European Conference on Trapped Ions | hybrid ECTI 2021

Monday, 22 November 2021 - Friday, 26 November 2021

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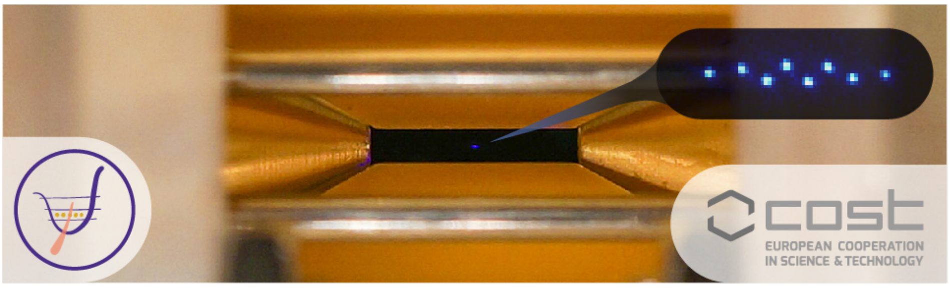

Book of Abstracts

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Correlation spectroscopy with multi-qubit-enhanced phase estimation

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Precision spectroscopy with trapped ion crystals subject to correlated dephasing can reveal a multitude of information in the absence of any single-particle coherences. We present measurements of ion-ion distances, transition frequency shifts and single-shot measurements of laser-ion detunings by analyzing multi-particle correlations in one- and two-dimensional ion crystals of up to 91 ions. We show that the information contained in N-particle correlations reduces the measurement uncertainty as compared to the case where only two-particle correlations are analyzed.

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Quantum technologies for molecular ions

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The development of quantum technologies for molecules has remained a long-standing challenge due to the complexity of molecular systems. We have recently developed a technique for the non-destructive detection of the internal quantum state of a single trapped molecular ion [1,2,3]. The method is based on the state-dependent coherent excitation of the motion of the molecular ion and subsequent measurement of the motional quantum state using a co-trapped atomic ion. This approach offers new perspectives not only for the detection, but also for the preparation and the manipulation of molecular quantum states on the single-particle level with a sensitivity several orders of magnitude higher compared to previously used destructive schemes. We present a characterisation of the technique using the homonuclear diatomic ion N2+ as an example and show how it can be used for non-invasive spectroscopic measurements on single molecules. We also discuss applications of this technique in the realm of precision molecular spectroscopy [4,5] using a newly established fibre network for the precise transfer of frequencies within Switzerland and their comparison to the primary frequency standard at Swiss Federal Institute of Metrology METAS.

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[2] M. Sinhal, Z. Meir, K. Najafian, G. Hegi and S. Willitsch, "Quantum non-demolition state detection and spectroscopy of single trapped molecules", Science 367 (2020), 1213
[3] K. Najafian, Z. Meir, M. Sinhal and S. Willitsch, "Identification of molecular quantum states using phase-sensitive forces", Nat. Commun. 11 (2020), 4470
[4] K. Najafian, Z. Meir and S. Willitsch, "From megahertz to terahertz qubits encoded in molecular ions: theoretical analysis of dipole-forbidden spectroscopic transitions in N2+", Phys. Chem. Chem. Phys. 22 (2020), 23083
[5] D. Husmann et al., "SI-traceable frequency dissemination at 1572.06 nm in a stabilized fiber network with ring topology", Opt. Expr. 29 (2021), 24592

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Recent results from the double ion-storage ring, DESIREE

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The storage ring facility, **DESIREE**, is briefly introduced and two examples of experiments and their astrophysical implications are discussed. **1: Mutual-neutralization** reactions between negative hydrogen and positive metal ions are studied in DESIREE to aid quantitative analysis of abundances of such metals from stellar spectra. **2: Polycyclic aromatic hydrocarbons** (PAHs) are believed to be ubiquitous in interstellar space. We have studied the stability of PAH fragments formed exclusively in collisions taking place at stellar-wind velocities by storing such collision products in DESIREE for up to seconds or minutes.

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EIT cooling of 2D arrays with hundreds of ions in a Penning trap

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Large trapped ion crystals with N > 100 ions provide a versatile platform for quantum simulations. Penning traps utilize static electric and magnetic fields to confine the ions and enable the formation of large two-dimensional ion crystals with hundreds of ions. In this talk, I will discuss recent results of electro-magnetically induced transparency (EIT) cooling that enables near ground-state cooling of the center-of-mass mode of hundreds of ions, as well as significant cooling of hundreds of drumhead modes [1]. We will discuss the implementation of EIT cooling, the observed cooling rates, and how we measure the temperature of large ion crystals. The experimental results are well described by numerical manybody simulations [2]. Near-ground state cooling will be used to initialize the axial modes to very low temperatures, thereby greatly improving the quality of quantum simulation and quantum metrology protocols.

References

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[2] A. Shankar et al. Phys. Rev. A 99, 023409 (2019)

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Observation of chemical reactions between a trapped ion and ultracold Feshbach dimers

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In this talk I will present measurements of chemical reactions between a single trapped Yb+ ion and an ultracold bath of Li atoms containing trace amounts of Li_2 dimers. This produces $LiYb^+$ molecular ions that we detect via mass spectrometry. Our results present a novel approach towards the creation of cold molecular ions and point to the exploration of ultracold chemistry in ion molecule collisions. What is more, with a detection sensitivity below molecule densities of $10^{14}m^{-3}$, we provide a new method to detect low-density molecular gases. I will also discuss the prospects and limitations of using general time-dependent traps in trapped ion buffer gas cooling and quantum chemistry.

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the PENTATRAP experiment

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The PENTATRAP experiment located at the Max-Planck Institute for nuclear physics aims to perform mass-ratio measurements on long-lived and stable nuclides with a fractional uncertainty below 1e-11. Such high-precision mass-ratio measurements are required to assist, e.g., experiments on the determination of the neutrino mass, on the search for the fifth force and on the investigation of atomic metastable states that can be suitable ion clock transitions. In this talk latest achievements and future plans with PENTATRAP are presented.

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Reaction studies with internally cold molecular ions in the CSR storage ring

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In last decades room-temperature ion storage rings have proven to be unique tools for investigating properties and reaction dynamics of molecular ions, in particular the low-energy electron-ion collisions in merged beams. This is mainly due to 1) the long storage of the ions allowing relaxation of the internal ion states and 2) the ion beam target preparation for experiments at high collision-energy

resolution by, e.g., electron cooling. The recently built Cryogenic Storage Ring (CSR) [1] in Heidelberg, Germany, with its < 6 K vacuum wall temperature brings these advantages to a new level: the low radiation field allows the molecules to relax down to their ro-vibrational ground-state. Studying collisions of cold molecular ions with electrons, photons, and atoms give access to unprecedented details on the respective reaction dynamics. Also, the CSR environment mimics well the conditions in the cold interstellar medium, which makes CSR an outstanding experimental set-up for laboratory astrochemistry.
In the talk the measurements from the first five years of CSR operation will be reviewed, with an emphasis on the recent rotational-state resolved dissociative recombination studies [2].
[1] R. von Hahn et al. Rev. Sci. Instr. 87 063115 (2016)
[2] O. Novotny et al., Science 365, 676 (2019)

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Ion-atom systems in the quantum regime

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The presence of strong interactions in a many-body quantum system can lead to a variety of exotic effects. For the case of a charged impurity in a weakly interacting bosonic medium the competition of length scales can give rise to a highly correlated mesoscopic state. Its properties are vastly different from neutral quantum impurities, with a large density increase close to the ion location and a huge effective mass. An experimental study of these effects requires reaching very low temperatures and controlling the ion-atom interaction strength. The combination of Ba ions and Li atoms features plenty of Feshbach resonances which can allow to enter this regime.

