ECT*

EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

TRENTO, ITALY

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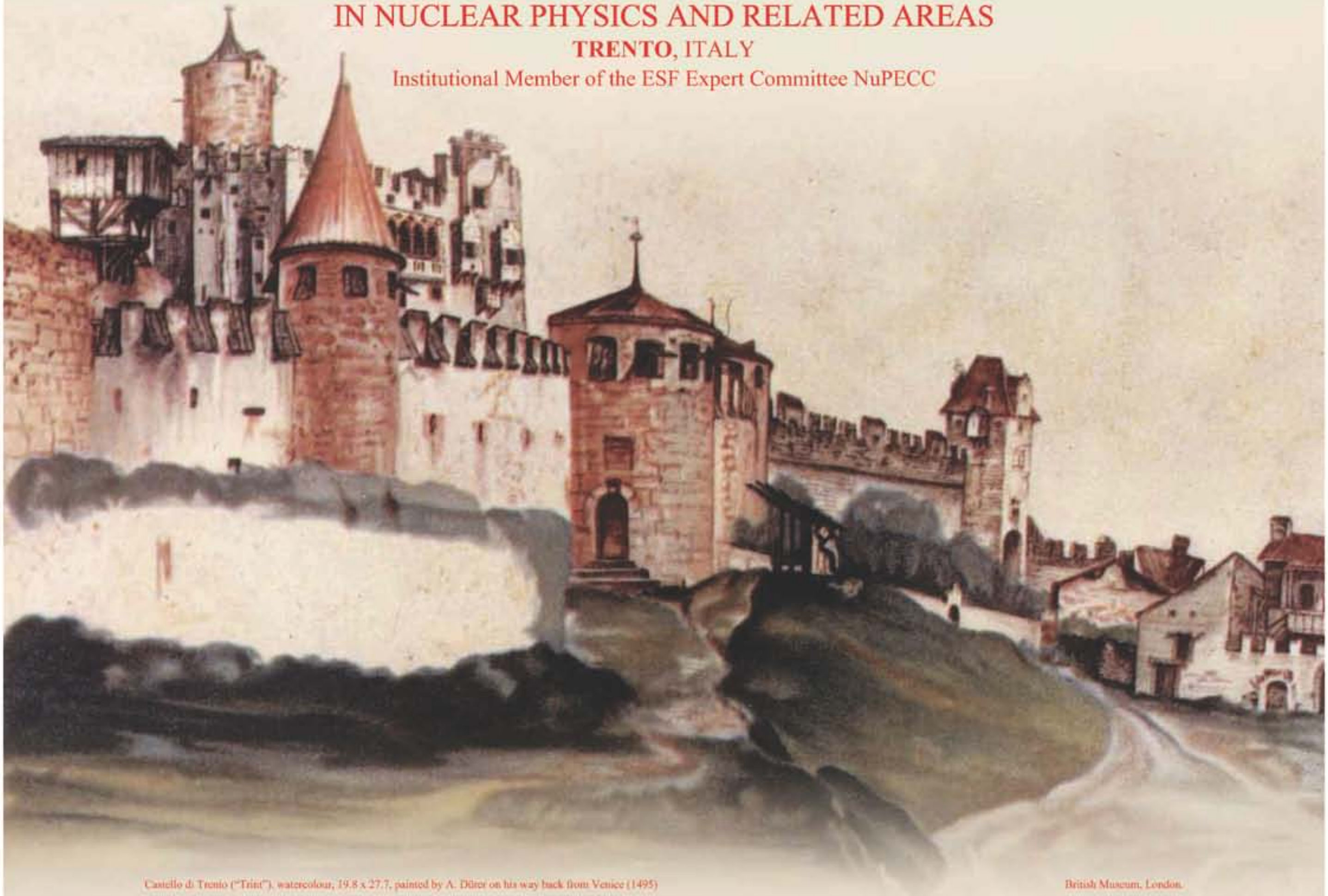

Castello di Trento ("Trint"), watercolour, 19.8 x 27.7, painted by A. Dürer on his way back from Venice (1495) British Museum, London.

Excited-State Quantum Phase Transitions

Trento, September 21-25, 2015

Main Topics

Theory and phenomenology of singularities in excited quantum spectra and their occurrence in diverse systems: atomic nuclei, molecules, quantum optical systems, Bose-Einstein condensates, optical lattices, microwave 2D crystals. Quenched, kicked and driven systems. Entanglement and chaos. Non-Hermitian quantum effects. Monodromy

Key Participants

V. Bastidas (Berlin), D. Brody (London), A. Buchleitner (Freiburg), L. Carr (Colorado), J. Cseh (Budapest), J. Dudek (Strasbourg), J. Dukelsky (Madrid), J.-E. Garcia Ramos (Huelva), E.-M. Graefe (London), D. Heiss (Stellenbosch), J. Hirsch (Mexico City), F. Iachello (Yale), M. Kastner (Stellenbosch), A. Kolovsky (Krasnoyarsk), V. Konotop (Lisbon), M. Macek (Yale), N. Moiseyev (Haifa), M. Oberthaler (Heidelberg), F. Perez Bernal (Huelva), P. Perez Fernandez (Sevilla), A. Relano (Madrid), A. Richter (Darmstadt), L. Santos (New York), P. Stransky (Prague), M. Vogl (Berlin), A. Volya (Florida), H. Waalkens (Groningen)

