II EARLY CAREER CONFERENCE in TRAPPED IONS

27 June - 1st July, 2022
CERN, Geneva, Switzerland

Book of Abstracts

Co-organized by

CERN

TIPICQA

cost
EUROPEAN COOPERATION
IN SCIENCE & TECHNOLOGY

Funded by the Horizon 2020
Framework Programme of the
European Union

Platinum & Gold Sponsors

IONQ

Atlas Copco

EDWARDS

Leybold
Part of the Atlas Copco Group

Contents

Detailed Timetable

Monday, June 26

8:30 - 9:24 Welcome & Registration

Council Chamber

8:30 Check-in and Registration at Pas Perdus

9:00 Welcome to ECCTI 2022

9:24 - 10:30 Antimatter I

Council Chamber, chair: Elise Wursten (RIKEN)

9:24 The PUMA Experiment: Investigating Short-lived Nuclei with Antiprotons
Alexander SCHMIDT (TU Darmstadt)

9:46 Ultra-high precision laser spectroscopy of anti-hydrogen
Janko NAUTA (Swansea University)

10:08 Sympathetic cooling of a single proton in a Penning trap by laser-cooled beryllium ions
Christian WILL (MPIK)

10:30 - 11:00 Coffee Break

Pas Perdus

11:00 - 12:10 Quantum Information & Computing I

Council Chamber, chair: Celeste Torkzaban (Leibniz Universität Hannover)

11:00 Qubit addressing in a standing wave light field from integrated photonics
Carmelo MORDINI (ETH Zürich)

11:23 Towards standing-wave quadrupole Mølmer-Sørensen gates
Oana BAZAVAN (University of Oxford)

11:45 Standing-Wave Mølmer–Sørensen Gate in the Adiabatic and Non-Adiabatic Regime
Sebastian SANER (University of Oxford)

12:10 - 14:30 Lunch Break & Tours

Meeting point for tours: in front of Council Chamber, arrive 5 minutes before start time

12:10 - 13:00 Tour: Synchrocyclotron

13:00 - 14:30 Tour: Antiproton Decelerator

13:00 - 14:30 Tour: ISOLDE

14:30 - 16:15 Nuclear Physics I

Council Chamber, session chair: Simon Lechner (McGill Univseruty)

14:30 High-Resolution Mass Measurements at the FRS Ion Catcher in the vicinity of ^{100}Sn
Ali MOLLAEBRAHIMI (University of Giessen & TRIUMF)

14:53 High precision mass measurement of ^{24}Si and a final determination of the rp-process at the A=22 waiting point
Daniel PUENTES (Michigan State University)

15:15 News From the ISOLTRAP Mass Spectrometer
Lukas NIES (CERN & University of Greifswald)

15:35 Ion Trapping Developments at Edinburgh University, Towards Precise Mass Measurements of Light Exotic Nuclei at TITAN
Callum BROWN (University of Edinburgh)

15:55 Implementation of the double Penning trap mass spectrometer MLLTRAP at ALTO
Elodie MORIN (IJCLab)

16:15 - 16:45 Coffee Break

Pas Perdus

16:45 - 18:45 Skill Session I

Council Chamber

16:45 Lecture: Making the most of your presentation
Jean-luc Doumont (Principiae)

Tuesday, June 27

9:00 - 10:30 Quantum Technologies I

Council Chamber, chair: Silke Auchter (Infineon Technologies Austria AG)

9:00 Multi-tone RF generation for intermediate-scale trapped-ion control
Martin STADLER (ETH Zürich)

9:23 A laser-cooled $^{40}\mathrm{Ca}^{+}$ ion and a $^{40}\mathrm{Ca}^{+} - {}^{40}\mathrm{Ca}^{+}$ ion crystal for systematic investigations of motional quantum metrology
Francisco DOMÍNGUEZ (Universidad de Granada)

9:45 Trapped ions in optical tweezers
Matteo MAZZANTI (University of Amsterdam)

10:08 Selective properties of a Paul trap with the asymmetrical power supply
Olga KOKORINA (ITMO University)

10:30 - 11:00 Coffee Break

Pas Perdus

11:00 - 12:10 Quantum Simulation I

Council Chamber, chair: Zachary Smith (United States Air Force Research Laboratory)

11:00 Trapping and ground-state cooling of planar ion crystals in a novel linear Paul trap
Dominik KIESENHOFER (University of Innsbruck)

11:23 Digital quantum simulation of a topological spin chain
Claire EDMUNDS (University of Innsbruck)

11:45 Fock state detection and simulation of sub- and superradiant emission with a single trapped ion
Harry PARKE (Stockholm University)

12:10 - 14:30 Lunch Break & Tours

Meeting point for tours: in front of Council Chamber, arrive 5 minutes before start time

13:00 - 14:30 Tour: Antiproton Decelerator

13:00 - 14:30 Tour: ISOLDE

14:30 - 15:55 Antimatter II

Council Chamber, chair: April Cridland (Swansea University)

14:30 muCool: A novel low-energy muon beam for precision experiments
Giuseppe LOSPALLUTO (ETH Zürich)

14:53 BASE: Towards a 10-fold improved measurement of the Antiproton Magnetic Moment
Markus FLECK (University of Tokyo)

15:15 Transportable Cryostat and Permanent Magnet Trap for Transporting Antiprotons
Daniel POPPER (Johannes Gutenberg University Mainz)

15:38 Construction and tests of image-current detection systems for the transportable antiproton trap BASE-STEP
Fatma ABBASS (Johannes Gutenberg University Mainz)

15:55 A word from our Sponsors: Atlas Copco

16:10 - 16:30 Coffee Break

16:30 - 19:00 Poster Session

Pas Perdus

16:30 - 19:00 Posters Session at Pas Perdus
16:30 - 19:00 Virtual posters presentation at Room D
16:30 - 18:00 Cocktail service at Pas Perdus

Wednesday, June 28

9:00 - 10:30 Precision Spectroscopy I

Council Chamber, chair: Laura Blackburn (University of Sussex)

9:00 Towards quantum control and spectroscopy of a single hydrogen molecular ion
David HOLZAPFEL (ETH Zürich)

9:23 Tests of QED with singly-ionized helium
Andres MARTINEZ DE VELASCO (Vrije Universiteit Amsterdam)

9:45 Penning-trap mass spectrometry using an unbalanced crystal and optical detection
Joaquín BERROCAL SANCHEZ (Universidad de Granada)

10:08 A Measurement of the $^{88}\mathrm{Sr}^{+}$ $S_{1/2} \rightarrow D_{5/2}$ / $^{171}\mathrm{Yb}^{+}$ $S_{1/2} \rightarrow F_{7/2}$ frequency ratio with in-situ BBR shift evaluation
Martin STEINEL (Physikalisch-Technische Bundesanstalt)

10:30 - 11:00 Coffee Break

Pas Perdus

11:00 - 12:10 Quantum Information & Computing II

Council Chamber, chair: Carmelo Mordini (ETH Zürich)

11:00 Operation of a microfabricated 2D trap array
Marco VALENTINI (University of Innsbruck)

11:23 Microfabricated 3D Ion Traps and Integrated Optics
Jakob WAHL (University of Innsbruck & Infineon Technologies Austria AG)

11:45 Signal Generation for Trapped Ion Quantum Gates
Norman KRACKOW (TU Berlin & QUARTIQ)

12:10 - 14:30 Lunch Break & Tours

Meeting point for tours: in front of Council Chamber, arrive 5 minutes before start time

13:00 - 14:10 Tour: Synchrocyclotron

13:00 - 14:10 Tour: LEIR

14:30 - 16:00 Antimatter III

Council Chamber, chair: Janko Nauta (Swansea University)

14:30 Fundamental tests of antimatter gravitation with antihydrogen accelerators
Jaspal SINGH (University of Manchester)

14:53 Positron plasma creation and manipulation in the ASACUSA Cusp experiment
Andreas LANZ (Austrian Academy of Sciences)

15:15 An Ion Trap Source of Ultracold Atomic Hydrogen via Photodissociation of the BaH^+ Molecular Ion
Steven Armstrong JONES (Swansea University)

15:38 ASACUSA's low energy proton source for matter studies
Alina WEISER (Austrian Academy of Sciences)

16:00 - 16:45 Coffee Break

Pas Perdus

16:45 - 18:15 Skill Session II

Council Chamber

16:45 Workshop: Grant Writing
Pablo Garcia Tello (CERN)

Thursday, June 29

9:00 - 10:30 Nuclear Physics II

Council Chamber, chair: Simon Lechner (McGill University)

9:00 Developments for an increased detection sensitivity of the neutrinoless double-beta decay ($0\nu\beta\beta$) mode in the NEXT experiment
Samuel AYET SAN ANDRES (JLU Giessen)

9:23 The commissioning of a Paul trap for laser spectroscopy of exotic radionuclides in an MR-ToF device
Carina KANITZ (German Aerospace Center)

9:45 Doppler- and sympathetic cooling for the investigation of short-lived radionuclides
Franziska MAIER (CERN-ISOLDE)

10:08 Trapping Swift Divergent Ions with Stacked Rings
Xiangcheng CHEN (University of Groningen)

10:30 - 11:00 Coffee Break

Pas Perdus

11:00 - 12:10 Quantum Information & Computing III

Council Chamber, chair: Amy Hughes (Oxford Ionics)

11:00 Collaborative design of a trapped-ion quantum computer with fully interconnected qubits
Celeste TORKZABAN (Leibniz Universität Hannover)

11:23 A two-node trapped-ion quantum network with photonics interconnects
Gabriel ARANEDA (University of Oxford)

11:45 Device-Independent Quantum Key Distribution Between Two Ion Trap Nodes
David NADLINGER (University of Oxford)

12:10 - 14:10 Lunch Break & Tours

Meeting point for tours: in front of Council Chamber, arrive 5 minutes before start time

12:10 - 13:20 Tour: CERN Data Centre

13:00 - 14:10 Tour: LEIR

14:10 - 14:55 Quantum Information & Computing IV

Council Chamber, chair: Gabriel Araneda (University of Oxford)

14:10 ABaQuS: A trapped-ion quantum computing system using $^{133}\mathrm{Ba}^{+}$ qubits
Ana SOTIROVA (University of Oxford)