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Trapping electrons in a room-temperature quadrupole trap: towards an all-electronic microwave-enabled trapped electron qubit system for QIP

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We explore the feasibility of processing quantum information encoded in the spin of electrons trapped ion a Paul trap. The main idea is to replace the ions in a QCCD(quantum charge-coupled device) ion trap quantum computer with electrons. The combination of the low mass and simple internal structure should enable high-speed operation while allowing for high-fidelity operation. In particular, our simulation of common two-qubit error sources show that error rates of less than 1E-4 at clock speeds of 1 MHz for transport and quantum gates should be feasible.

Towards this goal, we trap single to few electrons in a millimeter-sized quadrupole Paul trap driven at 1.6 GHz in a room-temperature ultra-high vacuum setup. Electrons with sub-5 meV energies are introduced into the trap by near-resonant photoionisation of an atomic calcium beam and confined by microwave and static electric fields for several tens of milliseconds. A fraction of electrons remains trapped and shows no measurable loss for measurement times up to a second. Electronic excitation of the motion reveals secular frequencies from several tens to hundreds of MHz. Operating an electron Paul trap in a cryogenic environment may provide a platform for all-electric quantum

computing with trapped electron spin qubits.

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Optical Traps for Ions & Ultracold Atoms: The onset of controlling atom-ion quantum effects via Feshbach resonances

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Isolating ions and atoms from the environment is essential for experiments, especially if we aim to study quantum effects. For decades, this has been achieved by trapping ions with radiofrequency (rf) fields and neutral particles with optical fields. We are trapping ions by the interaction with light and electrostatic fields, in absence of any rf-fields. We take our results as starting point for studying how to combine the advantages of optical trapping and ions.
In the first part of the talk, we will focus on the basics of optically trapping ions. We aim to demonstrate the prospects of our approach in the context of interaction and reaction at ultra-low temperatures as a showcase. Following the seminal work in other groups in hybrid traps, we embed optically trapped ions into quantum gases to reach lowest temperatures, circumventing the currently inevitable excess kinetic energy in hybrid traps, where ions are kept but also driven by rf-fields.
In the second part, we will discuss our recent results on optically trapping 138Ba+ and 6Li atoms during our preparation stage, that is, still in our hybrid trap, where we recently observed atom-ion Feshbach resonances.

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Precision Ramsey-comb spectroscopy at short wavelengths for fundamental tests

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Spectroscopy of atoms and molecules have played a central role in our understanding of physics. It has also become increasingly important to measure the fundamental physical constants such as the fine-structure constant, the Rydberg constant, the proton-electron mass ratio, or the charge radius of the proton, deuteron and the alpha particle. In order to do so, a single type of measurement is typically not enough. Instead, measurements are performed (either with spectroscopy or other methods) in many different systems to construct a consistent picture of the laws of physics, and the fundamental constants that are required for them.

We pursue several targets for this purpose, 1S-2S spectroscopy of trapped singly-ionized helium, a determination of the ionization potential of molecular hydrogen, and spectroscopy of ultra-cold metastable neutral helium. In particular with He+ one can test the value for the Rydberg constant, the charge radius of the alpha particle, or test higher-order QED. Both He+ and molecular hydrogen require light sources at deep-ultraviolet or shorter wavelengths for excitation from the ground state. Frequency comb generation in the deep- and extreme-UV has been demonstrated based on

enhancement cavities, which can be used for direct frequency comb excitation. However, we use and developed a different method, Ramsey-comb spectroscopy (RCS), that has been highly successful for precision spectroscopy at short wavelengths. It is based on direct excitation with only two amplified and upconverted frequency comb laser pulses to generate a form of Ramsey fringes. The required phase and timing control of the light pulses is provided by an ultra-stable fiber frequency comb, and the short pulses enable amplification to high peak power for efficient frequency upconversion. Ramsey signals recorded at two or more inter-pulse delays (spaced at multiples of the comb repetition time) are used to record the phase evolution of the excitation signal as a function of time, from which the transition frequency can be accurately determined.

In the talk I will introduce our goal of precision spectroscopy of the 1S-2S two-photon transition (using 32 nm and 790 nm) of trapped and sympathetically cooled He+ ions. I will discuss the principle of RCS and harmonic upconversion to generate the wavelengths required for He+ excitation, and illustrate it with our latest progress of spectroscopy of the X-EF transition in para-hydrogen at 202 nm, and xenon at 110 nm using high-harmonic generation (HHG). In the last part I will present the current status of the He+ experiment, which involves setting up a new vacuum system, a planer ion trap with electronics and control software, and a new low phase-noise Ramsey-comb laser system specifically for the He+ experiment.

The work is funded by an ERC Advanced grant no. 695677 and a NWO Program grant 16MYSTP.

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Scalable and programmable bosonic network and quantum simulation with 2D ion crystals

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In this talk, we discuss two directions of scaling up the trapped-ion system for quantum computation and quantum simulation. The first one is to use vibrational degrees of freedom in a linear chain of ions and the second one is to use internal degrees of freedom in the 2D crystals of ions.

Recently, the vibrational degrees of freedom of trapped ions have been extensively studied and are getting more attention [1]. The vibrational modes with phonons can be a good alternative candidate to realize a bosonic network that is able to reveal the advantage of quantum computation by sampling the output distributions. Until now, mostly optical systems have been used to demonstrate boson sampling, but the technical challenges faced in optical systems, such as photon losses, imperfect photon detectors, non-deterministic single-photon generation make it difficult to convincingly demonstrate quantum advantage. However, in the phononic system, the number states can be deterministically prepared and detected and the total number of phonons is well conserved for all the collective modes except the center of mass modes. The main remaining problem is to develop a scalable scheme to realize coherent beam splitters with multiple modes. Here we present the phononic network with up to 4 modes with the capability of the beam splitting operations between any pairs of modes in a programmable way [2]. As the demonstration of the capability of the phononic network, we realized the algorithms of tomography for any multi-modes phononic states in a single measurement configuration [3].

For the second, we present the strong experimental evidence of the quantum simulation by preparing the ground state of the frustrated 2D Ising models through adiabatic evolution. We have developed the 2D crystal of ions in our monolithic Paul trap. In the Paul trap, we have mitigated the micromotion problem of the 2D crystal of ions for the coherent manipulation by applying the propagation direction of Raman laser beams perpendicular to the micromotion direction [4]. In the experiment, we first realize the vibrational ground states of 2D crystals of ions by applying the EIT cooling method [5]. Then we globally apply the spin-dependent force and simultaneously drive the carrier transition

to realize the transverse field Ising model [6]. We start the ground state of the transverse field, which slowly ramps down while keeping the Ising spin-spin interactions. We control the character of the spin-spin interactions by changing the detuning of Raman laser beams to various vibrational modes, which result in different ground states of the corresponding spin models [7].
We believe that these examples open the usage of trapped ion systems for large-scale quantum computation and quantum simulation.

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[4] Ye Wang, Mu Qiao, et al., Adv. Quant. Techn. 3, 2000068 (2020).
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A multiqubit quantum network node with trapped ions

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Trapped ions are known for being one of the leading quantum computing platforms as well as for their potential in metrology and sensing. Efficient interfacing of registers of trapped ions with travelling photons would allow to link them into a distributed network trapped-ion-based nodes. This can enable remarkable applications of the quantum networks e.g. in quantum enhanced distributed sensing, timekeeping, cryptography and multiparty protocols [1].