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Monday 21.9.	Tuesday 22.9.	Wednesday 23.9.	Thursday 24.9.	Friday 25.9.
9.00 **Opening**	9.00 **L. Carr** BECs in ring traps: Topolo-gical unwinding, strongly correlated solitons, and metastable mesoscopic QPTs	9.00 **H. Waalkens** Scattering monodromy	9.00 **M. Oberthaler** Bose–Einstein condensates: An experimental model system for ESQPT?	9.00 **N. Moiseyev** Sudden transition from sta-ble to unstable harmonic trap as the adiabatic poten-tial parameter is varied in a time-periodic harmonic trap
9.10 **F. Iachello** QPTs in algebraic models	9.40 **A. Kolovsky** QPT from the Mott-insulator state of cold atoms to the density-wave state in tilted 2D optical lattices	9.40 **F. Pérez-Bernal** Modeling of bending vibrations with the 2D limit of the vibron model: ESQPT and monodromy	9.40 **L. Santos** Effects of perturbation strength, disorder, and ESQPTs in the quench dynamics of interacting quantum systems	9.40 **T. Novotný** Nonequilibrium heat transport in an exactly solvable quantum-critical model
10.10 **P. Cejnar** Hitchhiker's guide to ESQPTlandia	10.20 **coffee & discussion**	10.20 **coffee & discussion**	10.20 **coffee & discussion**	10.20 **coffee & discussion**
10.50 **coffee & discussion**	11.00 **Eva-Maria Graefe** Mean-field and many-particle correspondence for a bosonic atom-molecule conversion system	11.00 **J.E. García Ramos** ESQPT in two-fluid Lipkin models	11.00 **T. Brandes** Control of QPTs	11.00 **D. Heiss** QPTs and exceptional points
11.20 **M. Kastner** Stationary points imply nonanalyticities of the density of states	11.40 **V. Konotop** Controlled dissipation and nonlinear Zeno effect in a BEC	11.40 **M. Macek** Effects of generalized kinetic terms on ESQPTs in finite systems	11.20 **V. Kopylov** Time delayed control of the Lipkin-Meshkov-Glick and the Dicke-Hepp-Lieb model	11.40 **M. Dvořák** Exceptional points and QPTs in an extended Lipkin model
12.00 **A. Buchleitner** Instabilities, spectra, phase transitions: More than just avoided crossings	12.20 **M. Kloc** ESQPTs and entanglement in an extended Dicke model	12:00 **M. Gessner** Role of excitation spectrum during a QPT: Semiclassical approach	12:00 **R. Puebla** On the dynamical consequences of ESQPTs in isolated quantum systems: irreversible closed cycles	12.00 **discussion**
12.40 **discussion**	12.40 **discussion**	12.40 **discussion**	12.40 **discussion**	
13.00 lunch	13.00 lunch	13.00 lunch	13.00 lunch	13.00 lunch
15.00 **A. Richter** QPTs in microwave Dirac billiards	15.00 **P. Stránský** Classification of ESQPTs and finite-size effects		15.00 **J. Dukelsky** The elliptic Gaudin model	
15.40 **J. Hirsch** Coexistence of regularity and chaos in atom-field systems: Phase space semiclassical analysis	15.40 **J. Dudek** Geometrical symmetries in nuclei using dynamical microscopic approach: Approaching the issue of shape phase transitions		15.40 **D. Brody** Information geometry of complex Hamiltonians and QPTs	
16.20 **coffee & discussion**	16.20 **coffee & discussion**		16.20 **coffee & discussion**	
17.00 **M.A. Bastarrachea-Magnani** Coexistence of regularity and chaos in atom-field systems: Phase space quantum description	17.00 **M. Macek** ESQPTs in 1D and 2D bosonic lattice systems		17.00 **V. Bastidas** Quantum criticality and semiclassical structures in driven quantum systems	
17.40 **A. Relaño** Chaos, entanglement and ESQPTs	17.20 **P. Pérez Fernández** QPTs in a two-site Bose-Hubbard with a Feshbach resonance		17.40 **J. Chávez Carlos** Classical Chaos in atom-field systems: technical aspects	
18.20 **discussion**	18.00 **discussion**		18.00 **discussion**	

Affiliations, Emails, Abstracts…

Francesco Iachello (Yale University, email: francesco.iachello@yale.edu)

Title: **Quantum phase transitions in algebraic models**

Abstract: Quantum Phase Transitions (QPT) and Excited State Quantum Phase Transitions (ESQPT) have become in recent years one of the main subjects of research in physics and chemistry. They can be conveniently studied within the framework of algebraic models. For these models one can do both the *semi-classical* and *quantal* analysis, and study the *finite-size scaling* ($1/N$ expansion). The latter point is particularly important for applications to finite systems: nuclei, molecules, finite polymers, photonic crystals, optical lattices, etc. In the first part of this talk, QPT and ESQPT in models of many-body systems with $\mathrm{U}(n)$ algebraic structure will be discussed, and experimental evidence for its occurrence in nuclei and molecules presented. In the second part, QPT and ESQPT in lattice models with $\mathrm{U}_1(n) \oplus \mathrm{U}_2(n) \oplus ... \oplus \mathrm{U}_k(n) = \sum \oplus \mathrm{U}(n)$ algebraic structure will be discussed, especially in linear, square and hexagonal lattices with discrete symmetry of the unit cell $C_{\infty v}$, D_{4h}, D_{6h}, respectively. Experimental evidence for the occurrence of ESQPT in photonic crystals will also be presented.