14:33 Trapped Barium Ions at the United States Air Force Research Laboratory
Zachary SMITH (United States Air Force Research Laboratory)

14:55 A word from our Sponsors: Quantum FutureX

15:15 - 15:45 Coffee Break

Pas Perdus

15:45 - 18:15 Skill Session III

Council Chamber

15:45 Career Panel with CERN Alumni

18:15 - 18:35 Conference Photo

Outside Restaurant 1, in front of LHC dipole, weather permitting. Otherwise, Council Chamber

18:45 - 23:00 Conference Dinner

Mövenpick Hotel & Casino, Geneva

18:45 Bus departure from Bldg. 500

19:00 Dinner at Mövenpick Hotel

23:00 Return bus to CERN

Friday, July 1

9:00 - 12:00 Skill Session IV

9:00 - 12:00 COMSOL workshop Council Chamber
9:00 - 12:00 LabVIEW workshop Room 222/R-001, close to CERN Hotel

10:30 - 11:00 Coffee Break

Pas Perdus / Bldg. 222

Antimatter Session I

Antimatter I / Monday 9:24 - 9:46

The PUMA Experiment: Investigating Short-lived Nuclei with Antiprotons

Author: Alexander Schmidt[1]

Co-authors: Alexandre Obertelli[1]; Frank Wienholtz[1]

[1] *TU Darmstadt (DE)*

Corresponding Author: aschmidt@ikp.tu-darmstadt.de

The antiProton Unstable Matter Annihilation (PUMA) experiment is a nuclear physics experiment at CERN which will provide the ratio of protons to neutrons in the tail of the nucleon density distributions to constrain nuclear structure theories [1]. To determine this ratio, the interaction of antiprotons and nuclei at low relative energies is used [2]. Following the captures of the antiproton by the nucleus (formation of antiprotonic atom), the antiproton cascades towards the nucleus and eventually annihilates with a nucleon. This annihilation conserves the total charge, so that the annihilated nucleon can be identified by detecting all charged pions produced in the annihilation. The process takes place at larger radii than usual nuclear reactions (e.g. nucleon removal reactions) [1,3], making this method unique for nuclei with a high neutron-to-proton asymmetry, i.e. short-lived nuclei close to the driplines, halo nuclei and nuclei with a thick neutron skin [3]. As there is no joint facility for antiprotons and short-lived nuclei available, a transportable experimental setup is needed to bring antiprotons from ELENA/CERN to the nuclei at ISOLDE/CERN.
This talk will give an overview over the fundamental physics, the experimental setup and technique as well as the current status of the experiment.

[1] PUMA Collaboration, "PUMA: antiprotons and radioactive nuclei", Proposal SPSC P 361, CERN (2019)

[2] A. Trzcińska et. al., "Neutron Density Distributions Deduced from Antiprotonic Atoms", Phys. Rev. Lett. 87, 082501 (2001)

[3] J. Eades and F.J. Hartmann, "Forty years of antiprotons", Rev. Mod. Phys. 71, 373 (1999)

Antimatter I / Monday 9:46 - 10:08

Ultra-high precision laser spectroscopy of anti-hydrogen

Author: Janko Nauta[1]

Co-author: ALPHA Collaboration

[1] *Swansea University (GB)*

Corresponding Author: jan.nauta@cern.ch

Antihydrogen is an exciting system to perform tests of fundamental physics by comparing it with its matter counterpart: hydrogen. One of the most interesting transitions for such comparisons is the 1S-2S, since it has been measured with an extraordinary precision in hydrogen [1]. Over the last decades, the development of production and trapping techniques for antihydrogen [2] has enabled studying this transition using two photons from a 243 nm laser [3]. In a very recent experiment, it was shown that antihydrogen can be directly laser cooled [4], and together with the high detection efficiency due to annihilations, this paves the way for ultra-high precision spectroscopy on antihydrogen. I will discuss recent progress in ALPHA to prepare the laser system for such accurate measurements, involving the implementation of a maser and a cesium atomic fountain clock.

[1] C. G. Parthey et al. Improved Measurement of the Hydrogen 1S - 2S Transition Frequency. Phys. Rev. Lett. 107, 203001 (2011).

[2] G. B. Andresen et al. (ALPHA collaboration). Trapped Antihydrogen. Nature 468, 673-676 (2010)

[3] M. Ahmadi et al. (ALPHA collaboration). Characterization of the 1S-2S Transition in Antihydrogen. Nature 557, 71-75 (2018).

[4] C. J. Baker et al. (ALPHA collaboration). Laser cooling of antihydrogen atoms. Nature 592, 35-42 (2021).

Antimatter I / Monday 10:08 - 10:30

Sympathetic cooling of a single proton in a Penning trap by laser-cooled beryllium ions

Author: Christian Will[1]

Co-authors: Matthew Anders Bohman[2]; Thomas Driscoll[3]; Markus Wiesinger[2]; Fatma abbass[4]; Matthias Joachim Borchert[5]; Jack Devlin[6]; Stefan Erlewein[2]; Markus Fleck[7]; Julia Ines Jager[2]; Barbara Maria Latacz[8]; Peter Micke[6]; Andreas Mooser[2]; Daniel Popper[4]; Elise Wursten[8]; Klaus Blaum[2]; Yasuyuki Matsuda[7]; Christian Ospelkaus[5]; Wolfgang Peter Quint[9]; Jochen Walz[4]; Christian Smorra[4]; Stefan Ulmer[8]

[1] *Max-Planck-Institute for Nuclear Physics (DE)*

[2] *Max-Planck-Gesellschaft (DE)*

[3] *The University of Texas at Austin (US)*

[4] *Johannes Gutenberg-Universität Mainz (DE)*

[5] *Leibniz Universitaet Hannover (DE)*

[6] *CERN (CH)*

[7] *University of Tokyo (JP)*

[8] *RIKEN (JP)*

[9] *GSI - Helmholtzzentrum fur Schwerionenforschung GmbH (DE)*

Corresponding Author: christian.will@mpi-hd.mpg.de

The BASE collaboration performs high-precision Penning trap measurements of the g-factors and charge-to-mass ratios of the proton and antiproton to test CPT in the baryonic sector [1]. Currently, the g-factor measurement of the proton is limited by the statistical uncertainty. This uncertainty stems from finite particle temperatures, which were so far restricted to about 1K by the technique of resistive cooling [2]. However, cooling a single (anti-)proton to even lower temperatures is challenging as it has no electronic structure for laser-cooling. Moreover, sympathetic cooling methods typically rely on co-trapping another laser-cooled species, which is often detrimental to the precision measurement. As a consequence, proposals to cool arbitrary charged particles by coupling them to a laser-cooled species via image currents have been made [3]. The coupling can either be mediated by a common superconducting resonator, which is normally used for particle detection, or a common trap electrode.

Recently our group has published the first proof-of-principle measurement on sympathetically cooling a single proton from 17.0(2.4)K to 2.6(2.5)K [4]. The proton was coupled to laser-cooled beryllium ions via a common resonator. In order to optimize the experimental parameters and study different cooling schemes, simulation code has been developed. A comparison between simulation and existing experimental data yields good agreement. Furthermore, we find that temperatures in the 10mK-regime with cooling time constants of about 10s are feasible with dedicated cooling schemes. On the experimental side, at the time of this abstract a setup is being commissioned with which we anticipate to resolve the expected mK temperatures.

This talk will give an overview of the BASE-Mainz experiment as well as the most recent experimental results towards cooling a single proton in a Penning trap. A special focus will be placed on the simulation work towards improved cooling schemes.

[1] C. Smorra et al., The European Physical Journal Special Topics, 224, 16, 2015.
[2] G. Schneider et al., Science, 358, 6366, 2017.
[3] D. Heinzen, D. J. Wineland, PRA, 42, 5, 1990.
[4] M. Bohman et al., Nature, 596, 514–518, 2021.

Antimatter Session II

Antimatter II / Tuesday 14:30 - 14:52

muCool: A novel low-energy muon beam for precision experiments

Author: Giuseppe Lospalluto[1]

[1] *ETH Zurich*

Corresponding Author: glospalluto@phys.ethz.ch

High precision experiments using muons (μ^+) and muonium atoms ($\mu^+ e^-$) offer promising opportunities to test theoretical predictions of the Standard Model in a second-generation, fully-leptonic environment. Such experiments including the measurement of the muon g-2, muonium spectroscopy and muonium gravity would benefit from intense high-quality and low-energy muon beams.

At the Paul Scherrer Institute, a novel device (muCool) [1] is being developed to reduce the phase space of a standard μ^+ beam by a factor of 10^9 with 10^{-4} efficiency, for a 10^5 boost in brightness.

The muon beam is stopped in cryogenic helium gas and using complex electric and magnetic fields in combination with a gas density gradient the muons are steered to a mm-size spot, where they have an eV energy spread. From here, they are extracted through a small orifice into a vacuum and into a magnetic field free region. The entire process takes less than 10 μs, which is crucial given the short 2.2 μs muon lifetime.

In this talk the working principle, the present status and future prospects will be outlined.

