NEWSLETTER

PICC

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Project acronym: PICC
Project full title: The *P*hysics of *I*on *C*oulomb *C*rystals: Thermodynamics, Quantum control and Quantum simulators
Grant agreement: No. 249958
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THE PROJECT

PICC is a 3-year collaborative research project funded under the EC's 7th Framework Programme, ICT Future and Emerging Technology. The PICC project represents a joint theoretical and experimental effort whose aims are **(i)** to identify tools for controlling quantum physical systems as their size is scaled up, **(ii)** to develop strategies for implementing controlled quantum dynamics of mesoscopic systems in a noisy environment and **(iii)** to explore the capability of mesoscopic systems as quantum simulators. In order to achieve these goals, the project proceeds along three interconnected research lines:

Thermodynamics of ion Coulomb crystals

Quantum dynamics of ion Coulomb crystals

Ion Coulomb crystals as quantum simulators

Dear readers,

Yet another successful project year has passed and it is time for the 2nd PICC newsletter. The last twelve months saw a lot of achievements and we are proud to show you the most significant results in this newsletter edition. PICC has now entered its third and last project period and the Consortium is ready to tackle the research challenges PICC will bring about and to continue the PICC success story. You will read about it in our next newsletter edition. But let us now focus on the PICC achievements of 2012.

RESULTS ACHIEVED

Thermodynamics. One central subject of investigation is the linear-zigzag structural transition in ion crystals. Indeed, this transition is a paradigm of quantum statistical mechanics effect in a macroscopic physical system observable in laboratories. Partners of the consortium showed that the linear-zigzag transition is a natural realization of the dynamics predicted by the Ising model with transverse field, describing a quantum ferromagnetic transition at temperature T=0. These predictions have now been compared with numerical results obtained from sophisticated programs, developed by some PICC partners, and based on DMRG and Matrix-Product-State types of code.

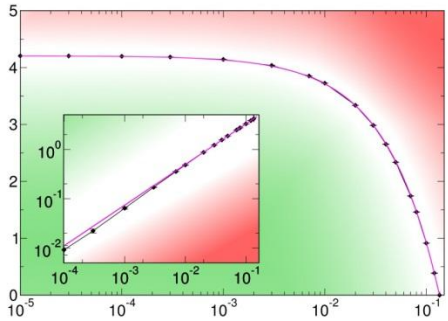

Figure 1: Figure 1: Phase diagram of the quantum phase transition from linear to zigzag structural equilibrium of a quantum ion chain. The critical trap frequency, numerically calculated, is plotted against the magnitude of the quantum fluctuations, expressed in terms of the renormalized Plank constant. At fixed trap frequency, increasing quantum fluctuations tend to destroy the antiferro-order parameter, driving the system towards the linear phase. From [1].

The numerical results confirm the prediction that the quantum-phase transition belongs to the universality class of the ferromagnetic transition of the Ising model with a transverse field. Figure 1 displays the phase diagram of the quantum phase transition from linear to zigzag, which has been numerically evaluated. The DMRG program provides a unique numerical tool for simulating the quantum dynamics of the crystal at criticality [1].

Another remarkable advance has been made in the coupling of ion crystals with the field of a high-finesse optical resonator. The control of the coupling between cavity mode and crystal is being pursued. Resonance fluorescence images of the crystal within the cavity have allowed us to develop methods for positioning the axial center of a cavity mode. Accompanying the experimental advances, first theoretical studies of the properties of ion crystals coupled with a mode of a high-finesse cavity have been performed. They show the appearance of multistable structures which emerge from the interplay between the Paul-trap potential, the Coulomb repulsion, and the mechanical forces of the cavity photons on the atoms. Their thermodynamic properties can be revealed at the cavity output. Spectra of the light leaking out from the cavity mirror are shown in Figure 2 for different values of the strength of the coupling with the cavity field. For large couplings (Figure 2b), the appearance of Fano-like resonances signals the presence of entanglement between vibrational and photonic excitations. Such entanglement is a stationary property of the system, which is cooled by the mechanical effects associated with scattering of cavity photons [2]