We present such light-matter interface, consisting of a string of ions in a linear Paul trap coupled to an optical cavity. The key capability we demonstrate is the pairwise entanglement distribution between several selected ions' qubits and several telecom band photons, travelling up to 100 km in a fibre. Together with the deterministic quantum logic, and quantum memory in the ion register this represents a functional quantum network node. As a test case, we demonstrate operation of our system as a 2-qubit quantum repeater node [2] in a middle of a 50 km fibre link.
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Improved isotope-shift-based bounds on bosons beyond the Standard Model through direct frequency-comb Raman spectroscopy of Ca^+ ions.

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I will present direct frequency-comb Raman spectroscopy of the $3d\ ^2D_{3/2}$ - $3d\ ^2D_{5/2}$ interval in all stable even isotopes of ^{A}Ca$^+$ (A = 40, 42, 44, 46, and 48) [1,2]. With an accuracy of $\sim$20 Hz on the deduced isotope shifts, these data, combined with measurements of the $4s\ ^2S_{1/2} \leftrightarrow 3d\ ^2D_{5/2}$ transition ($\sim$2 kHz accuracy), allowed us to carry out a King plot analysis with unprecedented sensitivity to the coupling between electrons and neutrons by bosons beyond the Standard Model. Furthermore, we estimate that with improved spectroscopic techniques already available, King plots based on data from spectroscopy of either Ca$^+$, Ba$^+$ or Yb$^+$ should be able to probe new physics interactions mediated by bosons with masses ≥ 0.3 MeV/c^2 that are so far unconstrained by other experiments.

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Quantum simulation and sensing with 2D ion crystals in a Penning trap\^{1,2}

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Co-authors: Kevin Gilmore [2]; Matthew Affolter [3]; Diego Barberena [4]; Robert Lewis-Swan [5]; Elena Jordan [6]; Ana Maria Rey [7]

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I will describe a quantum-enhanced sensor to detect weak motional displacements and electric fields using a large crystal of ~ 150 trapped ions. The center-of-mass vibrational mode of the crystal serves as high-Q mechanical oscillator and the collective electronic spin as the measurement device. By entangling the oscillator and the collective spin before the motional displacement is applied and by controlling the coherent dynamics via a many-body echo that disentangles the spin and motion, we can map the displacement into a spin rotation and avoid quantum back-action and cancel thermal noise. We report quantum enhanced sensitivity to displacements of 8.8 dB below the standard quantum limit and 19 dB below thermal noise. I will discuss how our current sensitivity is likely limited by poor cooling of the ExB in-plane modes. As time permits, I will describe a protocol for introducing general σ_z rotations on rotating 2d ion crystals that would increase the complexity of quantum simulations on this platform.

1. In collaboration with Kevin A. Gilmore, Matthew Affolter, Robert J. Lewis-Swan, Diego Barberena, Elena Jordan, and Ana Maria Rey.
2. K. A. Gilmore et. al., Science 373, 673 (2021).

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Communication and energy transfer between ionic chromophores in tailor-made systems

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In a network of chromophores (i.e., light-absorbers) such as that in photosynthetic proteins, the chromophores interact strongly at short distances where orbital overlap is significant, and new quantum states arise after photoexcitation. These states are no longer associated with one chromophore but spatially delocalized over two or more chromophores. On the other hand, when the chromophores are more separated and the electronic coupling weaker, we can to a good approximation talk about a "locally" excited chromophore that can transfer its energy to a nearby chromophore in a process called FRET (Förster Resonance Energy Transfer). In the case of ionic chromophores, there is an additional form of communication that occurs even in the ground state when the electric field from one chromophore is strong enough to polarize another and vice versa. This interaction affects the transition energy of the chromophore (i.e., Stark shift) and as a result has an impact on the exciton states and FRET. To reveal the maximum effect of a charged chromophore on another charged one, it is advantageous to study the systems isolated in vacuo where there are no solvent molecules to screen the charges, an extreme case so to speak. Our approach is gas-phase fluorescence spectroscopy based on the custom-made LUNA/2 (LUminescence iNstrument in Aarhus) setups where ions produced by electrospray ionization (ESI) are mass-selected (and cooled in LUNA2) and photoexcited in a cylindrical Paul trap followed by collection of emitted photons. We have chosen systems composed of rhodamine dyes for several reasons: They are strongly fluorescent, each dye carries a positive charge and has no dipole moment along its long axis in the absence of electric fields, and they are easily formed by ESI. Recent results on dyads and triads will be presented.

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Quantum state control and precision spectroscopy of single molecular ions

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We demonstrate coherent quantum state manipulation and precision spectroscopy of a CaH+ molecular ion based on quantum-logic spectroscopy [1-6]. Similar to atomic ions, nowadays single molecular ions can be initialized and nondestructively detected the in a pure quantum state, albeit in a probabilistic but heralded fashion [2-6]. Numerous terahertz transitions between CaH+ states with different principal rotational quantum number J are directly probed with an optical frequency comb (OFC) [2, 3, 7], recently attaining sub-10 Hz spectroscopic linewidths and sub-Hz statistical uncertainty [8]. The effect of trap radio-frequency (RF) electric field on the rotational transitions is characterized and exploited to measure the dipole moment of CaH+ [8]. Coherent Rabi flopping is observed between different rotational states [7]. The initial and final states of the transitions, separated by Delta J = 2, can both be nondestructively detected [4-6], which facilitates unambiguous assignment of the observed signal to the corresponding rotational transitions.

We have also demonstrated entanglement of a molecular ion with an atomic ion [9], with possible applications in quantum information science. To further expand and improve quantum state control over CaH+, a 285-GHz millimeter-wave source is incorporated in the experiment to complement the OFC in coherent manipulation of CaH+ rotational states. Aiming at minimizing the adverse

effects of blackbody radiation and background gas collision on molecular states, a new trap apparatus compatible to cryogenic operation is under development. Different molecular species could be introduced to the new trap via a molecular beam source attached to the set-up. Our methods are designed with the prospects of investigating and exploiting coherent rotational-vibrational transitions of a large class of diatomic and polyatomic molecules in the optical and infrared domains with high precision.

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MissIons: Missing Ions in Laboratory

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Ions play a key role in the chemical evolution of our universe. The process of star and planet formation is tightly connected to the presence and abundance of these species. Their spectra are diagnostic tools for various astrophysical environments and their temporal evolution. However, laboratory spectra of most ions relevant to astrophysics are not available. Moreover, predicted spectra from abinitio theory are not nearly accurate enough to guide astrophysical searches. Therefore, laboratory spectra of molecular ions are needed.
We will report on progress towards recording high-resolution spectra from the microwave to visible range using our unique and innovative light induced reactions (LIR) methods in ion traps [1]. It is molecule specific through mass selection, many orders of magnitude more sensitive and less complex due to buffer gas cooling as compared to conventional methods. Examples concern the molecule first observed in space, CH^+ [2] but also ions which can play an important role in the chemical development producing more complex species, e.g., C_3H^+ [3] and $C_3H_2^+$ [4]. For many reasons H_3^+ is the corner stone in ion chemistry. It gives away its proton to most other species. As a result, protonation of more complex species, like methanol, could be another key towards the formation of complex organic species, molecules which are observed with today's telescopes but how they come into existence is under debate. We will discuss the tools to record the spectra and to understand the relevant reactions in the laboratory.

