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

The ability to control the dynamics of quantum systems with increasing size and complexity is a prerequisite of quantum technologies [1]. Among the physical systems considered so far, trapped ions, laser cooled to form string-like ordered structures, occupy a prominent position in the quest for the realization of quantum information processors [1]. With this system, indeed, the basic logic gates of a quantum computer have been successfully demonstrated [2], and entangled states of several ions (a "quantum byte") have been experimentally realized and fully characterized [3]. These formidable achievements are based on the high degree of control of the internal and external degrees of freedom that can be achieved for small numbers of trapped ions [4]. The challenge of realizing large-scale processors and quantum simulators based on ions, however, requires that one deals with more complex structures, which may include mesoscopic ordered ion ensembles, i.e., ion Coulomb crystals [5]. In this regime, it is expected that the effect of noise will grow in importance and the control techniques, which have been so successfully applied to small numbers of ions, often become inefficient. This raises the timely issue of identifying novel and efficient strategies for controlling the quantum dynamics and manipulating the quantum state of Ion Coulomb Crystals (ICC).

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:

The research line **"A) Thermodynamics of ion Coulomb crystals"** identifies control tools by focusing on the crystal collective motion. Methods for monitoring the statistical properties of the ion crystal are developed and experimentally tested here.

The research line **"B) Quantum dynamics of ion Coulomb crystals"** is mainly concerned with developing strategies for robust and scalable quantum dynamics. It aims at identifying strategies for fighting the noise introduced by the coupling of the ICC with the external environment, and, when possible, at exploiting it for Quantum Information Processing (QIP) purposes.

Finally, the research line **"C) Ion Coulomb crystals as quantum simulators"** exploits this knowledge in order to implement biological, solid-state, and field-theoretical models with ICC. The long-term vision underlying this project is to engineer quantum correlations and entanglement in ICC in order to be able to achieve controlled quantum dynamics to study the physics of many-body systems and to exploit them for technological purposes of different kinds. Compared to the current ability to manipulate small numbers of ions, the PICC project breaks new ground in two directions. First, it directly tackles the outstanding problem of controlling the system dynamics when the number of ions is scaled up, by dealing with many-ion systems right from the start. Moreover, the project develops the recently proposed, but yet largely unexplored, concept of quantum simulators based on ultracold ions.

References
[1] P. Zoller, et al., Eur. Phys. J. D36, 223 (2005)
[2] F. Schmidt-Kaler, et al., Nature 422, 408 (2003), Leibfried et al., Nature 422, 412 (2003)
[3] D. Leibfried, et al., Nature 438, 639 (2005), Häffner et al., Nature 438, 643 (2005)
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[5] D.H.E. Dubin, et al., Rev. Mod. Phys. 71, 87 (1999)

RESULTS ACHIEVED SO FAR

Thermodynamics. One central subject of investigation of the PICC project is the linear-zigzag structural transition in ion crystals. This transition is controlled by ramping down the transverse trap frequency. When the transverse frequency crosses a critical value, a linear array of ions becomes unstable and makes a continuous transition to a double string. In the classical limit this structural transition is a second-order phase transition, which is well described by the Landau model. The effects of quantum fluctuations on the phase transition are being investigated within the PICC project. In particular, in Ref. [6] it has been theoretically shown that this structural transition is a quantum phase transition, which can be mapped to the Ising model in a transverse field, describing a quantum ferromagnetic transition at temperature T=0. A phase diagram has been determined for the quantum state of the crystal as a function of the temperature and of the trap frequency, which is displayed in Fig. 1(a). In the same publication, the experimental parameters have been identified for which the quantum effects at the phase transition can be detected: An example of the predicted structure form factor is displayed in Fig. 1(b). Codes for checking numerically this prediction and extending it to further regimes of experimental relevance have been developed and are being currently tested.

SEVENTH FRAMEWORK PROGRAMME

This work lays the ground for theoretical and experimental studies of quantum effects at the phase transition. If these predictions are confirmed, one immediate implication is that the linear-zigzag structural instability in ICC provides a natural playground for simulating quantum ferromagnetic systems.

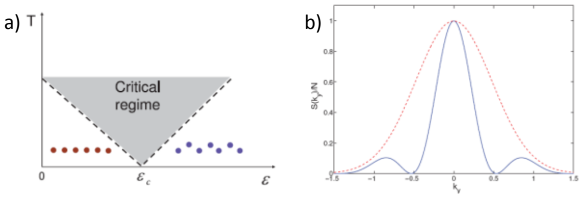

Fig.1 a) Phase diagram for a linear-zigzag quantum-phase transition. Here, T is the sample temperature and the dimensionless parameter ε is tuned by the confining potential or the interparticle distance. The classical instability of the linear chain occurs at ε = 0. The quantum critical point, at ε > 0, separates the linear from the zigzag phase at T=0. For $0 < \varepsilon < \varepsilon_c$, where classically a zigzag configuration is expected, quantum fluctuations dominate, and the crystal is in the linear (disordered) phase. The dashed lines indicate the boundaries of the quantum critical region. b) Structure form factor. The red dashed curve corresponds to the classically stable regime; the blue solid curve corresponds to the ion string in the quantum disordered phase regime.