Pavel Cejnar (Charles University Prague, email: cejnar@ipnp.troja.mff.cuni.cz)

Title: **The hitchhiker's guide to the ESQPTlandia**

Abstract: The intention of this talk is to identify key properties of ESQPTs in general quantum systems with a finite number of degrees of freedom, to demonstrate examples of the ESQPT behavior in specific models, and to outline some dynamical and thermodynamical consequences. The talk is conceived as a teaser for various topics that will be discussed during the Workshop.

Michael Kastner (National Institute for Theoretical Physics Stellenbosch, email: kastner@sun.ac.za)

Title: **Stationary points imply nonanalyticities of the density of states**

Abstract: To a large extend, Excited State Quantum Phase Transitions (ESQPTs) have been investigated in models that can be written in terms of macroscopic collective variables. In that case, a semiclassical analysis is often justified, and properties of the phase transition can be understood on the basis of the stationary points of an energy landscape. In this talk I review related results from classical physics, in which the link between thermal phase transitions and stationary points of energy landscapes in high-dimensional phase space is explored. I present results on the kind of nonanalyticities that are induced by a certain type of stationary point, on the role of dimensionality, and also on peculiarities of models with mean-field-type interactions.

Andreas Buchleitner (Albert-Ludwigs-Universität Freiburg, email: a.buchleitner@physik.uni-freiburg.de)

Title: **Instabilities, spectra, phase transitions: More than just avoided crossings**

Abstract: Unstable fix points give structure to classical phase space, and manifest in the spectra and eigenstates of the corresponding quantum system, in single as much as in many particle problems, and at finite size. A modern semiclassical approach often allows for a transparent interpretation of the spectral structure, as well as of the (non-equilibrium, of course) dynamical features in the vicinity of the instability. To which extent can such point of view de-mystify the "(quantum) phase transition" debate? This is a question which puzzles the author and will be at the centre of this talk.

Achim Richter (Institute of Nuclear Physics/TU Darmstadt, email: richter@ikp.tu-darmstadt.de)

Title: **Quantum phase transitions in microwave Dirac billiards**

Abstract: Experimental results on relativistic phenomena occurring in graphene which is modelled through Dirac billiards consisting of a photonic crystal encased in flat superconducting microwave billiards ("artificial graphene") are presented. Here the analogy between the associated scalar Helmholtz equation and the Dirac equation is used and also the fact that the spectral properties of graphene are solely characterized by the particular symmetry character of its hexagonal lattice structure. The measured resonance densities with unprecedented resolution for a rectangular (regular) billiard and one of the shape of the African continent (chaotic), respectively, exhibit both a minimum at the frequency of the Dirac point which separates the first two bands, and are bounded by sharp peaks. The latter are called van Hove singularities [1] that generally occur in two-dimensional crystals with periodic structure [2]. The van Hove singularities divide the two bands framing the Dirac point into two frequency ranges below and above them, where the system is described by the nonrelativistic Schrödinger equation, and one between them, where the underlying wave equation coincides with the Dirac equation [3]. Thus, at the van Hove singularities, a transition takes place between a nonrelativistic Schrödinger region and the relativistic Dirac region, which can be interpreted as a Lifshitz and excited quantum phase transition [4]. It will be shown that the measured spectral properties are similar in the different regions and agree with those of the corresponding empty quantum billiard and a graphene billiard, respectively.

[1] L. van Hove, Phys. Rev. 89, 1189 (1953)
[2] F. Iachello, B. Dietz, M. Miski-Oglu, and A. Richter, Phys. Rev. B, in press
[3] B. Dietz, T. Klaus, M. Miski-Oglu, and A. Richter, Phys. Rev. B 91, 035411 (2015)

[4] B. Dietz, F. Iachello, M. Miski-Oglu, N. Pietralla, A. Richter, L. von Smekal, and J. Wambach, Phys. B 88, 104101 (2013)

Jorge Hirsch (Universidad Nacional Autónoma de México, email: hirsch@nucleares.unam.mx)
Title: **Coexistence of regularity and chaos in atom-field systems: Phase space semiclassical analysis**
Abstract: The Dicke Hamlltonian describes a system of N two-level atoms interacting with a single monochromatic electromagnetic radiation mode within a cavity. It exhibits a second- order quantum phase transition (QPT) in the thermodynamic limit, and an excited-state quantum phase transition (ESQPT) along the energy spectrum, for fixed values of the Hamiltonian parameters, manifested by singularities in the level density, order parameters, and wave function properties. The coexistence of regularity and chaos in a semi-classical limit has been previously described employing Poincaré sections, and compared with their quantum counterpart using Peres lattices and the fluctuations in the energy spectrum. It was found that, for any coupling, a low energy regime with regular states is always present, and that coexistence regions emerge below the ESQPT. In the present contribution detailed analysis are presented of the emergence of chaos by analyzing both the Poincaré surface sections and the Lyapunov exponents, mapping the phase space for fixed Hamiltonian parameters and for different excitation energies.

Miguel Angel Bastarrachea-Magnani (Universidad Nacional Autónoma de México,
email: mamigre4008@gmail.com)
Title: **Coexistence of regularity and chaos in atom-field systems: Phase space quantum description**
Abstract: The Dicke Hamlltonian describes a system of *N* two-level atoms interacting with a single monochromatic electromagnetic radiation mode within a cavity. It exhibits a second- order quantum phase transition (QPT) in the thermody- namic limit, and an excited-state quantum phase transition (ESQPT) along the energy spectrum, for fixed values of the Hamiltonian parameters, manifested by singularities in the level density, order parameters, and wave function properties. The coexistence of regularity and chaos in a semi- classical limit has been previously described employing Poincaré sections, and compared with their quantum counterpart using Peres lattices and the fluctuations in the energy spectrum. It was found that, for any coupling, a low energy regime with regular states is always present, and that coexistence regions emerge below the ESQPT. In this work we explore the mixture of regular and chaotic regions around energies close to the ESQPT, where the chaos is manifest. In order to quantify chaos employing the quantum description we study the Husimi function of the quantum states in this energy region, and the scaling of the inverse participation ratio (IPR) of a coherent state defined via the semiclassical approximation of the Hamiltonian and spanned in the eigenstate basis. It allows for a detailed exploration of the semiclassical phase space, which can be compared with the classical tools like Poincare sections and Lyapunov exponents.