This work is supported by SNF grant 200441_172639

[1] Belosevic, I., Antognini, A., Bao, Y. et al. muCool: a next step towards efficient muon beam compression. Eur. Phys. J. C 79, 430 (2019). https://doi.org/10.1140/epjc/s10052-019-6932-z

Antimatter II / Tuesday 14:53 - 15:15

BASE: Towards a 10-fold improved measurement of the Antiproton Magnetic Moment

Author: Markus Fleck[1]

Co-authors: Matthias Joachim Borchert[2]; Jack Devlin[3]; Stefan Erlewein[4]; Julia Ines Jager[4]; Barbara Latacz[5]; Peter Micke[3]; Phil Nuschke[6]; Gilbertas Umbrazunas[7]; Frederik Volksen[8]; Elise Wursten[5]; Fatma Abbass[9]; Matthew Bohman[10]; Andreas Mooser[10]; Daniel Popper[11]; Markus Wiesinger[10]; Christian Will[12]; Klaus Blaum[12]; Yasuyuki Matsuda[13]; Christian Ospelkaus[14]; Wolfgang Peter Quint[15]; Jochen Walz[16]; Yasunori Yamazaki[5]; Christian Smorra[17]; Stefan Ulmer[5]

[1] *RIKEN, University of Tokyo*

[2] *RIKEN, Leibniz Universitaet Hannover, Physikalisch-Technische Bundesanstalt*

[3] *RIKEN, CERN*

[4] *RIKEN, CERN, Max Planck Institute for Nuclear Physics*

[5] *RIKEN*

[6] *RIKEN, Leibniz Universitaet Hannover*

[7] *RIKEN, ETH Zurich*

[8] *RIKEN, GSI-Helmholtzzentrum fuer Schwerionenforschung GmbH*

[9] *Institute for Physics, JGU Mainz*

[10] *RIKEN, Max-Planck-Institute for Nuclear Physics*

[11] *Johannes Gutenberg Universitaet Mainz*

[12] *Max-Planck-Institute for Nuclear Physics*

[13] *University of Tokyo*

[14] *Leibniz Universitaet Hannover, Physikalisch-Technische Bundesanstalt*

[15] *GSI - Helmholtzzentrum fur Schwerionenforschung GmbH*

[16] *Institut für Physik, JGU Mainz, Helmholtz-Institut Mainz*

[17] *RIKEN, Institute for Physics JGU*

Corresponding Author: markus.fleck@cern.ch

The BASE collaboration at the antiproton decelerator facility of CERN conducts antiproton g-factor and charge-to-mass ratio measurements with precisions on the parts per billion to parts per trillion level respectively. So far, we have measured the antiproton g-factor to 1.5 ppb and the antiproton's charge-to-mass ratio to 69 ppt respectively [Smorra et al. 2017, Ulmer et.al. 2015]. Limitations in the precision of these measurements stem from particle cooling statistics, systematic shifts imposed by magnetic field inhomogeneities and frequency measurement noise.
The recent shutdown of CERN (LS2), which included the switchover from the AD to ELENA, provided ample time to implement upgrades to fully take advantage of the exciting new capabilities of ELENA, to address precision limitations, and to advance the limits of our recent precision measurements by at least a factor of 10.

The first of these upgrades is a new multi-trap stack, which also includes a whole new dedicated cooling trap. This cooling trap is designed such, that the resistive cooling of the particle's cyclotron mode is being accelerated by a factor of approximately 60, cutting down the preparation time to achieve temperatures that allow single spin-flip resolution for g-factor measurements from several hours to only a few minutes. Along with the existing analysis trap, the cooling trap features an inhomogeneous magnetic field, which enables efficient energy evaluation and tracking via the continuous Stern-Gerlach effect.

This inhomogeneity, however, is detrimental for the operation of the precision trap, which is supposed to have a very homogeneous field. So far, the precision trap was only shielded from this field inhomogeneity by physical distance from the inhomogeneous traps, however, now a newly designed superconducting shielding and shimming system was implemented to cut out influences from both the other traps as well as from imperfections of the superconducting

magnet.
This system is estimated to suppress previous dominant systematic shifts of the cyclotron frequency by more than a factor of 100.

Finally, to accommodate the low-energy ELENA beam, a new degrader system was designed and implemented. The degrader's ultra-thin foils in combination with its support structure provide an acceptance of 17 percent while being capable of separating the inside of the experiment from pressures up to room conditions.

This contribution will go into each of these improvements as well as into the development of new detection systems and resistive coolers for the cyclotron mode in both the precision trap and the cooling trap.

Antimatter II / Tuesday 15:15 - 15:37

Transportable Cryostat and Permanent Magnet Trap for Transporting Antiprotons

Author: Daniel Popper[1]

Co-authors: Fatma Abbas[1]; Matthew Bohman[2]; Steffen Gavranovic[1]; Cristina Ibanez[1]; Ron Moller[1]; Samuel Ruhl[1]; Markus Wiesinger[2]; Christian Will[3]; Jack Devlin[4]; Stefan Erlewein[2]; Markus Fleck[5]; Julia Jaeger[2]; Barbara Latacz[6]; Peter Micke[4]; Elise Wursten[6]; Klaus Blaum[2]; Yasuyuki Matsuda[5]; Christian Ospelklaus[7]; Wolfgang Quint[8]; Jochen Walz[1]; Stefan Ulmer[6]; Christian Smorra[1]

[1] *Johannes Gutenberg-Universität Mainz (DE)*

[2] *Max-Planck-Gesellschaft (DE)*

[3] *Max-Planck-Institute for Nuclear Physics (DE)*

[4] *CERN (CH)*

[5] *University of Tokyo (JP)*

[6] *RIKEN (JP)*

[7] *Leibniz Universitaet Hannover (DE)*

[8] *GSI - Helmholtzzentrum fur Schwerionenforschung GmbH (DE)*

Corresponding Author: dapopper@uni-mainz.de

The ERC Project STE$\bar{P}$, "Symmetry Tests in Experiments with Portable Antiprotons", targets the development of transportable antiproton traps to enhance the sensitivity of CPT invariance tests with antiprotons that are conducted in the BASE collaboration. To enable antiproton measurements with improved precision, we are commissioning the transportable trap system BASE-STE$\bar{P}$ in the AD/ELENA facility, so that future measurements can be conducted outside of the Antiproton Decelerator hall at CERN to circumvent limitations by magnetic field fluctuations.

To achieve this, BASE-STE$\bar{P}$ uses a transportable superconducting magnet with 1 T field strength with a two-stage Penning trap system on a portable experiment frame.

In addition, we designed a transportable cryostat, a combination of a pulse-tube cooler and liquid helium tank to cool a Penning trap system down to 4K even during transportation. The transportable cryostat has a mechanical support structure for all cryogenic parts to withstand the mechanical stress of transportation on the road. For the magnetic field necessary to trap protons and later on antiprotons we want to use a permanent magnet system as an alternative approach to using a superconducting magnet.

In this presentation I will motivate the need for BASE-STE$\bar{P}$ and characterize the set-up of the transportable cryostat and the permanent magnet system.

Antimatter II / Tuesday 15:38 - 15:53

Construction and tests of image-current detection systems for the transportable antiproton trap BASE-STEP

Author: Fatma abbass[1]

Co-authors: Christian Will [2]; Daniel POPPER [1]; Matthew Anders BOHMAN [3]; Markus WIESINGER [3]; Klaus BLAUM [3]; Jack DEVLIN [4]; Matthias Joachim BORCHER [5]; Thomas DRISCOLL [6]; Stefan ERLEWEIN [3]; Julia Ines JAGER [3]; Markus FLECK [7]; Barbara LATACZ [8]; Yasuyuki MATSUDA [7]; Peter MICKE [4]; Andreas MOOSER [3]; Jochen Prof. WALZ [1]; Christian OSPELKAUS [5]; Elise WURSTEN [8]; Wolfgang Peter QUINT [9]; Stefan ULMER [8]; Christian SMORRA [1]

[1] *Johannes Gutenberg-Universität Mainz (DE)*

[2] *Max-Planck-Institute for Nuclear Physics (DE)*

[3] *Max-Planck-Gesellschaft (DE)*

[4] *CERN (CH)*

[5] *Leibniz Universitaet Hannover (DE)*

[6] *The University of Texas at Austin (US)*

[7] *University of Tokyo (JP)*

[8] *RIKEN (JP)*

[9] *GSI - Helmholtzzentrum fur Schwerionenforschung GmbH (DE)*

Corresponding Author: faabbass@uni-mainz.de

The ERC project STEP ”Symmetry Tests in Experiments with Portable Antiprotons“ is building a transportable antiproton trap BASE-STEP to relocate antiproton precision measurements and ultimately improve the limits of the measurement precision of CPT invariance tests comparing the fundamental properties of protons and antiprotons. Recently, the BASE collaboration ”Baryon Anti-baryon Symmetry Experiment” performed the most precise antiproton measurements at CERN in the antiproton decelerator (AD) hall, and we develop the transportable antiproton trap BASE-STEP to move the antiproton outside of CERN’s AD hall to reduce limitations caused by magnetic field fluctuations. We will place a trap system with the superconducting magnet in the AD hall to take the ELENA beam to commission BASE-STEP.

I have developed and tested image current detectors for the BASE-STEP. The image current detection systems which I developed and tested are made up of superconducting toroidal coils and cryogenic amplifiers. As a result, I was able to achieve a higher Q-value for the cyclotron detectors with toroidal coils than we had previously achieved using solenoids.
The image-current detection systems that I developed are essential parts of the transportable trap and will help detect trapped particles at various frequencies in a superconducting magnet at CERN and a permanent magnet trap at the University of Mainz.

Antimatter Session III

Antimatter III / Wednesday 14:30 -14:52

Fundamental tests of antimatter gravitation with antihydrogen accelerators

Author: Jaspal Singh[1]

Co-author: William Alan Bertsche [1]

[1] *University of Manchester (GB)*

Corresponding Author: jaspal.singh@cern.ch

The Antihydrogen Laser Physics Apparatus (ALPHA) collaboration at CERN has been successfully pushing the boundaries of high precision atomic physics with antihydrogen to characterise the peculiarities of antimatter in a universe suspiciously dominated by matter today. Starting from the blossoming expertise developed by the collaboration with antihydrogen traps and laser spectroscopy measurements, ALPHA is currently directing its efforts towards ALPHA-g, the next generation of antihydrogen traps, two Penning-Malmberg and neutral atom traps, intended to measure the gravitational acceleration g of antimatter on Earth with higher precision.

This challenging goal requires homogeneity and precise knowledge of the magnetic fields in the system with a careful analysis of the experimental protocol and diagnostic techniques, i.e. controlling the probe and background magnetic fields in the experiment. Starting from an analysis of the underlying principles and designs of the ALPHA-g machine underpinned by the recent contributions and results from the collaboration, the discussion will develop around the precision improvements in the magnet control system critical to achieve the aforementioned objective.

