qubit storage. These properties can be tuned by varying particle size, light frequency and light polarization, providing a toolbox for quantum optics and quantum information technologies. This system has multiple length-scales, from the μm-mm wavelength of the light, nm radius of the TINPs and Angstrom decay length of the surface states. The disparate scales of the nanoparticle radius and light wavelength allows for a quasi-classical approach, treating the incident light classically and the electronic states of the nanoparticle quantum mechanically.

[1] G Siroki, D.K.K. Lee, P.D. Haynes 2016 *Nature Comms* Vol, 7-12375

(i) The dispersive ultra-strong coupling regime between two bosonic fields and is applications

P Lorgere[1], S Felicetti[2], A Keller[3], T Coudreau[2], B Huard[1], D Markovic[4] and S Fedortchenko[2]

[1]CNRS, France [2]Universite Paris Diderot, France [3]Universite Paris Sud, France, [4]Ecole Normale Superieure, France

The ultra-strong coupling regime between two bosonic fields can lead to a number of interesting quantum optical phenomena in a broad range of energy scales. Consequently, it can both serve as a tool for applications, as for instance metrological ones, and to the study of fundamental aspects of quantum physics, as entanglement. In the present talk, we will discuss the generation of non-classical light by dynamical modulation of the coupling strength between two non-resonant bosonic fields ultra-strongly coupled in different contexts, leading to a variety of applications, such as the generation of non-classical light in the infra-red regime and quantum communications. We will also discuss how this difficult to control interaction can be successfully simulated in a superconducting device, together with some recent experimental results.

(i) Random access quantum information processors using multimode circuit quantum electrodynamics

S Chakram

University of Chicago, USA

A multimode superconducting cavity coupled to a single superconducting transmon circuit can be used to realize quantum information processors in which logic gates between arbitrary pairs of cavity modes can be performed with equal ease using sideband transitions with the transmon. We describe the implementation of a such a random access superconducting quantum information processor [1], with a single superconducting transmon qubit serving as the central processor, and the quantum memory comprised of the eigenmodes of a linear array of coupled superconducting resonators. We selectively stimulate vacuum Rabi oscillations between the transmon and individual eigenmodes through parametric flux modulation the transmon frequency, using it to perform a universal set of quantum gates on 38 arbitrary pairs of modes and prepare multimode entangled states, using only two control lines. We describe our progress towards realizing such processors using novel seamless 3D multimode cavities, with a tailored mode spectrum and single-photon lifetimes on the order of a millisecond. The fast and flexible control, achieved with efficient use of cryogenic resources and control electronics,in a scalable architecture compatible with state-of-the-art quantum memories, is promising for quantum computation and simulation.

[1] R. Naik, N. Leung, S. Chakram, P. Groszkowski, Y. Lu, N. Earnest, D. McKay, J. Koch, and D. Schuster, Nature communications (2017).

(i) 2D polariton lattices designed for Dirac-cone and flatband dispersions: A versatile platform for topological photonics

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Exciton-polaritons have emerged as a powerful system to study the collective behavior of microscopic coherent quantum states in a solid state environment as they fulfill a range of important prerequisites. The technical possibility to engineer polariton trapping potentials with a tunable tunnel coupling between single traps by elaborated lithography and etching techniques has triggered the interest in using polaritonic systems to emulate the physics of e.g. graphene, high-temperature superconductors, or frustrated spin lattices.

Recently, artificial lattices emulating graphene and related two-dimensional materials have attracted particular attention due to the unique properties of honeycomb lattices that allow for simulation of e.g. Dirac physics and topologically non-trivial states. This goes along with an increased effort to mimic topological electronic phases like the Quantum Hall and spin quantum Hall effect in photonic systems.

In our study, we use a GaAs-based high-Q microcavity fabricated by molecular beam epitaxy. We make use of an etch-and-overgrowth technique to create a 2D Lieb lattice potential landscape for exciton-polaritons that we study by angular resolved photoluminescence spectroscopy in real and Fourier space. Under suitable excitation conditions, we observe polariton condensation in a flatband-like state. In addition, we demonstrate and investigate Dirac-cone dispersions in Lieb as well as Honeycomb lattices using a hyper-spectral imaging approach to map out the full first Brillouin zone.