Armando Relaño (Universidad Complutense de Madrid, email: armando.relano@fis.ucm.es)
Title: **Chaos, entanglement and ESQPTs**
Abstract: I give a critical review of the links between ESQPTs and other characteristic features of quantum many-body systems – quantum chaos and entanglement. By means of numerical calculations in the Dicke model and an atom-molecule mixture, I show that quantum chaos and the dynamic creation of entanglement between the different parts of the system start near the critical energy of the ESQPT. I also show the weak points in this connection, both numerically and semiclassically. My aim is to open a discussion about these facts.

Lincoln Carr (Colorado School of Mines, USA, email: lcarr@mines.edu)
Title: **Bose-Einstein condensates in ring traps: Topological unwinding, strongly correlated solitons, and metastable mesoscopic quantum phase transitions**
Abstract: Ultracold quantum gases offer a wonderful playground for quantum many-body physics, as experimental systems are widely controllable, both statically and dynamically. One such system is the one-dimensional (1D) Bose gas on a ring. In this system binary contact interactions between the constituent bosonic atoms, usually alkali metals, can be controlled in both sign and magnitude; a recent experiment has tuned interactions over seven orders of magnitude, using an atom-molecule resonance called a Feshbach resonance. Thus one can directly realize the Lieb-Liniger Hamiltonian, from the weakly- to the strongly-interacting regime. At the same time there are a number of experiments utilizing ring traps. The ring geometry affords us the opportunity to study topological properties of this system as well; one of the main properties of a superfluid is its quantized circulation, in which the average angular momentum per particle, *L/N*, is quantized under rotation. Thus we focus on a tunable 1D Bose system for which the main control parameters are interaction and rotation. We show that there is a critical boundary in the interaction-rotation control-parameter plane over which the topological properties of the system change. This is the basis of our concept of metastable quantum phase transitions (QPTs). Moreover, we show that the finite domain of the ring is necessary for the QPT to occur at all because the zero-point kinetic pressure can induce QPTs, i.e., the system must be finite; we thus seek to generalize the concept of QPTs to inherently finite, mesoscopic or nanoscopic systems. In so doing we also generalize the notions of both superfluids and solitons to strongly interacting systems in terms of yrast states, and provide a clear physical interpretation of Lieb's Type-II excitations over all

interaction regimes. Our theoretical and numerical techniques include mean field theory, Bogoliubov-de Gennes theory, exact diagonalization, numerical Bethe ansatz, and the Tonks gas mapping.

Andrey Kolovsky (Kirensky Institute of Physics, Krasnoyarsk, email: andrey.r.kolovsky@gmail.com)
Title: **Quantum phase transition from the Mott-insulator state of cold atoms to the density-wave state in tilted 2D optical lattices**
Abstract: In 1D optical lattices the above quantum phase transition, driven by the lattice tilt, was predicted in Ref. [1] and studied experimentally in Ref. [2]. We theoretically analyze this transition in a tilted 2D square lattice where we have one additional parameter – orientation of a static field with respect to primary axes of the lattice. It is shown that the case where the static field is aligned with one of the primary axis (which is naively expected to be the best choice) contains intrinsic instability which makes impossible the formation of an ordered state. However, the ordered state can be obtained for other field orientations. The optimal strategy for producing the density-wave state is discussed.
[1] S.Sachdev, K.Sengupta, and S.M.Girvin, Mott insulators in strong electric fields, Phys. Rev. B 66, 075128 (2002).
[2] J.Simon, W.S.Bakr, R.Ma, M.E.Tai, P.M.Preiss, and M.Greiner, Quantum simulation of antiferromagnetic spin chains in an optical lattices, Nature (London) 472, 307 (2011).

Eva-Maria Graefe (Imperial College London, email: e.m.graefe@imperial.ac.uk)
Title: **Mean-field and many-particle correspondence for a bosonic atom-molecule conversion system**
Abstract: There is currently considerable interest in experiments with Bose-Einstein condensates (BECs) of cold atoms that can associate to form multi-atomic molecules and vice versa. A full theoretical description of cold atoms and BECs requires modelling of many-particle quantum dynamics, which quickly goes beyond the scope of computational accessibility for realistic setups. For low densities, large particle numbers, and short times, a BEC can be effectively described by a single macroscopic wave function. This mean-field approximation is closely related to the classical limit of single particle physics. Thus, semiclassical methods can be applied to model many-particle features on top of the mean-field description. Here we consider the simplest example system of an atom-molecule conversion system where atoms can combine into two-atomic molecules, and only one basis state is considered for atoms and molecules respectively. The many-particle system can be described by a deformed SU(2) algebra, and the mean-field dynamics is confined to a teardrop shape that replaces the Bloch sphere of a conventional two-mode system. We introduce a semiclassical quantisation condition and demonstrate that the many-particle spectrum can be accurately recovered from the mean-field dynamics. This allows us to derive an analytic expression for the many-particle density of states in the semiclassical limit of large particle numbers, which shows a divergence typical of a quantum-phase transition.