Antimatter III / Wednesday 14:53 -15:15

Positron plasma creation and manipulation in the ASACUSA Cusp experiment

Author: Andreas Lanz[1]

Co-authors: Eric Hunter [1]; Daniel James Murtagh [1]

[1] *Austrian Academy of Sciences (AT)*

Corresponding Author: andreas.lanz@cern.ch

The ASACUSA experiment aims to perform a ppm measurement of the ground-state hyperfine structure of antihydrogen using a spin-polarized antihydrogen beam. The production of antihydrogen in the mixing trap, the so-called Cusp trap – due to its cusped magnetic field – is done by merging positron and antiproton plasmas. To produce a sufficient amount of ground-state antihydrogen it is crucial to have control over the density and the temperature of the positron plasma. In order to increase the number of trapped positrons, we developed and built a new accumulator to separate the trapping and accumulation region. Additionally, a new trap that was formerly used at the University of Aarhus, will be installed and tested this year.

This talk will cover general aspects of the ASACUSA experiment, the new accumulator, the new trap and recent experiments to gain control of the plasma properties.

Antimatter III / Wednesday 15:15 -15:37

An Ion Trap Source of Ultracold Atomic Hydrogen via Photodissociation of the BaH$^+$ Molecular Ion

Author: Steven Armstrong Jones[1]

[1] *Swansea University (GB)*

Corresponding Author: steven.armstrong.jones@cern.ch

Hydrogen remains the go-to tool for testing fundamental physics, with the recent proton radius puzzle being a prime example. Here, I present a novel scheme for producing ultracold 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 photodissociating it on the single photon A1Σ+←X1Σ+ transition. The small mass ratio between Ba$^+$ and BaH$^+$ ensures a strong overlap and efficient cooling, and the large mass ratio between BaH$^+$ and H means that the released hydrogen will be 139 times colder than its parent molecular ion. I describe how the trap dynamics influence the energy of the hydrogen, and outline methods to optimise this. The low infrastructure costs and the ion trap nature of the scheme make it ideal for loading hydrogen into an antihydrogen exeriment, to support a direct matter-antimatter comparison.

Antimatter III / Wednesday 15:38 -16:00

ASACUSA's low energy proton source for matter studies

Author: Alina Weiser[1]

[1] *Austrian Academy of Sciences (AT)*

Corresponding Author: alina.weiser@cern.ch

Antihydrogen atoms can be formed via three body recombination of antiprotons and positrons. The ASACUSA collaboration will use this technique of forming atoms in order to perform a ppm measurement of the ground-state hyperfine structure of them.

A proton source was developed such that hydrogen can be produced using the same apparatus and techniques which are used in the antimatter experiment.

This device assures that the system can be optimized and tested whenever antiprotons are not available.

The proton source consists of three modules. The first is responsible for electron production, the second for proton formation via electron impact ionization of H_2-gas and the final one for focusing and steering of the resulting beam.

Molecular hydrogen and other impurities can be removed in the second module by applying a rotating electric field.

Integrated into the ASACUSA experimental setup, the source works as expected, enabling the accumulation of more than a million protons in the mixing trap.

Nuclear Physics Session I

Nuclear Physics I / Monday 14:30 - 14:52

High-Resolution Mass Measurements at the FRS Ion Catcher in the vicinity of ^{100}Sn

Authors: Christine Hornung[1]; Ali Mollaebrahimi[2]

Co-authors: Daler Amanbayev [3]; Irene Dedes [4]; Gabriella Kripko-Koncz [3]; Ivan Miskun [3]; Noritaka Shimizu [5]; Samuel Ayet San Andres [6]; Julian Bergmann [3]; Timo Dickel [7]; Jerzy Dudek [8]; Jens Ebert [3]; Hans Geissel ; Magdalena Gorska [9]; Hubert Grawe [10]; Florian Greiner [11]; Emma Haettner [10]; Takaharu Otsuka ; Wolfgang Plaß [12]; Sivaji Purushothaman [10]; Ann-Kathrin Rink [3]; Christoph Scheidenberger [13]; Helmut Weick [1]

[1] *GSI Helmholtzzentrum für Schwerionenforschung*

[2] *University of Giessen and TRIUMF*

[3] *II. Physikalisches Institut, Justus-Liebig-Universität Gießen*

[4] *Institute of Physics, Marie Curie-Sklodowska University*

[5] *Center for Nuclear Study, University of Tokyo*

[6] *GSI Helholtzzentrum GmbH*

[7] *GSI*

[8] *Université de Strasbourg, CNRS, Institute of Physics, Marie Curie-Sklodowska University*

[9] *GSI Darmstadt*

[10] *GSI Helmholtzzentrum für Schwerionenforschung GmbH*

[11] *GSI - Helmholtzzentrum fur Schwerionenforschung GmbH (DE)*

[12] *Justus Liebig University Gießen, GSI*

[13] *GSI Helmholtzzentrum für Schwerionenforschung GmbH, II. Physikalisches Institut, Justus-Liebig-Universität Gießen*

Corresponding Author: ali.mollaebrahimi@exp2.physik.uni-giessen.de

The study of exotic nuclei far from the valley of stability provides basic information for a better understanding of nuclear structure and the synthesis of the elements in the universe. It is of special interest to probe the edges of stability with their unexpected and novel properties. The nucleus ^{100}Sn is the heaviest self-conjugate doubly-magic nucleus in the chart of nuclides, and therefore, attracts a broad interest from both fields, experimental and theoretical nuclear physics. The experimental access to ^{100}Sn is still limited, most of the data obtained originate from nuclei in its vicinity. Therefore, the knowledge of their detailed structure is essential in understanding this region of the chart of nuclides.
At the FRS Ion Catcher [1] at GSI precision experiments on exotic nuclei are performed with the combination of a cryogenic stopping cell (CSC) and a multiple-reflection time-of-flight mass spectrometer (MR-TOF-MS). This setup enables to perform high precision mass measurements with the MR-TOF-MS of thermalized exotic ions produced at relativistic energies with mass resolving powers (FWHM) of up to 1,000,000 and relative mass uncertainties down to $1.7 \cdot 10^{-8}$ [2].
The nuclei ^{97}Ag and $^{101-109}$In and their long-living isomeric states were investigated in previous experiments [3]. In the isotope ^{97}Ag, a long-lived $(1/2^-)$ isomeric state was discovered, and its excitation energy was determined to be 618(38) keV. This marks the first discovery of

a nuclear isomeric state by an MR-TOF-MS. The properties of nuclear isomers are significant for the understanding of nuclear structure because they provide stringent tests for nuclear models. The measured excitation energies were compared to large-scale shell-model calculations, which indicate the importance of core excitation around ^{100}Sn. Furthermore, advanced mean-field calculations for the ^{97}Ag nucleus and relevant neighboring nuclei were performed, which support the discovery of the isomeric state in ^{97}Ag in a global shell-evolution scheme.
References:

[1] W.R. Plaß et al., Nucl. Instr. Meth. B 317 (2013) 457,
[2] I. Mardor et al., PRC 103 (2021) 034319,
[3] C. Hornung et al., Phys. Lett. B 802 (2020) 135200.

Nuclear Physics I / Monday 14:53 - 15:15

High precision mass measurement of ^{24}Si and a final determination of the *rp*-process at the A=22 waiting point

Authors: Daniel Puentes[1]; Zach Meisel[2]; Georg Bollen[1]; Alec Hamaker[1]; Christoph Langer[3]; Erich Leistenschneider[4]; Catherine Nicoloff[1]; Wei Jia Ong[5]; Matthew Redshaw[6]; Ryan Ringle[1]; Chandana Sumithrarachchi[7]; Jason Surbrook[1]; Adrian Valverde[8]; Isaac Yandow[1]

[1] *Michigan State University*

[2] *Ohio University*

[3] *University of Applied Sciences Aachen*

[4] *CERN*

[5] *Lawrence Livermore National Laboratory*

[6] *Central Michigan University*

[7] *National Superconducting Cyclotron Laboratory*

[8] *University of Manitoba*

Corresponding Author: puentes@nscl.msu.edu

Type I X-ray bursts occur at astrophysical sites where a neutron star accretes H/He-rich matter from a companion star, leading to nuclear burning on the neutron star surface. The only observable is the X-ray burst light curve, which is used as a unique diagnostic of the outer layers of accreting neutron stars such the accretion rate and fuel composition. In addition to the astrophysical conditions, the main determinant of the shape of the light curve is the nuclear physics involved. Variations within the uncertainty of the ^{23}Al(p,γ)^{24}Si reaction rate lead to significant shifts in simulated X-ray light curves, where the ground state mass of ^{24}Si is currently the dominant source of the reaction rate uncertainty (19 keV). A beam of ^{24}Si was produced at the National Superconducting Cyclotron Laboratory and delivered to the LEBIT facility, where Penning trap mass spectrometry was used to improve the mass uncertainty by a factor of 5 (3.7 keV). The impact of this new mass value on the reaction rate and the onset of the αp-process at the ^{22}Mg waiting point will be presented, settling the *rp*-process at the $A = 22$ mass region.

Nuclear Physics I / Monday 15:15 - 15:35

News From the ISOLTRAP Mass Spectrometer

Author: Lukas Nies[1]

[1] *CERN / University of Greifswald (DE)*

Corresponding Author: lukas.nies@cern.ch

Recent technical developments and experimental results from the ISOLTRAP mass spectrometer at ISOLDE/CERN will be presented in this contribution. During CERN's Long Shutdown 2 (LS2), a large variety of technical upgrades and maintenance work have been performed. Most significantly, a new offline reference ion source has been built and commissioned, combining a surface ion source and a laser ablation ion source. First results from the commissioning work will be shown, along with ideas for high-precision Q-value measurements of laser-ablated long-lived isotopes. Furthermore, since the restart of CERN after LS2 in June 2021, ISOLTRAP has performed several experiments on exotic radioisotopes and aided target and ion source developments at ISOLDE. Preliminary results for measuring ground and isomeric states in the neutron deficient region around ^{100}Sn using Multi-Reflection Time-of-Flight Mass Spectrometry will be given.