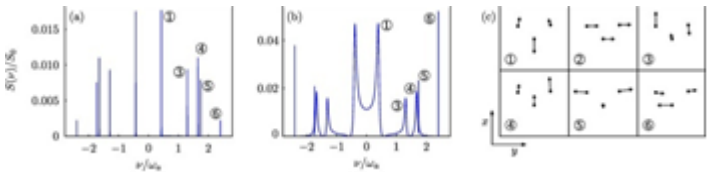

Figure 2: Spectra of the modes of an ion crystal measured at the cavity output. From [3]

Quantum Dynamics. The realization of robust and scalable quantum dynamics of crystalline structures is one of the goals of the project. An essential issue is whether one can create quantum superpositions of two visibly different crystalline structures in a similar way as a quantum superposition between the two states of a single atom. In the second project year, a protocol has been developed for creating quantum superpositions of crystalline states across the linear-zigzag phase transition. The coherent superposition is achieved by means of spin-dependent forces, such that a coherent superposition of the electronic states of one ion evolves into an entangled state between the chain's internal and external degrees of freedom. Such an entangled state can be revealed by performing Ramsey interferometry with one ion of the chain [3].

Quantum states and dynamics of macroscopic systems must be robust against noise and decoherence. PICC is developing a systematic characterization of strategies which allow minimization of the detrimental effect of noise. To mention some, a theoretical method has been developed based on dressing magnetic field sensitive states with microwave fields to prolong coherence times of qubits. It was shown that the scheme could work together with all the proposed gates while keeping the same efficiency of decoupling. Moreover, this scheme does not require magnetic gradients or microwave near fields. This decisively changes the prospect of microwave-driven ion trap QIP and offers a new route to extend coherence times for all systems that suffer from magnetic noise such as neutral atoms, NV-centres, quantum dots, or circuit-QED systems [4]. This gate has now been realised in the research group of Nobel Laureate Dave Wineland [5]. The key importance to them is that it obviates the need for interferometric stability a pair of laser beams has been replaced by a laser and a microwave. This makes implementations much easier and has indeed led to a very high fidelity implementation of quantum gates (97.4%).

One of the most significant limitations in the Paul traps is micromotion - the driven response of the ions to the external trapping potential. Micromotion is responsible for the severe instability of large ion crystals, and it requires careful compensation in experiments with small crystals. A fundamental understanding and a framework for the analysis of micromotion effects is therefore experimentally and theoretically important, and PICC partners provided a thorough analysis of the micromotion of ion crystals [6]. An analysis of the full time-dependent nonlinear problem of trapped Coulomb crystals was considered, and it was shown that the commonly used pseudopotential approximation is not always justified. In many cases, the time-dependent solution defers structurally from the pseudopotential prediction. The micromotion amplitude of the ions was derived for general three-dimensional crystals, confirming well-known experimental observations.

Insight into the effect of noise and decoherence can be gained by effectively simulating the coupling between system and reservoir. A possible platform analysed within this project contains crystalline structures composed by multi-species ions (see Figure 3). Here, the reservoir is provided by the second species in a two-component crystal. In these systems thorough understanding and control of finite-size effects has been pursued for the reliable implementation of quantum reservoir engineering.

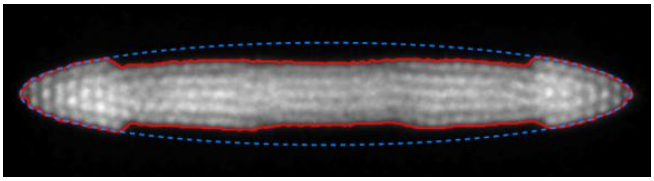

Figure 3: Bicrystal composed of Mg+ ions (bright core) and MgH+ molecular ions (invisible) [University of Aarhus, unpublished]

Another direction of studies is the formation of structural defects and their stability. PICC partners carried out the first experimental realization of topological defects in the ion traps (see Figure 4). It was experimentally possible to increase the defects life-time to approximately 10 seconds. This duration provides sufficient stability and precision for the vibrational spectroscopy. Stability and dynamics of such defects, indeed, provides a basis for simulating quantum field theoretical models with trapped ions [7].