Vladimir Konotop (University of Lisbon, email: vvkonotop@fc.ul.pt)
Title: **Controlled dissipation and nonlinear Zeno effect in a Bose-Einstein condensate**
Abstract: A Bose-Einstein condensate (BEC) subjected to action of a dissipative potential can be viewed as a meanfield model of the many-body system subjected to controlled removal of atoms. Such a system manifests a number of interesting phenomena including quantum switching and macroscopic manifestation of the Zeno effect (Macroscopic Zeno Effect). These effects have nonlinear nature and allow for efficient control of BECs. In this talk I will discuss a number of related phenomena ranging from switching of the wave function in Fock space between the ‘‘coherent’’ and ‘‘Bogoliubov’’ states controlled by a time-dependent parameter to strong suppression of losses by increase of the dissipation strength and excitation of solitons and vortices in BECs.

Michal Kloc (Charles University Prague, email: kloc@ipnp.troja.mff.cuni.cz)
Title: **ESQPTs and entanglement in an extended Dicke model**
Abstract: We analyze semiclassical and quantum properties of a single-mode superradiance model that permits a continuous crossover between the Jaynes-Cummings (integrable) and Dicke (nonintegrable) regimes. The model contains a ground-state QPT between normal and superradiant phases and shows several types of ESQPTs. Relation of these critical structures to the degrees of chaos and to the atom-field entanglement will be discussed.

Pavel Stránský (Charles University Prague, email: stransky@ipnp.troja.mff.cuni.cz)
Title: **Classification of ESQPTs and finite-size effects**
Abstract: An Excited-State Quantum Phase Transition (ESQPT) manifests itself as a nonanalytic behaviour of the smooth part of the quantum level density. It will be shown that a complete classification of singularities induced by nondegenerate stationary points of an analytic Hamiltonian is given by a pair of integers (f, r): the number f of degrees of freedom and the index r of the stationary point. The singularity occurs in the (f−1)-th derivative of the level density, which is discontinuous or logarithmically diverges for r even or odd, respectively. Growing flatness in a degenerate stationary point shifts the singularity towards lower derivatives. The same type of singularities appear also in the averaged variations of energy eigenvalues with the system’s control parameter, i.e., in the flow properties of the quantum spectrum (level dynamics). In the second part of the talk, the focus will be put onto the oscillatory component of the level density. It will be shown that in case of an effective partial separability of dynamics, this

component exhibits remarkable precursors of ESQPTs originating in lower dimension. The theoretical results will be demonstrated on models with *f*=1, 2 and 3.

Jerzy Dudek (Univerity of Strasbourg and IPHC/CNRS Strasbourg, email: Jerzy.Dudek@iphc.cnrs.fr)
Title: **Geometrical Symmetries in Nuclei Using Dynamical Microscopic Approach: Approaching the Issue of Shape Phase Transitions**
Abstract: We formulate first a microscopically realistic description of the nuclear point group (geometrical) symmetries employing the following strategy: 1. The microscopic descriptions of the nuclear geometry in general and of the geometrical symmetries in particular is realised using the phenomenological mean-field nuclear Hamiltonian: 2. The description of the collective nuclear motion in the nuclear deformation space in terms of the collective Schroedinger equation is formulated from the beginning in the curvilinear (Riemann) spaces. The metric tensor in the Riemann space is calculated microscopically and its strong variations as function of the deformation reflect the evolution of the nuclear shell structure´as function of the deformation. This element turns out to be decisive for the realistic description of the of the geometrical symmetries in nuclei. 3. The total nuclear potential energies are calculated using the standard phenomenological thus realistic methods. It follows that in many nuclei the most probable deformation (thus the geometrical symmetry) in which the nucleus is to be found in experiment and the deformation corresponding to the potential minimum are different - often significantly different. [This observation is particularly striking (even though obvious) for the one-phonon rotational bands for which the probability for the nucleus to be found in the potential minimum is strictly zero.] As the next logical step we arrive at the conclusion that the electromagnetic transitions which are the most precious sign of nuclear symmetries reflect not so much the symmetries of the potential minima but rather the symmetries deduced from a combined effect of optimising the product of the factors: $P(\alpha)\times B(E\lambda/M\lambda)(\alpha)$. Here, $P(\alpha)$ is the probability density calculated as $P \sim |\psi(\alpha)|^2 \sqrt{B(\alpha)}$ where $B(\alpha)$ is the (strongly) deformation dependent mass tensor and $B(E\lambda/M\lambda)$ is a short-hand notation for the reduced electromagnetic transition probabilities which themselves depend on alpha. We approach in this way a paradigm switch: Rather than studying the minima of the collective potential energies as the origin of information about nuclear symmetry we consider the deformations at which the transition probabilities are maximised - these values are comparable with experiment after all. The consequences of these conclusions from the microscopic and dynamical description of the nuclear geometry on the nuclear point-group symmetries, their manifestations and tests through experiments are discussed; particular attention is payed to the shape (thus symmetry) coexistence and transitions including the related critical points and large amplitude motion. Next we address the issue of the shape evolution taking into account the new viewpoints including the paradigm shift just presented. Introducing angular momentum as one of the dynamical co-ordinates we address the question of bifurcations (one potential minimum evolves into two) as is typically the case during the so-called nuclear Poincaré shape transitions during which the nuclei lose the left-right symmetry. We address specifically the this type of transitions at high nuclear temperatures (which are therefore not the result of the nuclear shell-effects) and provide a natural laboratory for studying nuclear level densities over (above) the double potential minimum landscape.