Nuclear Physics I / Monday 15:35 - 15:55

Ion Trapping Developments at Edinburgh University, Towards Precise Mass Measurements of Light Exotic Nuclei at TITAN

Author: Callum Brown[1]

Co-authors: Ali Mollaebrahimi [2]; Andrew Jacobs [3]; Anna Kwiatkowski [4]; Coulter Walls [5]; Moritz Pascal Reiter [1]; Peter Black [1]; Timo Dickel [6]; Tobias Murböck [5]; Wolfgang Plaß [6]

[1] *University of Edinburgh*
[2] *Justus Liebig University Gießen, TRIUMF*
[3] *TRIUMF, University of British Columbia*
[4] *TRIUMF, University of Victoria*
[5] *TRIUMF*
[6] *Justus Liebig University Gießen, GSI*

Corresponding Author: callum.brown@ed.ac.uk

High-precision mass measurements are essential for understanding the structure of exotic nuclei. These measurements serve as excellent tests of the latest nuclear models and provide key inputs for calculations in nuclear astrophysics. Light nuclei at the limits of nuclear binding are particularly important, as they are accessible with various ab-initio models, and so provide good tests for how these models perform in exotic conditions.

TRIUMF's Ion Trap for Atomic and Nuclear science (TITAN) [1] at TRIUMF has specialised in the measurement of short-lived nuclei using a Penning trap and a multiple-reflection time-of-flight mass spectrometer (MR-TOF-MS) [2].

However, many light exotic nuclei are currently inaccessible at TITAN. Among these are several halo nuclei, as well as many nuclei which would provide important insight on the $N = 20$ island of inversion. Of particular interest is the halo nucleus ^{14}Be. The halo nuclei ^{11}Li, ^{6}He, and ^{8}He have all been measured at TITAN using the Penning trap [3, 4], but a precise measurement of ^{14}Be remains elusive due to its exceptionally low half-life and production rate. A first direct measurement of its mass would be an unprecedented test of current nuclear models. Mass measurements of neutron-rich isotopes of Na and Mg have also been elusive. Measurements of these masses would provide stringent tests of modern ab-initio theories, and help chart the precise extent of the $N = 20$ island of inversion.

The MR-TOF-MS excels at measuring scarcely produced nuclei with very low half-lives, and as such it increases TITAN's reach to include more exotic nuclei. This has allowed many new measurements, a recent example being the precision measurement of neutron-rich scandium near the $N = 32$ and $N = 34$ shell closures [5]. But to leverage this strength towards the study of light nuclei, a high frequency driver must be developed for the radio-frequency quadrupole (RFQ) system. This is required due to the frequency-dependent mass selectivity of RFQs.

We have developed a low cost alternative to commercial high frequency drivers for nuclear physics experiments. Five sin-wave drivers have been developed and are currently undergoing testing. Prior to the end of the year they should be installed at TITAN. They will be first employed in a measurement campaign of neutron-rich Na and Mg isotopes approaching the $N = 20$ island of inversion. An important feature of these drivers is a sense circuit, allowing for phase amplitudes to be matched directly.

This contribution will report ongoing ion trapping developments for TITAN at the University of Edinburgh, that will enable precise mass measurements of several light nuclei. Results from recent mass measurements will be presented, concerning halo nuclei, the $N = 20$ or $N = 40$ island of inversion.

[1] J. Dilling et al., Journal of Mass Spectrometry, 251(2), 198–203, (2006)
[2] T. Dickel et al., Hyperfine Interact 240, 62, (2019)

[3] M. Smith et al., Phys. Rev. Lett. 101, 2025201, (2008)
[4] M. Brodeur et al., Phys. Rev. Lett. 108, 052504, (2012)
[5] E. Leistenschneider et al., Phys. Rev. Lett. 126, 042501, (2021)

Nuclear Physics I / Monday 15:55 - 16:15

Implementation of the double Penning trap mass spectrometer MLLTRAP at ALTO

Author: Elodie MORIN[1]

[1] *CNRS (FR)*

Corresponding Author: elodie.morin@ijclab.in2p3.fr

Mass measurements of exotic nuclei with high precision are of big interest for nuclear physics and nuclear astrophysics. They give access to nuclear binding energies permitting to explore nuclear shell structure. They are also entries for nucleosynthesis models and allow discriminating between different models. The principal spectrometers to perform high precision mass measurements are those based on ion traps. MLLTRAP is a double Penning trap mass spectrometer (PTMS) which is located at the ALTO facility (Accélérateur et Tandem à Orsay). At ALTO, it will mainly be dedicated to perform high precision mass measurements of neutron rich exotic nuclei around the shell closures N = 50 and N = 82. These nuclei far from the valley of stability of the nuclear chart have short lifetimes, and sometimes very short-lives isomers. Measuring their properties is a real challenge. The first mass measurements campaign for MLLTRAP will focus on the silver isotopes towards the shell closure N = 82. Neutron rich exotic nuclei are produced by photo-fission at ALTO. The element of interest can be selected using a laser ion source. The ions are accelerated up to a few tens of keV to provide a low energy beam to the experimental setups. Upstream from the PTMS, the low energy beam is transported to a linear segmented Paul trap (RFQCB) where the ions are cooled and bunched. When ejected from the RFQCB, they are decelerated to be injected into the PTMS. The off-line commissioning of the PTMS and the RFQCB will be performed with a high voltage stable ion source developed at Orsay. Alkali metals, ^{133}Cs and $^{85-87}$Rb will be produced with the stable ion source and accelerated up to 50 keV in order to caracterize the traps and the transport line in comparable energy conditions to on-line conditions. In order to implement the Phase-Imaging Ion-Cyclotron-Resonance (PI-ICR) technique at MLLTRAP, required to improve the precision of the mass measurements, the current control and detection systems are being upgraded. This technique will, in particular, allow to discriminate between ground and isomeric states of silver isotopes as a high resolution is necessary. Moreover, only a few ions are needed to get mass measurements when using PI-ICR technique. In parallel, a special magnetic probe has been developed and installed in the 7T superconducting magnet. This probe will be used to monitor the magnetic field variations in real time during the mass measurements experiments. In this contribution, the progress of the implementation of the different sections, the first off-line results and the schedule for the first on-line measurements will be presented.

Nuclear Physics Session II

Nuclear Physics II / Thursday 9:00 - 9:22

Developments for an increased detection sensitivity of the neutrinoless double-beta decay ($0\nu\beta\beta$) mode in the NEXT experiment

Authors: NEXT Collaboration; Samuel Ayet San Andres[1]

[1] *JLU Giessen*

Corresponding Author: s.ayet@gsi.de

The detection of the double-beta decay mode which would reveal the nature of the neutrino, Dirac or Majorana, is an extremely rare event where two emitted electrons share all the available energy of the decay and no neutrino is emitted. The current experiments in the search of such decay mode are far from a background-free condition, and the level of background achieved plays a crucial role in the limits of the sensitivity for the half-life of this decay mode. A method that allows discarding all the events except the ones produced via double-beta decay is the correlation of the events with the detection of the daughter nuclei of the decay, leaving only the two-neutrino double-beta decay the only background of the experiment. The different research lines within the NEXT collaboration in the pursuit of a background-free experiment in order to increase the half-life sensitivity for the neutrinoless double-beta decay, including the Barium tagging technique, will be presented.

Nuclear Physics II / Thursday 9:23 - 9:45

The commissioning of a Paul trap for laser spectroscopy of exotic radionuclides in an MR-ToF device

Author: Carina Kanitz[1]

Co-authors: Ivana Belosevic [2]; Fritz Buchinger [3]; Moritz Epping [4]; Paul Fischer ; Simon Lechner [5]; Erich Leistenschneider [6]; Franziska Maria Maier [7]; Stephan Malbrunot [6]; Peter Plattner [8]; Lutz Schweikhard ; Markus Kristian Vilen [6]; Simon Mark C Sels [9]

[1] *Friedrich Alexander Univ. Erlangen (DE)*

[2] *TRIUMF (CA)*

[3] *McGill University, Montreal, Canada*

[4] *Max Planck Society (DE)*

[5] *CERN, TU Wien*

[6] *CERN*

[7] *Universität Greifswald*

[8] *University of Innsbruck (AT)*

[9] *KU Leuven (BE)*

Corresponding Author: carina.kanitz@cern.ch

The Multi Ion Reflection Apparatus for Collinear Laser Spectroscopy (MIRACLS) represents a new approach for precision measurements of nuclear ground-state properties in short-lived radionuclides. Conventional Collinear Laser Spectroscopy (CLS) [1-3] requires ion yields of more than 100-10000 ions per second, depending on the element, delivered from a radioactive ion beam (RIB) facility to distinguish the fluorescence signal from background and, thus, to perform a successful measurement of radionuclides' electromagnetic moments or charge radii. Due to their low RIB production yields, the 'most exotic' radio-isotopes are often out of reach of traditional fluorescence-based CLS which is limited in observation time to a few microseconds while ions are passing once through a laser-ion interaction region. In the MIRACLS approach, however, the ion beam is stored in a Multi-Reflection Time-of-Flight (MR-ToF) device and probed repeatedly to increase the collected CLS signal with each ion revolution inside the trap.

After the successful completion of a MIRACLS proof-of-principle experiment [4-6], a new high-resolution apparatus is presently under construction at ISOLDE, CERN.
To accommodate the requirements on the ion beam properties of a small energy spread for CLS and a small temporal width for the MR-ToF operation, a linear Paul trap acting as radiofrequency cooler and buncher was constructed. In this talk, the design, simulation study of the operation, and commissioning of the Paul trap will be presented, together with an outlook on future studies of very exotic nuclei with MIRACLS.