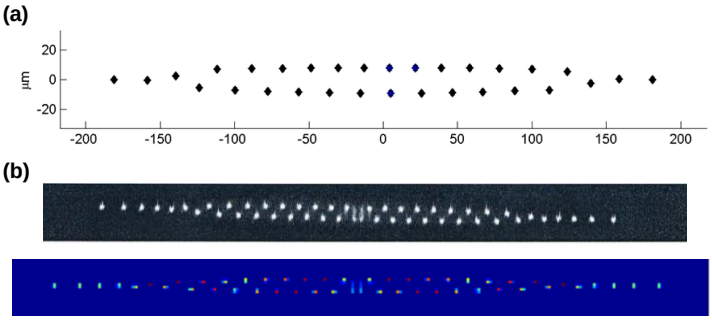

Figure 4: Topological defects in two-dimensional Coulomb crystals

Quantum simulators. The toolbox for a quantum simulator is being extended. Deterministic entanglement of selected pairs of ions in a three-ion chain (see Fig. 5 a) [8] was demonstrated. The entangling protocol that was developed is versatile, since it can be applied for neighbouring as well as nonneighbouring ions by taking advantage of a long-range spin-spin interaction due to magnetic gradient induced coupling (MAGIC). The deterministic creation of entangled pairs was proven by measuring the parity function along different measurement bases for neighbouring (see Fig. 5 c) and the nonneighbouring case (see Fig. 5 d) [8]. This deterministic entanglement was possible due to high-fidelity single-ion addressing using microwave radiation achieved by frequency selection in the presence of a magnetic gradient (see Fig.5b) [8]. Trapping conditions have been realized that allow for controlling the coupling between ions by merely changing voltages on electrode segments.

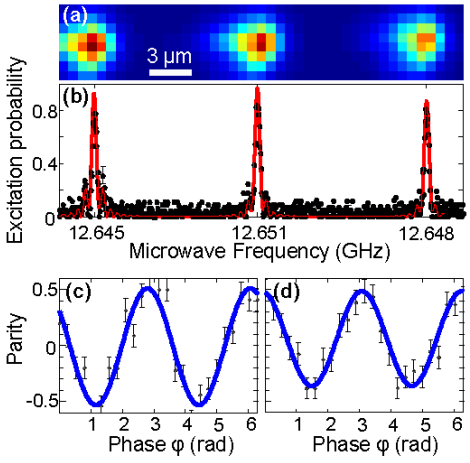

Figure 5: Image of three 171-Ytterbium ions (a) trapped in a gradient of magnetic field that allows addressing each one of them using microwaves as seen in the frequency spectrum (b). The entanglement of selected pairs is demonstrated by the measured parity function of the first two ions (c) as well as between the endpoints of the ion chain (d).

This remarkable progress opens the way for the realization of quantum simulations of dynamics of complex many-body systems. PICC partners have developed several protocols in the last year. One example is a protocol for the realization of the spin-Peierls instability, describing a structural transition of a crystal due to strong magnetic interactions (see Figure 6) [9]. Another protocol exploits the geometry of a zigzag cold-ion crystal in a linear trap to realize the quantum simulation of a paradigmatic model of long-ranged magnetic frustration (see Figure 7) [10]. Such quantum simulation would clarify the complex features of a rich phase diagram that presents ferromagnetic, dimerized-antiferromagnetic, paramagnetic, and floating phases, together with previously unnoticed features that are hard to assess by numerics. These studies indeed show that cold ICC provide an excellent experimental test-bed in which to study complex many-body problems.