Michal Macek (Yale University, email: michal.macek@yale.edu)
Title: **ESQPTs in 1D and 2D bosonic lattice systems**
Abstract: We overview the types of ESQPT singularities in the density of states (DoS) and its energy derivatives encountered in 1D bosonic chains and 2D bosonic lattices of different discrete symmetry. We classify the singularities with the help of Morse theory applied to the stationary points of the energy dispersion relations (EDRs) of the systems. The ESQPTs in the DoS itself (i.e. "its zeroth energy derivative") are shown to be equivalent to the Van Hove singularities. We analyze the structural changes of the eigenstates and the behavior of suitable order parameters (occupation number fluctuations, localization, fidelity) accompanying ESQPTs in the Bose-Hubbard model.

Pedro Pérez Fernández (Universidad de Sevilla, email: pedropf@us.es)
Title: **Quantum phase transitions in a two-site Bose-Hubbard with a Feshbach resonance**
Abstract: In this talk the two-site Bose-Hubbard with a Feschbach resonance is presented. We explore quantum phase transitions in this model and we perform a beyond mean field study in order to get corrections to the mean field approach. Analytical results for the ground state energy and the first gaps are presented. The computed corrections are compared with numerical calculations. Besides, we analyse the onset of chaos in this model and its relationship with the observation of an excited state quantum phase transition.

Holger Waalkens (University of Groningen, email: h.waalkens@rug.nl)
Title: **Scattering monodromy**
Abstract: The Liouville-Arnold theorem states that a compact preimage of regular value of the energy momentum map of a Liouville integrable system is an *f*-dimensional torus where *f* is the number of degrees of freedom, and in the neighbourhood of this torus one can construct action-angle variables. Isolated singular values of the energy momentum map can cause a twist in the torus bundle over the regular image of an energy momentum map. As a result action-angle variables cannot be defined globally. This obstruction to the global construction of action-angle variables has been coined Hamiltonian monodromy, and many prominent examples of

Liouville-integrable systems exhibiting this obstruction have been studied in recent years. Through the Bohr-Sommerfeld quantization of action variables monodromy carries over to quantum mechanics where it causes an obstruction to the global existence of quantum numbers. In this talk we discuss the classical and quantum mechanical implications of monodromy for scattering systems, i.e. for Liouville integrable systems where the pre images of the energy momentum map are not compact. As an example we study Euler's problem of two fixed centers.

Francisco Pérez-Bernal (Universidad de Huelva, email: francisco.perez@dfaie.uhu.es)
Title: **Modeling of bending vibrations with the 2D limit of the vibron model: ESQPT and monodromy**
Abstract: Results obtained for the modeling of bending vibrational degrees of freedom using the 2D limit of the vibron model are presented both for single and coupled benders. Special emphasis is devoted to the occurrence of ESQPT in this degree of freedom, and its relation to quantum monodromy.
References: The Journal of Chemical Physics 2014; 140(1):014304. Journal of Molecular Structure 2013; 1051:310-327.
Journal of Molecular Structure 2011; 1006 :611-628. Journal of Molecular Structure 2006; 798:1-26.

José Enrique García Ramos (University of Huelva, email: enrique.ramos@dfaie.uhu.es)
Title: **Excited-state QPT in two-fluid Lipkin models**
Abstract: Two-fluid algebraic models are of great interest in the context of quantum phase transition in nuclei. We intend to study the phase diagram of a two-fluid Lipkin model that resembles a nuclear proton-neutron interacting boson model Hamiltonian. We also will present an analysis of the ESQPT that appear in this model paying special attention to the relationship with onset of chaos in the energy spectra, and moreover we will study the effect of the relative size of both fluids on the appearance of a ESQPT.

Michal Macek (for affiliation and email see above)
Title: **Effects of generalized kinetic terms on ESQPTs in finite systems**
Abstract: We study the effects of non-quadratic kinetic terms typically occurring in finite models of collective many body dynamics (like rotations and vibrations in molecules and atomic nuclei) on the signatures of ESQPTs. We show that in case that no terms linear in momenta are present in the Hamiltonian, the ESQPT singularities corresponding to the stationary points of the potential energy are preserved. This applies in particular to all time-reversal invariant systems. On the other hand, complicated kinetic terms may introduce additional ESQPTs, not captured by the potential-based analysis. Examples will be given from the Interacting Boson Model of atomic nuclei.

Manuel Gessner (University of Freiburg, email: manuel.gessner@physik.uni-freiburg.de)
Title: **Role of excitation spectrum during a quantum phase transition: Semiclassical approach**
Abstract: We develop a multi-configurational mean-field method to reproduce semiclassical, spectral features of a family of spin chain models with variable range in a transverse magnetic field. The model continuously interpolates between the Lipkin-Meshkov-Glick model and the Ising model. The semiclassical spectrum is exact in the limit of very strong or vanishing external magnetic fields. Each of the semiclassical energy landscapes shows a bifurcation when the external magnetic field exceeds a threshold value. This reflects the quantum phase transition from the symmetric paramagnetic phase to the symmetry-breaking (anti-)ferromagnetic phase in the entire excitation spectrum--and not just in the ground state.