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Optical frequency measurements with sub-hertz accuracy using highly charged ions

Authors: Steven A. King[1]; Lukas Spieß[1]; Peter Micke[2]; Alexander Wilzewski[1]; Tobias Leopold[1]; Erik Benkler[1]; Nils Huntemann[1]; Richard Lange[1]; Lisa Schmöger[3]; Maria Schwarz[3]; José R. Crespo López-Urrutia[3]; Piet O. Schmidt[1]

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It has been more than a decade since highly charged ions (HCI) were first proposed as exciting candidates for next-generation frequency standards [1] and for precision tests of fundamental physics [2]. The technical obstacles hindering the development of a competitive clock based on a cold HCI have fallen one by one, starting with the extraction of an HCI from a hot plasma and sympathetic cooling using Be+ ions in a linear Paul trap [3], followed by quantum logic spectroscopy of the clock transition in a single HCI [4], and finally full control over the motional state of the HCI at the single-quantum level [5].

We will present preliminary results from the first measurement of the absolute frequency of an optical transition in an HCI using optical-clock-like spectroscopic techniques, obtained by local comparison to an optical frequency standard based on the electric octupole transition in 171Yb+ [6] using a femtosecond optical frequency comb. The measurement accuracy is almost eight orders of magnitude beyond the previous state of the art [7]. The main systematic perturbations of the clock transition are also evaluated, along with measurements of some important atomic properties such as the g-factor and quadrupole moment of the excited electronic state. These results bring HCI finally into the accuracy realm of optical atomic clocks.

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online ECTI / 22

Feedback cooling and efficient detection of a levitated nanoparticle in a Paul trap

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Optomechanical systems in the quantum regime allow us to probe quantum mechanics at the boundary between the microscopic and macroscopic; these systems are also promising candidates for precision sensors. By levitating an optomechanical system in an ion trap, we decouple it from its environment, a significant advantage for quantum applications.

Interferometric methods have been used in trapped-ion experiments for detecting mechanical motion at the level of single quanta [1]. We have recently adapted this approach for nanoparticles [2], and here, I will present experimental results on efficient position detection via self-interference. As an application, we cool a nanoparticle, via feedback, to temperatures below those achieved in the same setup using a standard position measurement. As an outlook, I will outline a route to the quantum regime and discuss the role that an atomic ion can play in enabling the preparation of nonclassical motional states of a nanoparticle.

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online ECTI / 23

Optical clocks with trapped Yb+ ions for autonomous operation

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The talk summarizes our work on optical atomic clocks at PTB and in the quantum technology project opticlock [1] both employing trapped Yb+ ions. The 171Yb+ ion provides two atomic transitions that are well suited as a frequency reference: the S-D electric quadrupole (E2) transition at 436 nm and the S-F electric octupole (E3) transition at 467 nm. The latter is known for its years-long excited state lifetime [2] and shows smaller sensitivity to external electric and magnetic fields. Consequently, smaller systematic uncertainties can be achieved with optical clocks based on the E3 reference transition [3], but their experimental complexity is significantly increased. Furthermore, the frequency ratio of the E3 and E2 transition is a sensitive measure for variations in the fine structure constant. Repeated measurements provide a test of local position invariance and we found the most stringent limits for temporal drifts and a potential coupling to gravity for the fine structure constant and the proton-to-electron mass ratio [4].
For applications beyond basic research, robust long-term operation is a particular requirement instead of the ultimate accuracy achieved with laboratory clock systems. In this context, we developed in collaboration with industry partners a demonstrator of an optical clock set up in two 19" racks that uses the E2 transition as the reference. This system recently demonstrated 14 days of operation with more than 99% availability enabled by fast optimization routines.
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online ECTI / 24

Tailored States and Measurements for Ion Clocks

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Optical atomic clocks based on cold trapped ions offer the possibilities to exploit the sophisticated tools of quantum control devoloped for quantum information processing for new protocols in frequency metrology. I will present results on optimization of such protocols towards tailored States and measurements for ion Clocks. I will also discuss prospects and challenges for quantum enhanced protocols in optical atomic clocks in general.

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A qudit quantum processor with trapped ions

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Today's quantum computers are almost exclusively built for binary information processing, inherited from classical computers. Yet, the underlying quantum systems, in particular trapped ions, are inherently multilevel systems. I will discuss how to construct a universal toolbox for quantum information processing in (almost) the full Hilbert space of Ca40 ions. We demonstrate that the performance of the quantum processor does not degrade with qudit dimension, making this a promising way to scale the computational power of existing quantum hardware.

Mainz satellite meeting + hybrid ECTI / 26

Quantum state-resolved collisions of cold trapped negative ions

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Negative molecular ions have drawn a lot of attention in recent years, because of their detection in interstellar space and of opportunities to use laser-cooled anions to cool antiproton. Cryogenic radiofrequency ion traps are well suited tools to study the quantum states and state-selected chemistry of negative ions. Using photodetachment spectroscopy we have probed rotational quantum states of cold trapped anions and studied rotational state-changing collisions at low temperature. This also allowed us to perform rotational terahertz spectroscopy and infrared overtone spectroscopy. We have further studied photodetachment of two interstellar anions near threshold. For CN- the measurements are well described by Wigner's threshold law. For C3N- the large permanent dipole moment of C3N leads to a qualitatively different cross section behavior. Furthermore, the rotational contour of a dipole bound state was resolved slightly below the detachment threshold in agreement with calculations. This state could serve as a doorway state to negative ion formation in interstellar clouds. Recently, we have developed a two-photon scheme to probe rotational and vibrational states of the homonuclear anion C2-, a candidate proposed for negative ion laser cooling. Results on electronic spectroscopy and vibrational relaxation collisions of this ion will be presented.

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High-fidelity laser-free universal control of trapped ion qubits

Authors: Raghavendra Srinivas[1]; Shaun Burd[1]; Hannah Knaack[1]; Robert Tyler Sutherland[2]; Alexander Kwiatkowski[1]; Scott Glancy[1]; Emanuel Knill[1]; David Wineland[1]; Dietrich Leibfried[1]; Andrew Wilson[1]; David Allcock[1]; Daniel Slichter[1]

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Universal control of multiple qubits – the ability to entangle qubits and to perform arbitrary individual qubit operations – is a fundamental resource for quantum computing, simulation, and networking. Qubits realized in trapped atomic ions have shown the highest-fidelity two-qubit entangling operations and single-qubit rotations to date. Universal control of trapped ion qubits has separately been demonstrated using tightly-focused laser beams or by moving ions with respect to laser beams, but at lower fidelities. Laser-free entangling methods may offer improved scalability by harnessing microwave technology developed for wireless communications, but so far their performance has lagged the best reported laser-based approaches. Here, we demonstrate high-fidelity laser-free universal control of two trapped-ion qubits by creating both symmetric and antisymmetric maximally entangled states with fidelities of $1^{+0}_{-0.0017}$ and $0.9977^{+0.0010}_{-0.0013}$, respectively (68% confidence level), corrected for initialization error. We use a new scheme based on radiofrequency magnetic field gradients combined with microwave magnetic fields that is robust against multiple sources of decoherence, usable with essentially any trapped ion species, and has the potential to perform simultaneous entangling operations on multiple pairs of ions in a large-scale trapped-ion quantum processor without increasing control signal power or complexity. Combining this technology with low-power laser light delivered via trap-integrated photonics and trap-integrated photon detectors for qubit readout offers a potential avenue for scalable, high-fidelity, fully-chip-integrated trapped-ion quantum computing.

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Optimal metrology with programmable quantum sensors

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Quantum sensors are an established technology that has created new opportunities for precision sensing across the breadth of science. Using entanglement for quantum-enhancement will allow us to construct the next generation of sensors that can approach the fundamental limits of precision allowed by quantum physics. However, determining how state-of-the-art sensing platforms may be used to converge to these ultimate limits is an outstanding challenge.