(i) Topological multi-terminal Josephson junctions

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Topological phases of matter have attracted much interest in recent years. Starting with gapped phases such as topological insulators and superconductors, more recently gapless topological phases possessing topologically protected band crossings have been discovered. Here we show that n-terminal Josephson junctions may provide a straightforward realization of tunable topological materials in n-1 dimensions, the independent superconducting phases playing the role of quasi-momenta. In particular, we find Weyl points in the Andreev bound state spectrum of 4-terminal junctions, both with conventional superconductors and with topological superconductors. The topological properties of the junction may be probed experimentally by measuring the transconductance between two voltage-biased leads, which we predict to be quantized: in units of $4e^{\wedge 2}/h$ in the case of conventional superconductors and in units of $2e^{\wedge 2}/h$ in the case of topological superconductors. Further, the analogy between the spectrum of Andreev bound states in an n-terminal Jospehson junction and the bandstructure of an n-1-dimensional material opens the possibility of realizing topological phases in higher dimensions, not accessible in real materials.

Optical chern insulators from conical refraction

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We develop a theory of the index surfaces of two-dimensional photonic crystals, and show that this provides a novel approach to the realization of topologically non-trivial photonic bandstructures. Conventional approaches rely on degeneracies associated with specific photonic lattices, such as photonic graphene. In contrast, we show that photonic spin-orbit coupling can be harnessed to generate an optical Chern insulator. We consider specifically biaxial materials, whose refractive index surfaces host polarisation degeneracies which are exact analogues of Dirac points. We show that in a 2D photonic crystal these Dirac points can be split to achieve a topologically non-trivial index surface. We demonstrate this by analysing the effective Hamiltonian which propagates the field through the structure in the paraxial limit, and show that such a theory agrees qualitatively with a full frequency-domain plane-wave simulation. This suggests that topological photonic bands can be achieved generally in optical materials with spin-orbit coupling, opening the path to exploring interacting topological phases in the nonlinear case.

Hybridization of bound states in a TSC/TI/TSC junction

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It has been shown previously that a highly isolated and coherent qubit can be engineered by combining a topological superconducting Josephson junction with a microwave resonator into a device known as the Majorana-Transmon. Here we consider a related device where a topological insulator nanowire of type Bi2Se3 is proximitized to an s-wave Josephson junction. The resulting system is a topological superconducting junction with a topological insulator as the weak link. The Bi2Se3 nanowire is known for its significant surface states bandwidth and thus is an ideal candidate for a realization of the topologically protected Majorana edge states.

We investigate the low energy Andreev bound states and the accompanying Majorana edge states residing in the junction. The hybridization between these states has a notable effect on the fermionic parity of the superconductors, and as a result on the dipole coupling between the junction and the cavity, which is evident in its electromagnetic signatures.

(i) Double-sided coaxial circuit QED for quantum computing

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Superconducting circuits are well established as a leading platform for the development of universal quantum computers. In order to advance to a practically useful level, architectures are needed which combine arrays of many qubits with selective qubit control and readout, without compromising on coherence. The strong coupling of superconducting qubits to microwave resonators, realising circuit quantum electrodynamics (QED), has been demonstrated to be a powerful architecture for controlling qubit coherence and implementing coupling and readout of qubits, however the circuit layout required to scale to many qubits rapidly becomes very complex. In this talk I will present our work on a coaxial version of circuit QED [1] in which qubit and resonator are fabricated on opposing sides of a single chip, and control and readout wiring are provided by coaxial wiring running perpendicular to the chip plane, providing a potentially simple route to scaling to grids of many qubits.

[1] Rahamim et al., Applied Physics Letters 110, 222602 (2017)

Analog quantum simulation of the Rabi model in the ultra-strong coupling regime

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The quantum Rabi model describes the fundamental mechanism of light-matter interaction. It consists of a two-level atom or qubit coupled to a quantized harmonic mode via a transversal interaction. In the weak coupling regime, it reduces to the well-known Jaynes–Cummings model by applying a rotating wave approximation. The rotating wave approximation breaks down in the ultra-strong coupling regime, where the effective coupling strength g is comparable to the energy ω of the bosonic mode, and remarkable features in the system dynamics are revealed. Here we demonstrate an analog quantum simulation of an effective quantum Rabi model in the ultra-strong coupling regime, achieving a relative coupling ratio of $g/\omega \sim 0.6$. The quantum hardware of the simulator is a superconducting circuit embedded in a cQED setup. We observe fast and periodic quantum state collapses and revivals of the initial qubit state, being the most distinct signature of the synthesized model [1].