Markus Oberthaler (University of Heidelberg, email: markus.oberthaler@kip.uni-heidelberg.de)
Title: **Bose–Einstein condensates: An experimental model system for ESQPT?**
Abstract: With the advent of Bose-Einstein condensates we have now a new experimental model system at hand which allows the exploration of many different avenues of fundamental physics. In my presentation I will focus on the realization of a special version of the Lipkin-Meshkov-Glick Hamiltonian with rubidium Bose-Einstein condensates. Special emphasize will be given to the discussion of the experimental control parameters, the experimental observables as well as the experimental limitation. I will also give an overview of the results we have obtained with this system over the last years touching on quantum bifurcation, generation of entanglement including state reconstruction and aspects of chaos.

Lea Santos (Yeshiva University, New York, email: lsantos2@yu.edu)
Title: **Effects of perturbation strength, disorder, and excited state quantum phase transitions in the quench dynamics of interacting quantum systems**
Abstract: We study the evolution of isolated two-level models with two-body interactions after an abrupt perturbation. Our focus is on the probability for finding the initial state later in time, the so-called survival probability. When the perturbation is strong, the dynamics is very fast. The behavior of the survival probability may be exponential, Gaussian, and even faster than Gaussian. We show how the limit imposed by the energy time uncertainty relation can be reached. In contrast, the time evolution slows down

significantly when the system undergoes an excited state quantum phase transition or when disorder is added to the Hamiltonian. In the latter case, a powerlaw decay emerges with an exponent determined by the level of delocalization of the initial state.

Tobias Brandes (Technische Universität Berlin, email: tobias.brandes@tu-berlin.de)
Title: **Control of quantum phase transitions**
Abstract: This is an overview of our recent activities in open and closed loop control of quantum phase transitions in ground and excited states, mostly for simple models (Lipkin-Meshkov-Glick, Dicke-Hepp-Lieb, Kicked Top).

Wassilij Kopylov (Technische Universität Berlin, email: kopylov@itp.tu-berlin.de)
Title: **Time delayed control of the Lipkin-Meshkov-Glick and the Dicke-Hepp-Lieb model**
Abstract: We apply the time-delayed Pyragas control scheme to the dissipative Dicke and LMG models via a modulation of the internal coupling. We show that for the Dicke model the feedback creates new non-equilibrium phases with fixed points and limit cycles instead of the common ground phase in the superradiant regime. Whereas the application of the feedback scheme to the LMG model allows us to restore the visibility of the ESQPT signal in the time-dependence of system observables, which is smeared out by the dissipative effects. For both models we analyze the appearing bifurcations as a function of time delay and determine analytical conditions for the phase boundaries.

Ricardo Puebla (University of Ulm, email: ricardo.puebla@uni-ulm.de)
Title: **On the dynamical consequences of ESQPTs in isolated quantum systems: irreversible closed cycles**
Abstract: For certain isolated quantum systems in which an ESQPT divides the spectrum into degenerated and non-degenerated eigenstates, the existence of symmetry-breaking states appears as a key signature that allows to characterize the phases at both sides of the ESQPT [1,2]. This provides a suitable scenario where we can analyse how this extra information, related to the broken symmetry, is eroded by an irreversible time-dependent protocol. To this aim, we consider a symmetry-breaking initial state and then, perform a closed cycle crossing an ESQPT. Interestingly, when the protocol is performed sufficiently slow to prevent diabatic transitions, the energy distribution is fully recovered and hence, there is no energy dissipation. However, the expectation value of a symmetry-breaking observable irreversibly changes from an initial non-zero value to zero after the closed cycle. This entails an unavoidable loss of information and constitutes a source of irreversibility, as the increment of von Neumann entropy of time-averaged equilibrium states shows. We support this result by means of numerical calculations in the Lipkin-Meshkov-Glick model [3].
[1] R. Puebla, A. Relaño, and J. Retamosa, Phys. Rev. A 87, 023819 (2013).
[2] R. Puebla, and A. Relaño, Europhys. Lett. 104, 50007 (2013).
[3] R. Puebla, and A. Relaño, arxiv:1404.6146 (2014).

Jorge Dukelsky (Instituto de Estructura de la Materia CSIC Madrid, email: j.dukelsky@csic.es)
Title: **The elliptic Gaudin Model**
Abstract: The Richardson-Gaudin integrable models have been widely applied in recent years to a large variety of mesoscopic systems, like quantum dots, small grains, atomic nuclei, cold atoms, etc. Moreover, particular realizations of the RG models lead to models with ESQPT's like Lipkin, Tavis-Cummings, two-level pairing, and IBM. Here we will introduce the yet unexplored EGM showing the kind of spin systems it can describe. In particular, we will present an EGM consisting of a spin 1/2 interacting with a large spin *J*. This model, which is a schematic realization of the anisotropic central spin model, contains two ESQPTs that we will describe in detail.

Dorje Brody (Brunel University London, email: dorje.brody@brunel.ac.uk)
Title: **Information geometry of complex Hamiltonians and quantum phase transitions**
Abstract: Information geometry provides a tool to systematically investigate parameter sensitivity of the state of a system. If a physical system is described by a linear combination of eigenstates of a complex (that is, non-Hermitian) Hamiltonian, then there can be phase transitions where dynamical properties of the system change abruptly. In the vicinities of the transition points, the state of the system becomes highly sensitive to the changes of the parameters in the Hamiltonian. The parameter sensitivity can then be measured in terms of the Fisher-Rao metric and the associated curvature of the parameter-space manifold. A general scheme for the geometric study of parameter-space manifolds of eigenstates of complex Hamiltonians is discussed, leading to generic expressions for the metric. (Based on joint work with Eva-Maria Graefe.)