In this talk I will present our progress in this regard, where we merge concepts from the field of quantum information processing with metrology, and successfully implement experimentally a programmable quantum sensor operating close to the fundamental limits imposed by the laws of quantum mechanics. We achieve this by using low-depth, parametrized quantum circuits implementing optimal input states and measurement operators for a sensing task on a trapped ion experiment, particularly generalized Ramsey interferometery. We further perform on-device quantum-classical feedback optimization to 'self-calibrate' the programmable quantum sensor. This ability illustrates

that this next generation of quantum sensor can be employed without prior knowledge of the device or its noise environment.

Mainz satellite meeting + hybrid ECTI / 29

Trapping and cooling of Be+-H2+ ion pairs

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The complexity and variety of molecules offer opportunities for metrology and quantum information that go beyond what is possible with atomic systems. The hydrogen molecular ion is the simplest of all molecules and can thus be calculated ab initio to very high precision [1]. Combined with spectroscopy this allows to determine fundamental constants and test fundamental theory at record precision [2–4]. Spectroscopy of H_2^+ should improve substantially by performing experiments with single hydrogen molecular ions, reducing systematic uncertainties and improving signal strength. This necessitates quantum control.

I will present our progress towards full quantum control of a single hydrogen molecular ion. Our most recent results demonstrate the co-trapping and cooling of single H_2^+ and $^9Be^+$ ions. The experimental apparatus features a cryogenic ultra-high vacuum chamber, housing a micro-fabricated monolithic linear Paul trap. H_2^+ is loaded into the trap by electron bombardment of H_2. We aim to use He buffer gas cooling in combination with quantum logic spectroscopy to initialize the internal state of H_2^+ in a pure quantum state and implement non-destructive readout [5-9].

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Mainz satellite meeting + hybrid ECTI / 30

Coherence of light scattered from ion crystals and quantum non-Gaussianity of atomic motion

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We present the experimental characterization of coherence of light scattered from trapped ion crystals. We study the first and second order coherences and their dependence on the number of optical modes of employed detection setups. We show how the indistinguishable contributions from a large number of ions result in the measurement of photon bunching in a single-mode Hanbury-Brown and Twiss arrangement. This corresponds to a new regime of observation of the emission from an independent and well-defined number of single-photon emitters, where mutually competing requirements on a single-mode detection and on a high number of independent, i.e. mutually distant, emitters typically limit the achievable detectable photon rates and the corresponding possibility of observation of multi-photon contributions.

We analyze the possibilities of employing the observed collective coherent contribution for the maximization of collection efficiency of light scattered from linear ion crystals. Considering realistic trapping parameters in a macroscopic linear Paul trap, the trapping parameters can be optimized to maximize a signal in the axial trapping direction. We find up to two orders of magnitude increase of the detection efficiency in the limit of small numerical apertures NA$\sim$ 0.1 for ion crystals containing at most 10˜ions.

We present our experimental advancements in controlling the corresponding dominant experimental limitations resulting from a finite thermal motion of trapped ions. We realize the method for a robust experimental accumulation of nonclassicality of motion by deterministic incoherent modulation of thermal phonon number distribution. We demonstrate that repetitive application of the nonlinear anti-Jaynes-Cummings interaction monotonically accumulates the observable state nonclassicality and entanglement potential. The output states converge to a phonon number distribution with high overlap with a particular Fock state and visible quantum non-Gaussian aspects including corresponding negative Wigner function. We demonstrate a hierarchy of quantum non-Gaussianity criteria suitable for the atomic-mechanical systems, where mechanical heating corresponds to the typical limitation for the preservation of such sensitive properties and present its implementation on up to 10-phonon states of a trapped ion oscillator.

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Four-second optical coherence between different atomic species and the search for new physics with atomic clocks

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In this talk, I will present incoherent and coherent frequency ratio measurements between optical atomic clocks, and the use of these measurements to constrain models of ultralight scalar dark matter. I will begin with a brief summary of the NIST Al^+ quantum-logic clocks, which use quantum-logic gates with a co-trapped second ion species for preparation and readout of the Al^+ state [1] and have achieved a fractional inaccuracy of 9.4×10^{-19} [2]. We have performed incoherent frequency ratio measurements between an Al^+ ion clock, a Sr lattice clock, and a Yb lattice clock with total

uncertainty below 10^{-17} and analyzed the results to place constraints on the coupling of ultralight scalar dark matter candidates to Standard Model particles and fields [3].

The sensitivity of these measurements is limited by the quantum-projection noise of the single Al^+ ion. Quantum-projection noise is minimized when the spectroscopic probe time is equal to the lifetime of the excited clock state, however for many clocks frequency noise of the clock laser limits the probe time to be much shorter. Coherent frequency ratio measurements, in which the atoms of one clock serve as the phase reference to probe the atoms of the other clock, can overcome this limitation.

I will proceed to describe coherent frequency ratio measurements between two independent Al^+ clocks, which reach the fundamental stability limit set by quantum projection noise with a probe time near the excited state lifetime, using the correlation spectroscopy technique [4]. Using a new technique called differential spectroscopy, we have recently performed coherent frequency ratio measurements between an Al^+ clock and a Yb clock with a 4 s coherence time, corresponding to a quality factor $Q \approx 1.4 \times 10^{16}$ [5].

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online ECTI / 32

Non-equilibrium coupling of a quartz resonator to the motion of ions in a Penning trap

Authors: Emilio Altozano[1]; Joaquín Berrocal[1]; Steffen Lohse[2]; Francisco Domínguez[1]; Jesús Del Pozo[1]; Francisco Javier Fernández[1]; Michael Block[2]; Juan José García-Ripoll[3]; Daniel Rodríguez[1]

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The use of quartz resonators for induced image current detection of trapped ions has been pioneered in a collaboration between the Universities of Granada and Mainz, aiming at developing a novel detection system for the measurement of the cyclotron frequencies of single ions. One of the anticipated applications is mass measurements of superheavy elements produced in fusion-evaporation reactions at lowest rates of single ions at a time. Since 2018, we have performed first experiments on ions, with two types of quartz crystals, demonstrating the functioning of the resonator together with a new amplifier [1], performing proof-of-principle mass measurements [2], and investigating the response of the resonator under non-equilibrium conditions [3]. The latter investigations have clearly shown the advantages of quartzes compared to superconducting resonators, enhancing their use for the envisaged experiments, still subject to reaching the single-ion sensitivity. In this contribution we will present these results, considering different models, and the on-going activities towards the use of quartz resonators on laser-cooled ions in a 7-Tesla open-ring Penning trap [4].

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online ECTI / 33

Integrated microwave quantum computation register with trapped 9Be+ ions

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This talk will summarize recent developments towards the realization of a universal integrated two-qubit quantum computation register for a register-based ion-trap quantum processor. We demonstrated high-fideltiy integrated two-qubit microwave quantum gates with infidelities approach 10-3. Through tailored pulse envelopes, we can suppress the sensitivity to the thus-far dominant source of gate errors - uncontrolled changes in motional mode frequency - by up to two orders of magnitude. We report on the implementation of individual-ion addressing and our current plans for extension to a prototype processor with separate storage, computation and detection registers.