[1] Braumueller et al., Nature Communication, 8: 779 (2017)

Posters

P1. Tuning across universalities with a driven open condensate

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Driven-dissipative systems in two dimensions can differ substantially from their equilibrium counterparts. In particular, a dramatic loss of the algebraic order and superfluidity has been predicted to occur due to the interplay between coherent dynamics and external drive and dissipation in the thermodynamic limit.

We show that the order which can be adopted is, remarkably, not an intrinsic property of the system alone but can be decided by the parameters of the driving process, easily tuned in current experiments.

By considering the long-wavelength phase dynamics of a polariton system in the optical parametric oscillator regime, we demonstrate that simply tuning the pump strength can substantially change the effective spatial anisotropy, driving the system into distinct scaling regimes:

(i) the classic algebraically ordered below the Berezinskii-Kosterlitz-Thouless transition, as in equilibrium; (ii) the nonequilibrium Kardar-Parisi-Zhang phase; and the two disordered topological defects dominated phases caused by (iii) entropic BKT vortex-antivortex pairs or (iv) repelling vortices in the KPZ phase.

Our findings highlight the importance of the driving mechanism in establishing the relevant order of collective light-matter systems, shining a new light on the ongoing debate about their phases.

P2. Searching for the KPZ phase in microcavity polaritons

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Due to their driven-dissipative nature, microcavity polaritons in two dimensional quantum wells can exhibit collective quantum behaviour which differs from equilibrium systems. Particularly, recent studies [1] show that they can fall into the Kardar-Parisi-Zhang (KPZ) universality class, characterized by a stretched exponential decay of the first order spacial correlation function. Unfortunately, the length scales at which the signatures of this phase should become visible are usually much larger than the typical system sizes of current experiments, and may also be preempted by a vortex-dominated phase characterized by repelling vortices [2]. However, within the optical parametric oscillator (OPO) regime, an interesting region of pump powers has been found where the KPZ phase could become observable at accessible length scales [3]. We now study this interesting subsection of the OPO region using numerical simulations based on a truncated Wigner representation of the polariton field, which provide a much more accurate model of the full behaviour of experimental systems, to determine whether the characteristic stretched exponential decay of spacial correlations in the KPZ phase can be observed when going beyond the approximations of the previous analytical studies.

[1] E. Altman, L. M. Sieberer, L. Chen, S. Diehl and J. Toner, Phys. Rev. X 5 011017 (2015)
[2] G. Wachtel, L. M. Sieberer, S. Diehl, and E. Altman, Phys. Rev. B 94 104520 (2016)
[3] A. Zamora, L. M. Sieberer, K. Dunnett, S. Diehl, and M. H. Szymańska, Phys. Rev. X 7 041006 (2017)

P3. Can coherently driven microcavity-polaritons be a superfluid?

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Due to their driven-dissipative nature, photonic quantum fluids present new challenges in understanding superfluidity. Some associated effects have been observed, and notably the report of nearly dissipationless flow for coherently driven microcavity-polaritons was taken as a 'smoking gun' for superflow. Here we show that the superfluid response --- the difference between responses to longitudinal and transverse forces --- is zero for coherently driven polaritons. This is a direct consequence of the gapped excitation spectrum caused by external phase locking. Furthermore, while a normal component exists at finite pump momentum, the remainder forms a rigid state that does not respond to either longitudinal or transverse perturbations. Interestingly, the total response almost vanishes when the real part of the excitation spectrum fulfils the Landau criterion, which was the regime investigated experimentally. This suggests that the observed suppression of scattering should be interpreted as a sign of this new rigid state and not of a superfluid.