Victor Manuel Bastidas Valencia (Technische Universität Berlin, email: victor@physik.tu-berlin.de)
Title: **Quantum criticality and semiclassical structures in driven quantum systems**
Abstract: A quantum phase transition (QPT) is characterized by non-analyticities of ground-state properties at the critical points. Recently it has been shown that quantum criticality emerges also in excited states of the system, which is referred to as an excited-state quantum phase transition (ESQPT). This kind of quantum criticality is intimately related to a level clustering at critical energies,

which results in a logarithmic singularity in the density of states. Most of the previous studies on quantum criticality in excited states have been focused on time independent systems. Here we study spectral singularities that appear in periodically-driven many-body systems and show how the external control allows one to engineer geometrical features of the quasienergy landscape. In particular, we study singularities in the quasienergy spectrum of a fully-connected network consisting of two-level systems with time-dependent interactions. We discuss the characteristic signatures of these singularities in observables like the magnetization, which should be measurable with current technology.

Jorge Chávez Carlos (Universidad Nacional Autónoma de México, email: jorge.chavez@correo.nucleares.unam.mx)
Title: **Classical Chaos in atom-field systems: technical aspects**
Abstract: A classical Hamiltonian is obtained as the expectation value of the Dicke Hamiltonian between Glauber and Bloch coherent states. Classical trajectories of the canonical variables in phase space are calculated solving the semiclassical equations of motion. We employ the Lyapunov exponents as a quantitative measure of the chaos associated with each point in phase space, and compare them with the Poincaré sections. In this way regular and chaotic regions are characterized for different energies and coupling strengths. The distribution of Lyapunov exponents in phase space and along trajectories, for fixed energies, exhibit the presence or absence of ergodic dynamics. We study the stability and robustness of our analysis, by evaluating the Lyapunov exponents using different definitions and numerical methods.

Nimrod Moiseyev (Technion - Israel Institute of Technology, Haifa, email: nimrod@tx.technion.ac.il)
Title: **Sudden transition from a stable to an unstable harmonic trap as the adiabatic potential parameter is varied in a time-periodic harmonic trap**
Abstract: The purpose is to study the dynamics of a single ion in a magnetic, optical, or rf trap, and of diluted gases of ultracold atoms in optical traps. When the harmonic trap is opened (or closed) as a function of time while keeping the adiabatic parameter $\mu = [d\omega(t)/dt]/\omega^2(t)$ fixed, a sharp transition from an oscillatory to a monotonic exponential dynamics occurs at $\mu = 2$ [R. Uzdin *et al.*, PRA 88, 022505 (2013)]. This sudden transition is due to a third order non-hermitian degeneracy (so called a branch point or exceptional point) which is very different from other known cases since the entire spectrum of the harmonic trap coalesce at all instants. A simple physical explanation which was given in [NM, PRA 88, 034502 (2013)] by using time-dependent linear coordinate transformation will be described. A sharp transition from a potential parabolic well to a parabolic potential barrier takes place at $\mu = 2$. While in an harmonic trap non-interacting particles have classical periodic motions, they are pushed apart exponentially in time as the potential well is suddenly transformed into a parabolic potential barrier in the new variable representation. An extension of this study to many-body problem is mostly desired.

Tomáš Novotný (Charles University Prague, email: tno@karlov.mff.cuni.cz)
Title: **Nonequilibrium heat transport in an exactly solvable quantum-critical model**
Abstract: I study heat transport in an exactly solvable modification of the nonequilibrium transverse-field Ising-chain model originally studied by M. Vogl, G. Schaller, and T. Brandes in Phys. Rev. Lett. 109, 240402 (2012) & J. Phys. Cond. Matt. 26, 265001 (2014). The spin-chain model can be fermionized by the Jordan-Wigner transform to equivalent non-interacting fermions and consequently exactly diagonalized for any value of the model parameters, in particular, the coupling to the heat spin baths. I verify the conclusions of the approximate master-equation treatment a la Vogl et al. in the limit of very weak coupling to reservoirs and extend those results to finite coupling strengths. It turns out that for finite couplings the fate of the quantum-phase-transition-like singularities in the heat current depends crucially on the way, how the thermodynamic limit is performed, more specifically, whether the full coherence along the (infinite) chain is preserved or not. I will discuss the physical interpretation of the importance of the dephasing in the transport and will also comment on the relation to the “conventional” equilibrium QPT via the behavior of the correlation functions. I will argue that the non-equilibrium phenomenon appears to be actually closer to the Electronic Topological Transitions (cf. Ya. M. Blanter et al., Physics Reports 245, 159 (1994)) than standard QPTs.

Dieter Heiss (University Stellenbosch, email: dieter@physics.sun.ac.za)
Title: **Quantum phase transitions and exceptional points**
Abstract: A short rehash about the nature and the physics of Exceptional Points (EP) is given. We then concentrate on the Lipkin model being a representative toy model to study the connection of EPs and a quantum phase transition. It is argued that for the plain Lipkin model the thermodynamic limit yields two analytically disconnected phases. The slightest perturbation of the model leads to chaotic behaviour in the transitional region and appears to soften the strictly disconnected pattern.

Martin Dvořák (Charles University Prague, email: dvor.martin@gmail.com)
Title: **Exceptional points and quantum phase transitions in an extended Lipkin model**

Abstract: Distribution of exceptional points in the complex plane of control parameters is presented for the Lipkin Hamiltonian containing both first- and second-order QPT. Impact of exceptional points on the real level dynamics is analyzed, with emphasis on the scaling behavior near the first- and second-order critical points.

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