Oxford satellite meeting (BrECTI) + hybrid ECTI / 34

Welcome to hybrid ECTI

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Zoom starts

Oxford satellite meeting (BrECTI) + hybrid ECTI / 36

Charge transfer reactions between rare gas ions and polar molecules

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Ca+ Coulomb crystals, containing up to a few hundred laser-cooled ions, are used as a cold scaffold to undertake reaction studies between sympathetically cooled, rare gas ions (Xe+
, Kr+ and Ar+) and polar molecules (NH3, ND3, H2O and D2O) [1-3]. The Coulomb crystal environment allows for the accurate calculation of reaction rate coefficients under almost perturbation-free conditions, thanks to the combination of two complementary and sensitive detection techniques (fluorescence imaging and time-of-flight mass spectrometry). Experimental findings are compared to theoretical predictions from capture theory models, developed to describe the interaction between ions and polar neutrals. The success of capture theories in predicting the behaviour of these reactions, and potential implication for astrochemical models, will be discussed.

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Oxford satellite meeting (BrECTI) + hybrid ECTI / 37

Dawn of Precision Measurements with Cold Antihydrogen

Author: April Cridland[1]

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The ALPHA (Antihydrogen Laser PHysics Apparatus) Collaboration at CERN is engaged in precise measurements of the antihydrogen spectrum with a view to studying the fundamental symmetries between matter and antimatter. In 2018, ALPHA measured the 1S-2S transition to one part in 1012 [1]. Since then, ALPHA has gone on to measure the
transitions between the 1S ground state and the 2P1/2 and 2P3/2 excited states to infer the fine structure splitting in the n=2 manifold [2] and more importantly the very first demonstration of laser cooling of antihydrogen atoms [3] which will improve the precision of all future spectroscopy measurements. ALPHA continues to pursue additional techniques to increase the precision of these frequency measurements by using beryllium ions to sympathetically cool positrons, thereby increasing the number of trapped $\bar{H}$, and introducing a maser and atomic clock to improve the frequency metrology of the experiment. In the last
two years, it has also been necessary to prepare for the ELENA era of operation in the Antiproton Decelerator. This has required significant upgrades to the structure of the ALPHA experiment to work under different vacuum conditions and with slower moving antiprotons.
Finally, the new experiment, ALPHA-g, has been assembled in its final form to begin moving towards a measurement of the effect of gravity on antihydrogen, which would be a test
Einstein's equivalence principle. ALPHA-g is currently undergoing commissioning of all its essential systems and will be ready for data taking in 2022.

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Oxford satellite meeting (BrECTI) + hybrid ECTI / 38

Sympathetic cooling of positrons to cryogenic temperatures for antihydrogen production

Authors: Daniel Maxwell[1]; the ALPHA collaboration[None]

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The ALPHA (Antihydrogen Laser Physics Apparatus) collaboration has performed several precision tests of fundamental symmetries through laser and microwave spectroscopy of atomic transitions in the antihydrogen atom [1, 2, 3]. Since typically only around only twenty antihydrogen atoms are trapped per experimental cycle, in these experiments antihydrogen atoms are accumulated [4] over time scales ranging from tens of minutes to many hours. The temperature of the positrons used to synthesise antihydrogen is thought to be the current limitation to the antihydrogen trapping rate.

Here we present sympathetic cooling of large, dense positron plasmas to temperatures below 7 K using laser cooled Be+ ions [5,6] in a Penning trap used for antihydrogen synthesis. Our experimental methodology, and the current limitations of sympathetic cooling will be presented. The factor of 2.5 decrease in temperature compared to our typical positron plasmas will likely result in a significant increase in the amount of trappable antihydrogen, facilitating improvements in future measurements.

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An Ion Trap Source of Cold Atomic Hydrogen via Photodissociation of the BaH+ Molecular Ion

I present a novel scheme for producing cold (magnetically trappable) atomic hydrogen, based on threshold photodissociation of the BaH+ molecular ion. BaH+ can be sympathetically cooled using laser cooled Ba+ in an ion trap, before it is photodissociated on the single photon A1Σ+⟵X1Σ+ transition. The small mass ratio between Ba+ and BaH+ ensures a strong overlap within the ion trap for sympathetic cooling, whilst the large mass ratio between BaH+ and H means that the released hydrogen can be up to 139 times colder than the parent molecular ions. I examine the hydrogen production rate, and describe how the trap dynamics and photodissociation laser detuning influence the achievable energies. The low infrastructure costs and the ion trap nature of the scheme make it the ideal (and perhaps only) technique for loading hydrogen into an antihydrogen experiment. This would support a direct matter-antimatter comparison, which could provide important clues as to why our universe contains so little antimatter.

Oxford satellite meeting (BrECTI) + hybrid ECTI / 40

A High-fidelity Quantum Matter Link between Ion Trap Modules

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A practical quantum computer, capable of solving disruptive problems, may require thousands to millions of qubits in order to execute the required quantum error correction. Scaling ion trap quantum computers to larger numbers of qubits has become a prominent area of research [1,2]. However, the number of ions that can be hosted on a single quantum computing module is limited by the size of the chip or wafer being used. Therefore a modular approach is of critical importance and requires quantum connections between individual modules. One approach has been to use a photonic link to probabilistically generate entanglement between remote modules; 94 % is the highest fidelity achieved so far at a connection speed of 182 1/s for modules that are separated by 2 m [4]. We present an alternative approach by making use of a quantum matter link in which ions themselves are transferred between adjacent quantum computing modules. Demonstrating this method, we achieved a connection speed of 2400 1/s over a distance of 692 μm with a transfer fidelity between modules of

99.999995%. We have also verified the coherence of the quantum state of the transferred ion using a Ramsey experiment. The connection speed is limited by the update rate of the DC control system (100 kS/s) and the DC filters (70 kHz cut-off frequency).

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Fast Two-Ion Entangling Gate via Rydberg Interaction

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Trapped Rydberg ions [1] are a novel approach for quantum information processing. By combining the high degree of control of trapped ions with the strong dipolar interaction of Rydberg atoms, fast and motion-independent entangling gates may be realized in large ion crystals.
In our experiment, we excite trapped 88Sr+ ions to Rydberg states. We have observed strong interaction between microwave-dressed Rydberg ions. We have realized a controlled phase gate between two ions in a two-ion crystal [2] and in a 12-ion crystal, both within only 700 ns. This fast gate does not rely on ion motion, so it could also be applied in longer ion crystals. These are fundamental steps towards a trapped Rydberg ion quantum computer or simulator.

References
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Collective optical pumping into a maximally entangled state

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Two-qubit entangled states are usually generated by a two-step process: first, the qubits are dissipatively initialised by optical pumping into a separable state, and then the entanglement is generated through a unitary transformation. However, entangled states can also be generated directly using dissipative engineering [1]. We propose and implement a novel scheme for what can be described as "optical pumping into a maximally entangled state". We apply the method to deterministically prepare two trapped 40Ca+ ions in a maximally entangled singlet state with a fidelity of 93(1)% [2].