[1] R. Neugart, J. Phys. G: Nucl. Part. Phys. 44 (2017)
[2] P. Campbell et al., Prog. Part. Nucl. Phys. 86, 127-180 (2016)
[3] K. Blaum et al., Phys. Scr. T152, 014017 (2013)
[4] S. Sels et al., Nucl. Instr. Meth. Phys. Res. B 463, 310 (2020)
[5] V. Lagaki et al., Nucl. Inst. Meth. Phys. Res. A 1014, 165663 (2021)
[6] F. M. Maier et al., Hyperfine Interact 240, 54 (2019)

Nuclear Physics II / Thursday 9:45 - 10:07

Doppler- and sympathetic cooling for the investigation of short-lived radionuclides

Author: Franziska Maria Maier[1]

Co-authors: Simon Mark C Sels [2]; Mia Au [3]; Paul Fischer [1]; Carina Kanitz [4]; Varvara Lagaki [5]; Simon Lechner [6]; David Leimbach [7]; Marilena Lykiardopoulou [8]; Tom Manovitz [9]; Erich Leistenschneider [3]; Peter Plattner [10]; Lutz Christian Schweikhard [1]; Marco Rosenbusch [11]; Sebastian Rothe [3]; Markus Kristian Vilen [3]; Robert Wolf [12]; Stephan Malbrunot [3]

[1] *University of Greifswald (DE)*
[2] *KU Leuven (BE)*
[3] *CERN (CH)*
[4] *Friedrich Alexander Univ. Erlangen (DE)*
[5] *Ernst Moritz Arndt Universitaet (DE)*
[6] *CERN (CH), TU Wien (AT)*
[7] *Johannes Gutenberg Universitaet Mainz (DE)*
[8] *University of British Columbia (CA)*
[9] *Weizmann Institute of Science (IL)*
[10] *University of Innsbruck (AT)*
[11] *RIKEN (JP)*
[12] *University of Sydney (AU)*

Corresponding Author: franziska.maria.maier@cern.ch

Ever since its introduction in the mid 1970s, laser cooling has become a fundamental technique to prepare and control ions and atoms for a wide range of precision experiments.
In the realm of rare isotope science, for instance, specific atom species of short-lived radionuclides have been laser-cooled for fundamental-symmetries studies [1] or for measurements of hyperfine-structure constants [2] and nuclear charge radii [3].
Nevertheless, because of its simplicity and element-universality, buffer-gas cooling in a linear, room-temperature Paul trap is more commonly used at contemporary radioactive ion beam (RIB) facilities. Recent advances in experimental RIB techniques, especially in laser spectroscopy or mass spectrometry, would however strongly benefit from ion beams at much lower beam temperature as in principle attainable by laser cooling. The possibility of sympathetic cooling of ions which are co-trapped with a laser-cooled ion species could open a path for a wide range of sub-Kelvin RIBs.
In a proof-of-principle experiment within the MIRACLS setup [4], we demonstrated that laser cooling is compatible with the timescale imposed by short-lived radionuclides as well as with existing instrumentation at RIB facilities. To this end, a beam of hot ^{24}Mg^{+} ions is injected into a linear Paul trap in which the ions are cooled by a combination of a low-pressure buffer gas and a 10-mW, cw laser beam of 280 nm. Despite an initial kinetic energy of the incoming ions of a few eV at the trap's entrance, temporal widths of the extracted ion bunch corresponding to an ion-beam temperature of around 6 K are obtained within a cooling time of 100 ms. Moreover, sympathetic cooling of co-trapped K^{+} and O^{2+} ions was successfully demonstrated. As a first application of the technique, a laser-cooled ion bunch is transferred into a multi-reflection time-of-flight mass spectrometer. This improved the mass resolving power by a factor of 4.5 compared to conventional buffer-gas cooling.
The presentation will include the experimental results of our laser-cooling studies as well as a comparison to our 3D simulations of the cooling process which paved the way for further improvements of the technique. An outlook to future experiments with laser- and sympathetically cooled ions at radioactive ion beam facilities will be given.

[1] G. D. Sprouse and L. A. Orozco, Annu. Rev. Nucl. Part. Sci.. 47, 429 (1997)
J. A. Behr et al., Phys. Rev. Lett. 79, 375 (1997).
M. Trinczek et al., Phys. Rev. Lett. 90, 012501 (2003).
P. A. Vetter et al., Phys. Rev. C 77, 035502 (2008).

J. R. A. Pitcairn et al., RRC 79, 015501 (2009)
B. Fenker et al., Phys. Rev. Lett. 120, 062502 (2018)
[2] A. Takamine et al., Phys. Rev. Lett. 112, 162502 (2014)
[3] L. B. Wang et al., Phys. Rev. Lett. 93, 142501 (2004).
P. Mueller et al., Phys. Rev. Lett. 99, 252501 (2007).
[4] S. Sels et al., Nucl. Instrum. Meth. B, Vol 463 310-314

Nuclear Physics II / Thursday 10:08 - 10:30

Trapping Swift Divergent Ions with Stacked Rings

Author: Xiangcheng Chen[1]

Co-authors: Julia Even [1]; Paul Fischer [2]; Maarten Mijland [1]; Moritz Schlaich [3]; Thomas Schlathölter [1]; Lutz Schweikhard [2]; Arif Soylu [1]; Lisa van der Werff [1]; Frank Wienholtz [3]

[1] *University of Groningen (NL)*

[2] *University of Greifswald (DE)*

[3] *Technische Universität Darmstadt (DE)*

Corresponding Author: xiangcheng.chen@rug.nl

Study on exotic nuclei has become one of the research frontiers in nuclear physics. They can be produced by bombarding an energetic (MeV~GeV) projectile onto a target. Among various products, the ions of interest can be promptly and efficiently selected by in-flight separation. To precisely measure their properties, it is preferable to couple a low-energy (eV~keV) experimental terminal to the separation beam line. A gas-filled stopping cell is usually adopted as the first stage to thermalize the relativistic ions. However, the supersonic gas jet bursting out of the submillimeter orifice will accelerate the ions and result in a divergent beam. It is therefore important to confine the swift (a few eV) ions before they are diluted by diffusions in the residual gas. Sometimes it is also necessary to bunch the ions before sending them to the next experimental stage, which entails trapping the ions in three dimensions. In this contribution, we will present a unified solution with stacked rings to meet all the above requirements. The proposed ion cooler and buncher consists of a stack of ring electrodes with varying apertures to fit its geometric boundary to the envelope of a focused beam. The pitches of the rings are adjusted accordingly to produce a consistent pseudopotential barrier in the radial direction and a deep enough pseudopotential well for ion bunching at the exit where the swift ions are expected to be thermalized already. All the rings will be driven by a square-wave radio-frequency (RF) to avoid the requirement of resonance tuning as typically used for sinusoidal guiding fields. An RF-only traveling wave is employed to shorten ions' axial diffusion times. This device is being developed within the NEXT project at University of Groningen towards the aim of mass measurements of Neutron-rich EXotic nuclei produced in multi-nucleon Transfer reactions. It can be used, for example, as an injector for a Multi-Reflection Time-of-Flight Mass Spectrometer (MR-ToF MS).

Precision Spectroscopy Session I

Precision Spectroscopy I / Wednesday 9:00 - 9:22

Towards quantum control and spectroscopy of a single hydrogen molecular ion

Author: David Holzapfel[1]

Co-authors: Nick Schwegler [1]; Jonathan Home [1]; Daniel Kienzler [1]

[1] *ETH Zurich*

Corresponding Author: dholzapfel@phys.ethz.ch

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 of single H_2^+ and $^9Be^+$ ions. We observe trapping durations of H_2^+ of up to eight hours. For the ion pair's axial in-phase mode of motion we estimate a temperature of $\approx 130\ \mu K$ after Doppler cooling of $^9Be^+$, which is a reduction by a factor of ≈ 80 over current state-of-the-art [2-4].

The experimental apparatus features a cryogenic ultra-high vacuum chamber, housing a microfabricated 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 [5,6].

References

[1] V.I. Korobox, J.-P. Karr, M. Haidar, and Z.-X. Zhong, ''Hyperfine structure in the H_2^+ and HD^+ molecular ions at order $m\alpha^6$" *Phys. Rev. A*, vol. 102, p. 022804, Aug 2020.

[2] S.Alighanbari, G.S. Giri, F.L. Constantin, V.I. Korobov, and S.Schiller, ''Precise test of quantum electrodynamics and determination of fundamental constants with HD^+ ions" *Nature*, vol. 581, no. 7807, pp. 152-158, 2020.

[3] S. Patra, M. Germann, J.-P. Karr, M. Haidar, L. Hilico, V.I. Korobov, F.M.J. Cozijn, K.S.E. Eikema, W. Ubachs, and J.C.J. Koelemeij, ''Proton-electron mass ratio from laser spectroscopy of HD^+ at the part-per-trillion level" *Science*, vol. 369, no. 6508, pp. 1238-1241, 2020.

[4] I.V. Kortunov, S. Alighanbari, M.G. Hansen, G.S. Giri, V.I. Korobov, and S. Schiller, ‘’Proton-electron mass ratio by high-resolution optical spectroscopy of ion ensembles in the resolved-carrier regime” *Nature Physics*, 2021.

[5] S. Schiller, I. Kortunov, M. Hernández Vera, F. Gianturco, and H. da Silva, ‘’Quantum state preparation of homonuclear molecular ions enabled via a cold buffer gas: An ab initio study for the H_2^+ and the
D_2^+ case” *Phys. Rev. A*, vol. 95, p. 043411, Apr 2017.

[6] P.O. Schmidt, T. Rosenband, C. Langer, W.M. Itano, J.C. Bergquist, and D.J. Wineland, ‘’Spectroscopy using quantum logic” *Science*, vol. 309, pp. 749-752, 2005.

Precision Spectroscopy I / Wednesday 9:23 - 9:45

Tests of QED with singly-ionized helium

Author: Andres Martinez de Velasco[1]

Co-authors: Elmer Grundeman [1]; Charlaine Roth [1]; Vincent Barbé [1]; Mathieu Collombon [1]; K. S. E. Eikema [1]

[1] *Vrije Universiteit Amsterdam (NL)*

Corresponding Author: a.martinezdevelasco@vu.nl

The 1S-2S transition of hydrogenic systems is a benchmark for tests of fundamental physics [1]. The most prominent example is the 1S-2S transition in atomic hydrogen, where impressive relative accuracies have been achieved [2-3]. Nowadays, these fundamental physics tests are hampered by estimates of uncalculated higher-order QED terms and the uncertainties in the fundamental constants required for their calculation [4]. An independent, experimental approach to contribute to and further improve these fundamental physics tests is to measure the 1S-2S transition in He^+. Because He^+ has twice the nuclear charge of hydrogen, certain interesting QED contributions are strongly enhanced and can therefore be tested more precisely than in hydrogen. Furthermore, nuclear properties such as the alpha particle charge radius or nuclear polarizability contributions can be probed [4].