Experimental tools for characterising the thermodynamic properties of ICC are being set: The first measurement of the temperature of ICC by means of an optical cavity has been reported. Non-harmonic trapping potentials have been realised: A notable example is the successful trapping of a single ion by means of lasers [7]. This progress opens new perspectives in the manipulation and control of ICC, such as the possibility of simulating the Frenkel-Kontorova model with trapped ions.

Quantum Dynamics. The issue of controlling noise and decoherence becomes increasingly relevant when the size of the ICC becomes larger. During the first year of the project techniques for minimising their detrimental effects have been proposed and characterised, which range from optimised trap designs to active methods for suppressing decoherence. Of remarkable impact is a protocol that uses dressing magnetic field sensitive states with microwave fields to prolong coherence, which has been reported in Ref. [8]. Measurements of a single-qubit gate with dressed states, realised by means of this protocol, are displayed in Fig. 2. This result 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.

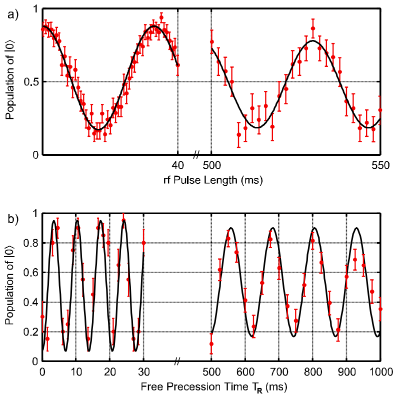

Fig. 2. Single-qubit gates with dressed states. a) Rabi oscillations between dressed state |B⟩ and |0'_⟩ induced by an rf field for times up to more than 500 ms. Population in |B⟩ is mapped onto state |0⟩ at the end of the STIRAP and detection sequence (each datapoint is the average of 50 [up to 40 ms] or 25 repetitions [over 500 ms]). b) Ramsey-type measurement preparing a coherent superposition of |B⟩ and |0'_⟩ and probing it after time T_R. Two rf π/2-pulses separated by time T_R of free evolution are applied to the qubit transition.

Further theoretical studies developed protocols based on optimal-control and quantum-reservoir-engineering techniques, which can allow to control the many-body dynamics of quantum systems. In Ref. [9] it is shown that non-equilibrium dynamics of an ion chain in a Paul trap constitutes an ideal scenario to test the inhomogeneous extension of the Kibble-Zurek mechanism, which lacks experimental evidence to date. An example of defects (kinks) formed when quenching the trap frequency across the linear-zigzag critical point is displayed in Fig 3.

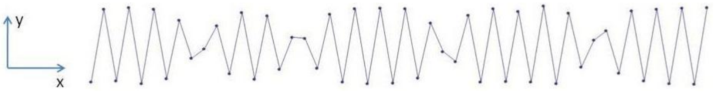

Fig. 3. Ion chain in a zigzag configuration exhibiting structural defects: the distribution of charges in two dimensions is mapped to a line for clarity. The solid line joining the ions serves as a guide to the eye. In the example reported, there are four defects.

Quantum Simulators. Protocols for simulating quantum field theoretical models, condensed-matter systems, and biological systems have been proposed. Specifically, it has been shown that an ion chain can simulate spin-models exhibiting frustration, Anderson localization [10] (see Fig. 4), the Fermi effect, and noise-assisted quantum dynamics (a physical mechanism presently discussed in the framework of light harvesting in biological complexes). The experimental groups have characterised spin-spin coupling in ion chains and demonstrated the ability to split and shuttle ICC by means of suitably designed trap setups. The stage has been thus set for novel and exciting experimental realisations of quantum simulators.

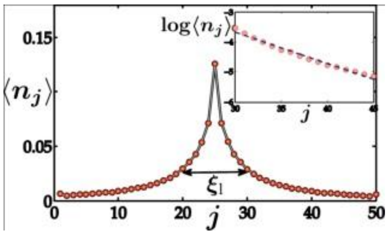

Fig. 4. Anderson localization of a vibrational excitation in an ion chain. The figure displays the calculated number of phonons per ion in a chain of 50 ions. An initial state with one phonon in the centre of the chain is created but cannot propagate freely due to the disorder induced by the internal states. The inset shows the exponential decay of the localized phonon wavefunction.