References
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[2] arXiv: 2107.10374

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A low-noise, ultrastable 674 nm laser for quantum metrology with entangled 88Sr+ ions

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Optical qubit transitions in laser-cooled, trapped ions are used in precision quantum metrology [1] and in quantum information processing [2,3]. In linear ion strings, each qubit and the quantised collective motion are controlled coherently via the ion-laser laser interaction to create scalable entanglement. Such systems could realise a gain in precision and overcome the quantum projection noise limitation in single ion clocks [1] to reach their systematic uncertainty level at 10-18 with short averaging timescales.
For precision spectroscopy utilising scalable entanglement of trapped-ion optical qubits, the ultrastable frequency typical of optical clock lasers is necessary, but on its own is insufficient. Two further challenges need to be addressed.
Firstly, minimal noise at high Fourier frequencies is essential, as noise at frequencies in the MHz range causes off-resonant ion-laser interactions, which degrade the fidelity of entanglement operations utilising motional sidebands of the ion crystal. Such noise is typically present in semiconductor laser systems [3]. Secondly, a high-power source is required to generate laser pulses that are agile in amplitude, phase and frequency, and which illuminate an ion string evenly with the requisite Rabi frequency.
We report on the realisation of an ultrastable 674 nm laser suited for the optical qubit transition in 88Sr+. We use a commercial Ti:sapphire laser source optimised for the low wavelength end of its gain range. Stabilisation to a high-finesse, low-drift cavity, including fast feedback to an external AOM, results in a 1 Hz fluctuation of the optical frequency measured from 1 s to beyond 100 s averaging times. We evaluated the noise at Fourier frequencies out to 10 MHz and find it to be mostly below a white frequency noise level of a few Hz⊠Hz-1/2. With 1 W of spectrally pure cw laser light at the 1 Hz level at our disposal we could supply up to four independent systems, each delivering tens of milliwatts of stable and fully agile light to trapped ions.
Our measurements show the characteristically rapid decrease of intrinsic noise towards high Fourier frequencies for this type of laser. Following the argument in [4] they would indicate that a infidelity contribution of ≤ $2\dot{1}0^{-4}$ from off-resonant excitation at 1 MHz can be achieved without the need for further spectral filtering [3].
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Ion-photon interfaces for quantum networking

A system that can combine the complementary strengths of trapped ions and photons as carriers of quantum information is an appealing prospect. Ions provide long coherence times, high levels of quantum control and high-fidelity state readout, while photons are a natural choice for transmitting information over anything but very short distances. To interface these two platforms we use calcium ions, trapped close to the mode centre of a high-finesse optical cavity. The resulting ion-photon coupling allows us to produce single photons via a Raman transition. To study the properties of single photons produced via this method we use a linear Paul trap with macroscopic mirrors installed in its endcaps. With this weakly-coupled system we are able to compare the indistinguishability of the photons that are produced by two different schemes [1]. Alongside this work, we utilise a specialised endcap trap with an integrated fibre Fabry–Pérot cavity [2]. After optimisation of the position and localisation of the ion inside this cavity we have obtained a cavity coupling rate of 16.7 MHz, which is greater than both the rate of photon loss from the cavity, and the decay rate of the relevant excited state of the ion [3]. As a next step we have designed and are in the process constructing a next-generation, flexible, multi-zone trap system with strongly coupled ion-photon interface. This will act as a node of a distributed quantum computer, and allow for increased rates of remote ion-ion entanglement than can be achieved in free space systems.

References
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Device-Independent Quantum Key Distribution Between Two Ion Trap Nodes

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Co-author: et al.

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Private communication over shared network infrastructure is of fundamental importance to the modern world. In classical cryptography, shared secrets cannot be created with unconditional security; real-world key exchange protocols rely on computational conjectures such as the hardness of prime factorisation to provide security against eavesdropping attacks. Quantum theory, however, promises that measurements on two entangled systems can yield correlated outcomes that are fundamentally unpredictable to any third party, which forms the basis of quantum key distribution (QKD) [1]. The security of existing QKD implementations has relied on detailed knowledge of the states and measurements involved, however, enabling attacks that exploit imperfections in the quantum devices (e.g. [2]). Following the pioneering work of Ekert [3] proposing the use of entanglement to bound an adversary's information from Bell's theorem, we present the experimental realisation of a complete quantum key distribution protocol immune to these vulnerabilities. The security of our protocol is device-independent [4]: we treat the systems as "black boxes", relying only on measurement statistics observed during the key generation process for the security analysis. This requires a great number of observations of a large, detection-loophole-free Bell inequality violation. We achieve this using two $^{88}Sr^{+}$ ion trap nodes connected by an optical fibre link. A heralded entanglement generation scheme yields about one hundred Bell pairs per second with a fidelity of 96.0(1)%, a new record for optical entanglement of distant matter qubits. We combine this experimental platform with theoretical advances in finite-statistics analysis, error correction, and privacy amplification to generate, for the first time, a shared key with device-independent security. Our result [5] demonstrates that provably secure cryptography is possible with real-world devices, and paves the way for further quantum information applications based on the device-independence principle.

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A quantum network of entangled optical atomic clocks

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Optical atomic clocks are our most precise tools to measure time and frequency. Their precision enables frequency comparisons between atoms in separate locations to probe the space-time variation of fundamental constants, the properties of dark matter, and for geodesy. Measurements on independent systems are limited by the standard quantum limit (SQL); measurements on entangled systems, in contrast, can surpass the SQL, to reach the ultimate precision allowed by quantum theory — the so-called Heisenberg limit. While local entangling operations have been used to demonstrate this enhancement at microscopic distances, frequency comparisons between remote atomic clocks require the rapid generation of high-fidelity entanglement between separate systems that have no intrinsic interactions. We demonstrate the first quantum network of entangled optical clocks [1], using two 88Sr+ ions, separated by a macroscopic distance (≈2m), that are entangled using a photonic link. We characterise the entanglement enhancement for frequency comparisons between the ions. We find that, in the absence of decoherence due to the probe laser, entanglement improves the single-shot uncertainty by a factor close to $\sqrt{2}$, as predicted for the Heisenberg limit, thus halving the number of measurements required to reach a given precision. Practically, today's optical clocks are typically limited by laser decoherence; in this regime, we find that using entangled clocks confers an even greater benefit, yielding a factor 4 reduction in the number of measurements, compared to conventional correlation spectroscopy techniques [1].
As a proof of principle, we demonstrate this enhancement for measuring a frequency shift applied to one of the clocks. Our results show that quantum networks have now attained sufficient maturity for enhanced metrology. This two-node network could be extended to additional nodes, to other species of trapped particles, or to larger entangled systems via local operations.
References
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Solitons and thermal effects in ion chains

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TBA

Author: Georg Bruun[None]

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Energy-dependence and quantum logic detection of atom-ion interactions

Author: Or Katz[1]

Co-authors: Jonathan Wengrowicz ; Meirav Pinkas ; Nitzan Akerman ; Roee Ozeri ; Ruti Ben-Shlomi ; Tomas Sikorsky ; Ziv Meir

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Studies of interactions between a single ion and a neutral atom, in a well-defined quantum state, constitute a corner stone in quantum chemistry. Yet, the number of techniques which enable measurement of cold collision processes and cross-section measurement is handful. We present three different fronts to improve the measurements resolution, applicability and accuracy in the measurements of such interactions between laser-cooled atoms and ions trapped in RF Paul traps.
First, by controlling the velocity atoms in trapped in optical lattices with high resolution, we investigated the energy dependence of several processes within the 0.1-10 millikelvin range. Second, we developed a quantum logic technique that enables the measurement of collision and reaction cross-sections between ultra-cold atoms and any ion species with the help of an ancillary logic-ion. We further used this technique to measure the cross-seciton of spin-exchange and charge-exchange processes between atom-ion pairs that are otherwise inaccessible in our system. Finally, we present a new calibration technique that enables an in-situ estimation of the Langevin rate coefficient to high certainty. Preliminary results of the measured cross-sections possibly hint for quantum effects associated with the ultracold regime.