We aim to use the Ramsey-comb spectroscopy (RCS) method [5] developed in our lab in order to measure the 1S-2S transition in singly-ionized helium in the extreme ultraviolet (XUV) spectral range and contribute to fundamental tests of QED. RCS uses two amplified and up-converted pulses out of the infinite pulse train of a frequency comb laser to perform a Ramsey-like excitation. The He^+ spectroscopy scheme is based on two-photon excitation, using one XUV photon at 32 nm (generated through High-Harmonic Generation, the 25th harmonic) and one infrared photon at 790 nm from the fundamental beam. The atomic sample will consist of a He^+ ion confined in a Paul trap, sympathetically cooled by a Doppler- and Raman-cooled Be^+ ion, which has a cycling transition at 313 nm that we also use to monitor the Be^+ ion. The readout scheme for two-photon He^+ excitation is based on quantum logic spectroscopy [6], which relies on detecting the recoil of He^+ upon excitation, transferred to the Be^+ ion.

Recently we demonstrated that RCS can be combined with HHG [7] leading to a high precision measurement in xenon at 110 nm [8]. The many new components required for the He^+ experiment, such as a new RCS laser, the ion trap, laser cooling and imaging systems, are approaching completion and we will report on their current status. Using the RCS method we aim to do a first 1S-2S measurement of He^+ with an accuracy of 1-10 kHz, while an accuracy of better than 50 Hz should be ultimately achievable.

References:
[1] Herrmann et al., Phys. Rev. A 79, 052505 (2009)
[2] Niering et al., Phys. Rev. Lett. 84, 5496 (2000)
[3] de Beauvoir et al., Eur. Phys. J. D 12, 61 (2000)
[4] Krauth et al., PoS(FFK2019) 49, (2019)
[5] Morgenweg et al., Nature Phys. 10, 30–33 (2014)
[6] Schmidt et al., Science 309, 749 (2005)
[7] Dreissen et al., Phys. Rev. Lett. 123, 143001 (2019)
[8] Dreissen et al., Phys. Rev. A 101, 052509 (2020)

Precision Spectroscopy I / Wednesday 9:45 - 10:07

Penning-trap mass spectrometry using an unbalanced crystal and optical detection

Authors: Joaquín Berrocal[1]; Francisco Domínguez[1]; Emilio Altozano[1]; Javier Cerrillo[2]; F. Javier Fernández[1]; Michael Block[3]; Daniel Rodríguez[1]

[1] *Universidad de Granada (ES)*

[2] *Universidad Politécnica de Cartagena (ES)*

[3] *GSI (DE)*

Corresponding Author: jberrocal@go.ugr.es

A novel Penning-trap mass spectrometry technique based on optical detection is under development at the University of Granada. This technique is universal, non-destructive, and single ion-sensitive. The scattered photons by a ^{40}Ca^{+} ion will be used to measure the normal mode eigenfrequencies of the unbalanced crystal formed by this ion and a target one [1] when the crystal is cooled to the ground state of motion [2]. The dynamics of the two-ion crystal has been studied, including the quantification of frequency shifts due to the Coulomb repulsion, and a procedure to perform motional quantum metrology has been deduced. Experimentally, the magnetic field of the open-ring Penning trap is the largest ever used in laser-cooling experiments [3], which together with the level structure of the calcium ion has made Doppler cooling challenging.

We have recently demonstrated Doppler cooling of a single ^{40}Ca^{+} ion and the crystallization of small ion structures [4]. To achieve this point, a new self-designed optical system has been tested and implemented. Furthermore, improvements on the injection of externally produced ions and on the vacuum system have been introduced. At this moment, we are taking the first steps towards the demonstration of the technique after Doppler cooling on a ^{40}Ca^{+} - ^{48}Ca^{+} crystal. In this contribution, we will describe the TRAPSENSOR facility, and the results obtained so far. We will end presenting the status on the laser system to perform side-band cooling to reach the ground state of motion in this Penning trap.

[1] M. J. Gutiérrez *et al.*, Phys. Rev. A **100**, 063415 (2019).
[2] J. Cerrillo and D. Rodríguez, EPL- Perspective **134**, 38001 (2021).
[3] M. J. Gutiérrez *et al.*, New J. Phys. **21**, 023023 (2019).
[4] J. Berrocal *et al.*, in preparation.

Precision Spectroscopy I / Wednesday 10:08 - 10:30

Measurement of the $^{88}\mathbf{Sr}^{+}$ $S_{1/2} \rightarrow D_{5/2}$ / $^{171}\mathbf{Yb}^{+}$ $S_{1/2} \rightarrow F_{7/2}$ frequency ratio with in-situ BBR shift evaluation

Authors: Martin Steinel[1]; Hu Shao[2]; Melina Filzinger[2]; Nils Huntemann[2]; Richard Lange[2]; Burghard Lipphardt[2]; Tanja Mehlstäubler[2]; Christian Tamm[2]; Ekkehard Peik[2]

[1] *Physikalisch-Technische Bundesanstalt*

[2] *Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany*

Corresponding Author: martin.steinel@ptb.de

A significant contribution to the uncertainty budgets of optical clocks based on the ^{171}Yb^{+} $S_{1/2} \rightarrow F_{7/2}$ electric octupole (E3) transition results from the Stark shift induced by blackbody radiation (BBR) of the environment of the trapped ion. Even if precise knowledge on the thermal environment is available, uncertainty in the sensitivity of the shift to thermal radiation, the differential polarizability $\Delta\alpha$ of the E3 transition, limits a shift evaluation to 2%. For the $S_{1/2} \rightarrow D_{5/2}$ electric quadrupole (E2) transition of ^{88}Sr^{+} $\Delta\alpha$ is known to 0.15% [1]. By trapping both atomic species in a linear segmented ion trap and irradiating infrared laser light of the same intensity on both the ^{88}Sr^{+} E2 and ^{171}Yb^{+} E3 while monitoring their transition frequencies, permits a transfer of the relative uncertainty of $\Delta\alpha$ from ^{88}Sr^{+} to ^{171}Yb^{+}.

In preparation to this experiment, the ratio of the unperturbed frequencies of the ^{88}Sr^{+} E2 transition and the ^{171}Yb^{+} E3 transition is measured. Since the ^{88}Sr^{+} E2 is prone to BBR shifts, the thermal field at the position of the ion must be evaluated. While the ambient temperature of the vacuum chamber can be determined with low uncertainty, the effect of the temperature rise during operation needs to be evaluated independently. Under the assumption, that the heating of the trap results from Joule heating and a T^4-dependence of the BBR shift, the temperature can be inferred from measurements with different settings of the applied trap drive power. In this way, we determine the frequency of the ^{88}Sr^{+} E2 transition for three different settings relative to an independent clock based on the ^{171}Yb^{+} E3 transition. Within the statistical uncertainty, we find no significant change in the ratio and can determine its value with a fractional uncertainty of 8.0×10^{-17}. With the currently best-known frequency of the ^{171}Yb^{+} E3 transition [2], the absolute ^{88}Sr^{+} E2 frequency is evaluated to an uncertainty of 80 mHz.

Quantum Information & Computing Session I

Quantum Information & Computing I / Monday 11:00 - 11:22

Qubit addressing in a standing wave light field from integrated photonics

Authors: Carmelo Mordini[1]; Alfredo Ricci Vasquez[1]; Chi Zhang[1]; Maciej Malinowski[1]; Daniel Kienzler[1]; Karan Mehta[1]; Jonathan Home[1]

[1] *ETH Zurich*

Corresponding Author: cmordini@phys.ethz.ch

Pairing integrated photonics with surface-electrode ion traps is an emerging technology, potentially opening the way to build novel architectures for quantum information processing [1, 2, 3]. Other than solving the scalability issues presented by individual addressing of multiple ions with free-space laser setups, it allows engineering the optical fields coupled to the ions and hence exploiting particular properties of the ion-light interaction.

Here we present a surface-electrode Paul trap where $^{40}\mathrm{Ca}^+$ ions are illuminated with two interfering beams at 729 nm forming a standing wave. The light is delivered to the trapping zone by silicon nitride waveguides, and coupled out of the chip with grating couplers. The beams intersect at $z = 50\,\mu$m above the chip, where the ions are trapped. Additional waveguides are used to send repumper light at 854 nm and 866 nm [2].

The beams are sent along the trap axis x and are linearly polarized along the orthogonal direction y. The field near the intersection of the two beams can be modeled by two interfering plane waves, $E_y(\mathbf{r}) = E_0(e^{i(k_z z + k_x x)} + e^{i(k_z z - k_x x)}) = 2E_0 e^{ik_z z}\cos(k_x x)$. This configuration modulates the field intensity along the trap axis, as well as the orientation of the electric field gradient $\partial_i E_y$. Light at this wavelength is resonant with the quadrupole transition between $|4S_{1/2}\rangle$ and $|3D_{5/2}\rangle$, whose coupling strength depends on the relative alignment between the external magnetic field and the field gradient, which then can be tuned by appropriately positioning the ion in the beam profile.

We probe the optical field with sub-wavelength resolution scanning the position of a single ion through the standing wave, and observing Rabi oscillations for transitions with $\Delta m_j = 0, -1, -2$. We measure both the Rabi frequency of the resonant optical coupling and the differential AC Stark shift induced by off-resonant coupling to other transitions, for both the carrier and the first motional sidebands transitions. We observe that a position that maximizes the carrier coupling suppresses the sideband, and vice versa [4], although the maximum carrier coupling is located at an intensity node, antinode, or in between, depending on the choice of carrier transition.

The study of the interaction of such a light field with single ions is relevant in the context of achieving faster and lower error Mølmer-Sørensen entangling gates with suppressed off-resonant carrier coupling [5], and for exploring laser cooling in unusual regimes.

[1] K. K. Mehta et al. “Integrated optical addressing of an ion qubit”, Nature Nanotechnology 11.12 (2016).

[2] K. K. Mehta et al. “Integrated optical multi-ion quantum logic”, Nature 586.7830 (2020).

[3] R. J. Niffenegger et al. “Integrated multi-wavelength control of an ion qubit”, Nature 586.7830 (2020).