References:

[6] E. Shimshoni et al, Phys. Rev. Lett 106, 010401 (2011) and Phys. Rev. A 83, 032308 (2011)
[7] Ch. Schneider et al, Nature photonics 4, 772 (2011)
[8] N. Timoney et al, Nature 476, 185–188 (2011)
[9] A. del Campo et al, Phys. Rev. Lett. 105, 075701 (2010)
[10] A. Bermudez et al, New J. Phys. 12 123016 (2010)

SELECTED PUBLICATIONS

- Structural defects in ion crystals by quenching the external potential: the inhomogeneous Kibble-Zurek mechanism; A. del Campo, G. De Chiara, G. Morigi, M. B. Plenio, A. Retzker; Phys. Rev. Lett. 105, 075701 (2010); arXiv:1002.2524
- Optical Trapping of an Ion; Ch. Schneider, M. Enderlein, T. Huber and T. Schaetz; Nature Photonics 4, 772-775 (2010); arxiv.org:1001.2953
- Localization of phonons in ion traps with controlled quantum disorder; A. Bermudez, M.A. Martin-Delgado, and D. Porras; New J. Phys. 12, 123016 (2010). arxiv.org:1002.3748
- Quantum zigzag transition in ion chains; E. Shimshoni, G. Morigi, S. Fishman; Phys. Rev. Lett 106, 010401 (2011); arXiv:1008.2326
- Optimal control technique for Many Body Quantum Systems dynamics; P. Doria, T. Calarco, and S. Montangero; Phys. Rev. Lett. 106, 190501 (2011); arxiv.org:1003.3750
- Quantum Gates and Memory using Microwave Dressed States; N. Timoney, I. Baumgart, M. Johanning, A. F. Varon, Ch. Wunderlich, M. B. Plenio, A. Retzker Nature 476, 185–188 (2011); arxiv.org:1105.1146
- Cavity electromagnetically induced transparency and all-optical switching using ion Coulomb crystals; M. Albert, A. Dantan, and M. Drewsen; Nature Photonics 5, 633–636 (2011); arxiv.org:1102.5010

RELATED EVENTS

- QIon11 – Workshop on Quantum Information and Quantum Dynamics in Ion Traps, Madrid (Spain), April 26-29, 2011 http://qion11.info/
- QIPC 2011 - Conference at ETH Zurich Zurich (Switzerland), September 5-9, 2011 http://www.qipc2011.ethz.ch/
- Workshop on "Engineering and Control of Quantum Systems"; Dresden, October 10-14, 2011 http://www.mpipks-dresden.mpg.de/~ecoqas11/
- IOTA-COST Workshop and Training Event on Cold Molecular Ions; Sandbjerg Estate (Denmark); November 23-25, 2011; http://iota-cost.au.dk/
- Winter School on Physics with Trapped Charged Particles, Les Houches, France, January 9-20, 2012 http://indico.cern.ch/conferenceDisplay.py?confId=127522

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 and are reported below:

Universität des Saarlandes
Giovanna Morigi
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Imperial College London
Richard Thompson and Danny Segal
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Aarhus Universitet
Michael Drewsen
http://phys.au.dk/research/amo/the-ion-trap-group/

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Universität Ulm
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Universität Siegen
Christof Wunderlich, Michael Johanning
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Universidad de Complutense de Madrid
Miguel A. Martin-Delgado, Diego Porras
http://www.ucm.es/info/giccucm/index.php/GICC.html

Max Planck Gesellschaft zur Förderung der Wissenschaften e.V.
Tobias Schätz
http://www.mpq.mpg.de/qsim/

PICC PEOPLE

Universität des Saarlandes, Prof. Giovanna Morigi (Scientific Coordinator)

Giovanna Morigi was awarded the Heisenberg professorship by the German Research Foundation in 2008 and has been holding the chair of Theoretical Quantum Optics at Saarland University's physics department since fall 2009. She has been working, amongst other theory subjects, on the theory of ion Coulomb crystals since 1999, exploring several aspects such as laser cooling and statistical mechanics of ion Coulomb crystals and is closely collaborating with ion-trap experimental groups with focus on quantum technological implementations. She is also internationally recognized for her contributions to the theory of Laser cooling of atoms, ions, and molecules, and of Cavity Quantum Electrodynamics with cold atoms.

The other project partners will be presented in our next newsletters.

MISCELLANEOUS

- The PICC website: http://qphys.uni-saarland.de/index.php/picc
- PICC people welcoming science-loving children for hands-on experiments: http://qphys.uni-saarland.de/index.php/picc/events/ ("Open House at USIEG")

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