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Advancing clock measurement precision to the 21st digit

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TBA

Author: Karan Mehta[None]

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Fault-tolerant parity readout on a trapped-ion quantum information processing node

Author: Janine Hilder[1]

Co-authors: A. Rodriguez-Blanco [2]; A. Stahl ; B. Lekitsch ; D. Pijn [3]; F. Schmidt-Kaler ; M. Müller [4]; M. Orth ; O. Onishchenko ; U. G. Poschinger

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Trapped-ion quantum technology is among the most promising candidates for the realization of a scalable quantum processor. To address individual ions and perform high-fidelity two-qubit entangling gates in a linear segmented Paul trap, we employ dynamical register reconfiguration operations to place specific qubits in a laser interaction zone. To realize fault-tolerant quantum information processing, it is of crucial importance to be able to perform quantum error correction [1]. One essential

building block is to perform error syndrome readout, which allows the detection of errors through quantum non-demolition parity check measurements on the encoded states [2]. Recently, the fault-tolerant weight-4 parity check measurement scheme on a shuttling-based trapped-ion quantum processing node has been experimentally demonstrated [3,4].
After a short introduction of the shuttling-based quantum information processing node the measurements were performed on, recent results of a fault-tolerant weight-4 parity check measurement are going to be presented, using four data and two ancilla qubits. The flag qubit is used to detect errors occurring during the syndrome readout circuit, which is an essential building block of multiple quantum error correction circuits, including topological color codes. A flag-conditioned single-shot fidelity of the syndrome readout of 93.2(2)% is achieved [3]. The error catch rate is determined by injection of bit and phase-flip errors at a critical position of the circuit, where the error does propagate onto two out of the four data qubits. Error catch rates of 90.6(6)% and 89.7(6)% are obtained, verifying the capability of the flag to detect the potentially detrimental weight-2 errors onto the data qubits. Additionally, the generation of six-qubit multipartite entanglement on all ions participating in this flag-based fault-tolerant parity readout circuit will be presented [3].
References
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Thermodynamics of trapped-ion machines

Trapped ions confined in radiofrequency traps offer an excellent degree of control, in terms of unitary operations, initialization and readout. Furthermore, advanced techniques can be employed to control external (motional) degrees of freedom. Complementing the toolbox with non-unitary operations such depolarization channels or controlled coupling to microscopic environments (ancillas) renders trapped-ion platforms ideal for studying concepts from microscopic and quantum thermodynamics.
In this talk, we show the realization of a single-ion spin heat engine, where the work agent is a controlled two-level system. Coupling to heat baths is emulated via controlled incomplete optical pumping. An oscillatory degree of free serves as a flywheel, where energy generated by the engine operation is deposited. We study the deposition process via quantum state tomography on the flywheel, showing the useful fraction of the deposited energy – the ergotropy – is inherently limited by intrinsic work fluctuations [1].
We also show results from a recently completed experiment, where heat leaks occurring throughout the unitary evolution of two trapped-ion qubits are detected using the frameworks of global passivity [2] and passivity deformation [3]. We demonstrate that both approaches can detect heat leaks with a sensitivity beyond the microscopic version of the 2nd law, and that passivity deformation is more sensitive as compared to global passivity [4].

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Structured light beams and phase-stable optical forces for physics with trapped ions

Author: Christian Schmiegelow[None]

I will review two experimental developments and its applications to experiments with ion traps. First I will show how we implemented phase-stable optical forces on trapped ions, and will discuss several applications, both realized and planned. These include: spin-dependent kicking which lead to the realization of a spin heat engine, the possibility of generating giant cats, and a special kind of doubly squeezed state. Next I will show how the use of structured light on quadrupole transitions can be used for various tasks. These include: reducing ac stark shift, controlling selection rules and imaging motional wave packets with superresolution. Finally I will discuss how these ideas are shaping future experiments we are carrying out at the University of Buenos Aires.

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hybrid ECTI - closing remarks

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Ions in atomic Bose-Einstein condensates and Fermi gases

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We investigate the properties of ions immersed in an atomic Bose-Einstein condensate (BEC) or an ultracold Fermi gas using variational and diagrammatic methods. For both cases, we show that the ion can form several quasiparticle states, which are charged analogues of the Fermi and Bose polarons observed in neutral atomic gases. Due to the long-range nature of the atom-ion interaction, these ionic polarons have several properties distinct from their neutral counterparts such as the simultaneous presence of several stable states and smooth transitions from repulsive to attractive polarons with increasing interaction strength. We also show that an ion in a BEC can form a number of charged molecular states by binding an increasing number of bosons. Finally, we discuss the induced interaction between two ions mediated by density oscillations in the surrounding medium.

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Quantum Simulations and Algorithms with Ion Trap Systems

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Laser-cooled trapped atomic ions are well-established as possessing the highest performance of any platform for quantum computing. But as importantly, the path to scaling trapped ion quantum computers involves well-defined architectural plans, from shuttling ions between quantum processor unit (QPU) cores and modular photonic interconnects between multiple QPUs to gradual error-correction strategies. Full-stack ion trap quantum computers have thus moved away from the physics of qubits and gates and toward the engineering of optical control signals, quantum gate

compilation for algorithms, and high level system design considerations. I will summarize the state-of-the-art in these quantum computers, covering recent algorithms and quantum simulations of physical processes, and speculate on how they might be used in the future.

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Integrated optical control of trapped-ion systems

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The optics required for control of trapped-ion quantum systems have posed a major obstacle in scaling experimental systems, despite these qubits' fundamental qualities. I will discuss recent work on integrated photonic approaches to trapped-ion control [1,2], which may facilitate scaling and simultaneously reduce relevant noise sources even in current small-scale experiments. In addition, tailored optical field profiles achievable with such methods enable atom-light interactions that may allow extensions and improvements to currently used schemes for quantum logic and laser cooling, and in this vein I will discuss recent results from our lab on control of single ion qubits in passively phase stable optical standing waves.

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Trapped Rydberg ions- Stockholm University

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The virtual lab tour will show you the key components of an ion trap with all the lasers and control systems used to perform trapped Rydberg ion gate.

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Amsterdam Labs - Group Rene Gerritsma

Authors: Eleanor Trimby[1]; Rima Schüssler[2]; Matteo Mazzanti[2]

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Lab tour of the atom-ion setup and the 2D crystal and tweezers labs at the University of Amsterdam. In the atom-ion lab we study molecular ion formation and in the 2D crystal lab we study quantum information with tweezers.

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Virtual lab tour: Ion Trap Group, Aarhus University

Author: Frederik Skifter Tribler[None]

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During this live lab tour, I will present the exiting lab of the Ion Trap group at Aarhus University!

The lab includes 3 linear Paul traps, lasers for cooling and capturing both Calcium and Barium ion, and and our ultra stable Menlo Frequency comb.

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Theory of ultracold ion-atom collisions

Author: Michał Tomza[1]

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We work on ultracold interactions and collisions of atoms, ions, and molecules using ab initio electronic structure and quanutm scattering methods.

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Lab tour - Leibniz Universität Hannover

Authors: Ludwig Krinner[None]; Amado Bautista Salvador[None]

Our colleague Ludwig Krinner, is surely participating to present our lab.

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PTB's atomic clock hall

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We will show our laboratory in which PTB's Caesium beam and fountain clocks are set up and we perform research on optical atomic clocks with trapped ions.

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Ion trapping experiment at LENS (Italy)

Authors: Lucia Duca[1]; Elia Perego[2]; Federico Berto[3]; Naoto Mizukami[3]; Massimo Inguscio[4]; Carlo Sias[5]

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In the virtual lab tour we will present the experimental apparatus that we have recently used to trap Ba+ ions, thus realizing the first ion trapping experiment in Italy. Moreover, we will discuss our future plans and in particular our strategy for immersing the ions into a cloud of fermionic Li atoms to observe atom-ion interactions at ultra-low temperatures.

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Oxford lab, 'Two-node two-species trapped ion quantum network'

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Oxford lab, 'Two-node two-species trapped ion quantum network'