P4. Effecting spontaneous coherence in hybridised cavity-spin ensemble systems with incoherent driving

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Ex nihilo nihil fit. Nothing comes of nothing, as they say. Now the plan is to consider the possibility to contradict this philosophy with nonequilibrium condensation phenomena. Can we develop spontaneous coherence in a driven-dissipative quantum cavity system? A pumping bath adds energy into the cavity by coupling to the fermionic levels of a two-level system (TLS). Energy is passed to photons by dipole-coupling, which leak into the decay bath. While such losses are normally compensated by laser pumping, we now weaken this mechanism. Can the decay bath develop spontaneous coherence in the cavity?

We use Keldysh technique to explore the Tavis-Cummings system [1]. The aim is to realise spontaneous coherence in the system (in the spirit of BECs) following incoherent driving. To implement the mechanism, incoherent photon fluctuations from the decay bath are included in the analysis, in addition to coherent photon dynamics. The strategy would ensure that the effective Keldysh action describing the system contains additional terms or alterations to the expression in which only coherent photons are considered [2]. As well as searching for exotic nonequilibrium phase transitions, it is possible to experimentally verify any observations with hybrid quantum structures. These may comprise a superconducting resonator coupled strongly to crystalline impurity spin centres in diamond [3].

[1] Kamenev, *Field Theory of Non-Equilibrium Systems*, Cambridge University Press (2011)
[2] H. Szymańska et al, Phys. Rev. B **75**, 195331 (2007)
[3] I. Schuster et al, Phys. Rev. Lett. **105**, 140501 (2010)

P5. Superconducting quantum circuits with Majorana fermions

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The theory and the engineering of the Transmon qubit [1] was the first step toward the creation of a 2-level system which is suitable for Quantum Computing and more robust than the previous Cooper Pair Box against some decoherence effects [2]. Recently, the study of Topological states of matter and in particular Majorana Fermions in Topological 1D Superconductors has led to new ideas about the exploitation of these quasi-particles in hybrid Superconducting circuit devices [3, 4]. In this poster I present my first studies about the advantages of using these topological hybrid devices instead of the Transmon qubits, about the decoherence effects affecting them and about their possible gates operations.

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[3] J. Q. You, Z. D. Wang, W. X. Zhang and F. Nori, Sci. Rep. 4, 5535; DOI:10.1038/srep05535 (2014).
[4] K. Yavilberg, E. Ginossar and E. Grosfeld, Phys. Rev. B 92 (7), 075143 (2015).

P6. Phases of driven dissipative atomic dipoles with nonlocal dissipation

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We study an open quantum system of cold atoms illuminated by an external plane wave, which drives the dipolar transition between two energy levels. In this set up, the cold atoms map to a two-level spin system with long range interactions and nonlocal dissipation. We determine at the mean-field level the long-time phase diagram of the system as a function of external drive and detuning. We find a multitude of phases including antiferromagnetism, spin density waves, oscillations and phase bistabilities. We investigate some of these phases in more detail and explain how nonlocal dissipation plays a role in the long time dynamics. Furthermore, we discuss what features would survive in the full quantum regime.

P7. Tricritical behavior in the Chern-Simons-Ginzburg-Landau theory of Josephson junction arrays

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We study a U(1)×U(1) model in 3D space-time with a potential of sixth order in the fields coupled to mixed Chern-Simons gauge fields [1]. This model is relevant for Josephson junction arrays which capture the superconducting-insulating transition in many systems. The expectation that the transition is continuous leads to an effective Ginzburg-Landau functional, which is a coarse-grained path integral decoupling procedure for the Josephson energies. This procedure generates fourth-order terms in the potential which change sign when the screening length is large; consequently, sixth order terms in the fields become decisive for stability. The associated tricritical behavior at the intersection of the lines of second order transition and first order is important to investigate. Furthermore, gauge fields describe the fluctuating currents of vortices and Cooper pairs, and their interplay with the scalar fluctuations is crucial in the critical regime.

We analyze the effective potential and the renormalization group functions using a large N expansion and demonstrate spontaneous breaking of scale symmetry accompanied by a massless dilaton (Goldstone mode). Gauge fluctuations are shown to split the zeros of the beta functions and generate non-trivial fixed points. We identify a window in the Chern-Simons parameter where the RG flow has a stable infrared fixed point at which scale invariance is recovered [2]. The experimental implications of the quantum transitions are addressed.

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