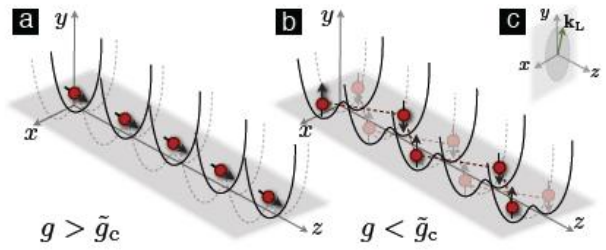

Figure 5: Spin-Peierls transition with trapped ions

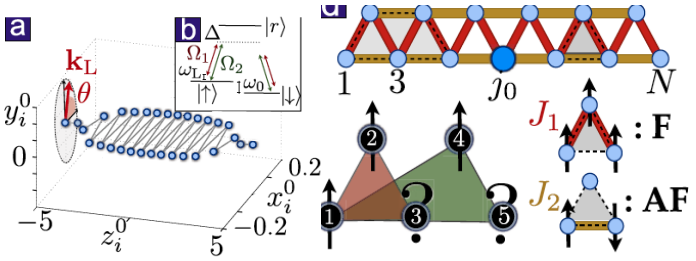

Figure 6: Zigzag ladder and scheme of spin interactions

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RELATED PAST EVENTS

- Spring Meeting of the German Physical Society of the AMOP and Condensed-Matter divisions, 12-16 March 2012, Stuttgart, Germany
- QION12 - Workshop on Quantum Information and Quantum Dynamics in ion Traps, 25-29 March 2012, Tel Aviv, Israel
- International Conference on Quantum Optics, 12-18 February 2012, Obergurgl, Austria

THE CONSORTIUM

The consortium is composed of 4 experimental and 4 theory partners. All partners are recognized and long-standing experts in the physics of ion Coulomb crystals:

Universität des Saarlandes
Giovanna Morigi
http://qphys.uni-saarland.de/

Imperial College London
Richard Thompson and Danny Segal
http://www.lsr.ph.imperial.ac.uk/iontrap/

Aarhus Universitet
Michael Drewsen
http://phys.au.dk/research/amo/the-ion-trap-group/

Tel Aviv University
Benni Reznik
http://www.tau.ac.il/~quantum/Reznik/Reznik.html

Universität Ulm
Martin B. Plenio & Susana F. Huelga
http://qubit-ulm.com/ and
Tommaso Calarco
http://www.uni-ulm.de/en/nawi/institute-for-quantum-information-processing.html

Universität Siegen
Christof Wunderlich, Michael Johanning
http://www.uni-siegen.de/fb7/quantenoptik/

Universidad de Complutense de Madrid
Miguel A. Martin-Delgado, Diego Porras
http://www.ucm.es/info/giccucm/index.php/GICC.html

Albert Ludwigs Universität Freiburg
Tobias Schätz
http://www.qsim.uni-freiburg.de/

PICC PEOPLE

The first PICC newsletter presented the coordinator and principal investigator of the theory node at Saarland University. This second newsletter is presenting the other theory partners. The third newsletter will finally introduce PICC experimental partners in more detail.

Tel Aviv University

Prof Benni Reznik

Leader of WP6

Benni Reznik is a member of the School of Physics and Astronomy at Tel Aviv University. His earlier works involved topics in quantum gravity, quantum foundations and quantum information. More recently he has been interested in quantum simulations of quantum field effects, such as black hole radiation and topological defects with trapped ions, and in the simulation of dynamical gauge fields using ultra cold atoms.

Universidad Complutense de Madrid

Prof Miguel Martín-Delgado

Leader of WP8

Miguel Angel Martín-Delgado has been holding a chair of theoretical physics at the Universidad Complutense de Madrid since 2002. He has been working in quantum field theory and lately on the theory of quantum information and application to atomic and molecular systems. Within PICC he is developing proposals for the implementation of topological codes with trapped ions.

Universidad Complutense de Madrid

Dr Diego Porras

Diego Porras has been a Ramón y Cajal Fellow at Universidad Complutense de Madrid since 2009. He works on the theoretical description of many-body effects in trapped ion crystals, in particular in the implementation of strongly correlated phases of effective spin-phonon systems. This is an exciting multidisciplinary field at the interface between condensed matter physics and quantum optics. He started this research line in 2004 when he was a post-doc at the Theory Division of the Max-Planck Institute, and works in close collaboration with several experimental groups. Most recent interests include the theoretical investigation of dissipative phase transitions and spin-glass physics in trapped ion systems.

University of Ulm, Institute of Theoretical Physics

Dr Alex Retzker

Alex Retzker has been an active collaborator of the PICC project for more than two years. His fields of interest include: Quantum technologies, Quantum sensing, Quantum optics Quantum information, Quantum Simulations, Trapped IonsNV centers in diamond, Nanomechanics and optomechanics Bose Einstein condensates. His work is strongly connected to experimental implementations and is conducted in close collaboration with experimentalists. He recently moved from the University of Ulm to the Hebrew University in Jerusalem.

University of Ulm, Institute of Theoretical Physics

Prof Susana Huelga

Susana Huelga joined the Institute of Theoretical Physics of Ulm University in October 2009 after more than 13 years working in England, where she led the Quantum Information group at the University of Hertfordshire. She has experience in theoretical quantum optics and quantum information, her research focusing in analysing the interplay between coherent and dissipative interactions and the persistence of quantum effects in noisy environments. She has contributed towards the development of quantum metrology and has recently pioneered work in the newly developed field of quantum biology.

University of Ulm, Institute of Theoretical Physics

Prof Martin Plenio

Leader of WP9

Martin Plenio (PhD 1994), is Director of the Institute for Theoretical Physics at Ulm and holds a part time position at Imperial College London. He has made fundamental contributions that shaped the development of entanglement theory, the implementation of quantum information processing and quantum simulation with atoms, ions and photons, noise-assisted quantum processes and quantum biology. He has been working on the physics of ion traps since 1999 and has become interested in the physics of Coulomb ion crystals and their non-equilibrium properties in 2007. His awards and prizes include the Maxwell Medal and Prize of the UK Institute of Physics 2004, an Alexander-von-Humboldt Professorship in 2008 and the Max-Born Medal and Prize of the German Physical Society and the UK Institute of Physics in 2012.

University of Ulm, Institute for Quantum Information Processing

Prof Tommaso Calarco

Leader of WP5

Tommaso Calarco has been professor at the Institute for Quantum Information Processing at the University of Ulm since 2007. He is an expert in optimal control of quantum systems, in both quantum optical and many-body contexts. He actively participated in several European projects related to quantum computation, information, communication and technology: among these ACQUIRE (Atom Chips for QUantum Information REsearch), ACQP (Atom-Chip Quantum Processor), SCALA (SCAlable quantum computation with Light and Atoms), AQUTE (Atomic Quantum Technologies, which he coordinates) and PICC. He is executive secretary and roadmap coordinator of the Coordination Action QUROPE (Quantum information processing and communication in eUROPE). He is acknowledged for his contributions in building bridges between theoretical and experimental physics, and in networking among research groups in the field of quantum technology.

University of Ulm, Institute for Quantum Information Processing

PD Dr Simone Montangero

Simone Montangero has been assistant professor at Ulm University since 2008 and "Privat Dozent" since 2010. He has been Humboldt Fellow at Karlsruhe University and Postdoc at Scuola Normale Superiore in Pisa. He is principal investigator in European and DFG projects on quantum information and correlated quantum systems. His research interests cover quantum information and condensed matter, extreme simulations, quantum (many-body) optimal control and complex systems. Within PICC he is coordinating the efforts to develop numerical tools to characterise, simulate and control the dynamics of quantum Ion Coulomb Crystals. The results of these ongoing studies include the full characterisation of the linear-zigzag quantum phase transition and the study of the quantum Kibble-Zurek mechanism in ion chains.

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