[4] A. B. Mundt et al. “Coupling a Single Atomic Quantum Bit to a High Finesse Optical Cavity”, Phys. Rev. Lett.89 (2002).

[5] K. K. Mehta et al. “Towards fast and scalable trapped-ion quantum logic with integrated photonics”, Advances in Photonics of Quantum Computing, Memory, and Communication, XII 10933 (2019).

Quantum Information & Computing I / Monday 11:23 - 11:45

Standing-Wave Mølmer–Sørensen Gate in the Adiabatic and Non-Adiabatic Regime

Author: Sebastian Saner[1]

Co-authors: Oana Bazavan [1]; Mariella Minder [1]; Amy Hughes [1]; Vera Schäfer [1]; David Lucas [1]; Chris Ballance [1]

[1] *University of Oxford*

Corresponding Author: sebastian.saner@physics.ox.ac.uk

In trapped-ion systems, the majority of entangling operations are implemented in the adiabatic regime [1,2]. Adiabatic in this context means that we can selectively excite a single set of terms in the Lamb-Dicke expansion and are able to neglect the remaining off-resonant terms. Then only a single motional mode (with secular frequency ν) participates in the interaction. This is possible if the interaction is slow compared to the frequency gap between adjacent motional modes. Restricting operations to a small subspace of the Hilbert space makes high-fidelity control easier yet poses severe limitations on the achievable gate speed.

Operating in the non-adiabatic regime allows for a significant gate speed-up. Dominating error contributions are shifted towards a few coherent effects which are potentially controllable while incoherent errors, which dominate in the adiabatic regime, become less significant.

The non-adiabatic regime is rich in novel physics. For example, as the gate time becomes comparable to the timescale of the mediating ion crystal we can study the origin of entanglement creation [3].

Recent advances have increased gate speeds by around an order of magnitude (resulting in gate durations of ~1 us) using Rydberg interactions [4], or by operating in the non-adiabatic regime [5], where several additional effects must be accounted for in order to retain high fidelity.

We investigate a Mølmer–Sørensen (MS) gate [6] in a beam configuration where the unwanted carrier coupling is nulled, allowing its use in the non-adiabatic regime for the first time. More precisely, we choose an optical addressing beam configuration in which the carrier term and all higher order even contributions are cancelled by interference. This configuration, realised by two counter-propagating beams, is a standing-wave optical lattice. Phase stabilisation of an optical lattice in free space has been demonstrated [7].

We present the theoretical treatment and in-depth simulations of the standing-wave MS-gate in both the adiabatic and the non-adiabatic regime. In the adiabatic regime we identify operating ranges where the standing-wave MS-gate outperforms a conventional MS-gate. In the non-adiabatic case we introduce amplitude modulation techniques [8] to ensure phase-space loop closure for all motional modes. We present gate solutions for up to five-ion crystals with sub-microsecond entangling times with fidelities $\mathcal{F} \geq 99.9\%$, and analyse the impact of experimental imperfections on the entanglement fidelity.

[1]: Physical Review Letters, 117(6):60504, 2016.
[2]: Physical review letters, 117(6):60505, 2016.
[3]: Physical Review Letters, 94(5), 50504, 2005.
[4]: Nature, 580(7803), 2020.
[5]: Nature, 555(7694), 2018.
[6]: Physical Review A, 62(2):11, 2000.
[7]: Physical review letters, 116(3):33002, 2016.
[8]: New Journal of Physics, 16(5):53049, 2014.

Quantum Information & Computing I / Monday 11:45 - 12:07

Towards standing-wave quadrupole Mølmer-Sørensen gates

Author: Oana Bazavan[1]

Co-authors: Mariella Minder [1]; Sebastian Saner [1]; Amy Hughes ; Vera Schäfer [1]; Chris Ballance [1]; David Lucas [1]

[1] *University of Oxford*

Corresponding Author: oana.bazavan@physics.ox.ac.uk

Free-space optical lattices are ubiquitous in atomic physics and are often employed for creating spin-dependent forces used for entangling gate operations and neutral atom trapping. Recently, there has been an interest in gaining control over the absolute phase of the optical lattice [1] and harnessing it for applications in quantum metrology, quantum information processing with continuous variables [2] and quantum simulations [3]. Moreover, controlling this absolute phase enables complete control over all the degrees of freedom of the laser-ion interaction and hence allows for development of fast, high-fidelity entanglement schemes for trapped ions [4, 5].

Driving a quadrupole transition with a standing wave yields orthogonal coupling of the carrier and the sideband transitions depending on the position of the ion in the lattice [3, 6]. By controlling the phase of the optical lattice, ions can be placed at the antinodes of the standing wave where the coupling to the carrier is strongly suppressed while the motional coupling is maximised. Employing such a lattice for implementing a Mølmer-Sørensen (MS) gate scheme on multiple ions removes a dominant source of error in quadrupole gates: off-resonant excitation of the carrier. In our experiment, we are aiming to drive an MS gate using a standing wave instead of a travelling wave. This will allow us to implement high-fidelity gates in a regime where otherwise the unwanted excitation of the carrier would be a dominant error. The realisation of the carrier-nulled gate mechanism is a key step towards overcoming the current speed and fidelity limits on entangling gates in trapped ions, as described in more detail in the submission by S. Saner.

The free-space optical lattice is formed by two counter-propagating beams which couple the quadrupole transition, $5S_{1/2}, \leftrightarrow 4D_{5/2}$, in $^{88}Sr^+$. They make up an interferometer with the closing point at around 50 cm from the ion position, where the residual phase fluctuations are, after stabilisation, $\sim 0.02\pi$ rad. We then measure the lattice phase seen by the ion and adjust the interferometer lock point to compensate for any changes in the optical path length between the ion position and the closing point. We show coherent operations with the lattice for one and two ions and present progress towards implementing the MS gate using the standing wave on two ions.

References

[1] C. T. Schmiegelow et al., Phys. Rev. Lett., 116, p.033002, (2016)
[2] M. Drechsler et al., Phys. Rev. A, 101, p.052331 (2020)
[3] T. E. deLaubenfels et al. Phys. Rev. A, 92, p.061402 (2015)
[4] V. M. Schäfer et al. Nature, 555, pp.75–78 (2018)
[5] A. M. Steane et al., New J. Phys., 16, p.053049 (2014)
[6] A. Mundt et al., Phys. Rev. Lett., 89, p.103001 (2002)

Quantum Information & Computing Session II

Quantum Information & Computing II / Wednesday 11:00 - 11:22

Operation of a microfabricated 2D trap array

Author: Marco Valentini[1]

Co-authors: Silke Auchter [2]; Philip Holz [3]; Matthias Dietl [4]; Gerald Stocker [5]; Clemens Rössler [5]; Elmar Aschauer [5]; Philipp Schindler [1]; Thomas Monz [6]; Rainer Blatt [7]

[1] *University of Innsbruck*

[2] *University of Innsbruck, Infineon*

[3] *Alpine Quantum Technologies*

[4] *University of Innsbruck, Infineon Technologies*

[5] *Infineon Technologies*

[6] *University of Innsbruck, Alpine Quantum Technologies*

[7] *University of Innsbruck, Institute for Quantum Optics and Quantum Information*

Corresponding Author: marco.valentini@uibk.ac.at

We investigate scalable surface ion traps for quantum simulation and quantum computing. We have developed a microfabricated surface trap consisting of two parallel linear trap arrays with 11 trapping sites each. The trap design requires two interconnected metal layers to address the island-like DC electrodes and a third to shield the substrate.

The trap fabrication is carried out by Infineon in an industrial facility, which allows for complex electrode designs and ensures high process reproducibility.

We demonstrate trapping and shuttling of multiple ions in the trap array, and form square and triangular ion-lattice configurations with up to six ions. We characterize stray electric fields and measure ion heating rates between 131(13) and 470(50) ph/s in several trapping sites [1].

Furthermore, the design of the trap array allows for tuning of the inter-ion distance across the lattice, which we will use to demonstrate motional coupling of ions in neighboring sites.

[1] Philip C. Holz et al., Adv. Quantum Technol. 3.11 (2020)

Quantum Information & Computing II / Wednesday 11:23 - 11:45

Microfabricated 3D Ion Traps and Integrated Optics

Authors: Jakob Wahl[1]; Silke Auchter[1]; Thomas Monz[2]; Philipp Schindler[2]; Klemens Schueppert[3]; Clemens Roessler[4]; Oliver Blank[4]; Christian Roos[2]

[1] *Universtiy of Innsbruck, Infineon Technologies Austria AG*

[2] *University of Innsbruck*

[3] *UIBK*

[4] *Infineon Technologies Austria AG*

Corresponding Author: jakob.wahl@infineon.com

A future quantum computer will potentially outperform a classical computer in certain tasks, such as factorizing large numbers [1]. A promising platform to implement a quantum computer are trapped ions, as long coherence time, high fidelity quantum logic gates and the implementation of quantum algorithms, such as the shore algorithm, have been demonstrated [2], [3]. To evolve trapped ion quantum computers from laboratory setups to devices able to solve real world problems, the amount of controllable qubits must be increased.

In recent trapped ion quantum computers, ions are often trapped in macroscopic linear ion traps which are not capable of hosting large numbers of ions. Moreover, trapped ions are addressed with free space optics, making it difficult to scale qubit numbers, because vibrations of the trap relative to the beam introduce beam-pointing errors, and the access for free space optics to address arrays of > 100 ions is geometrically limited. Additionally, small distances between neighbouring ions lead to crosstalk errors.

Microfabricated surface ion traps produced on a wafer level, are promising devices for scalable quantum computers, since they can host and control many ions. These traps are not limited to linear trapping potentials; they can be designed to generate individual trapping sites for each ion, leading to increased ion-ion distance and thus reduced crosstalk [4]. However, surface traps suffer from weak confining potential, limiting the lifetime of the ions and gate fidelity, and making ion shuttling unstable. To overcome the limit of small trapping potentials, we developed a microfabricated 3D ion trap, produced and assembled on wafer level by waferbond techniques. This trap contains structured electrodes on two opposing wafers, separated by a glass wafer as a spacer. In the diced trap, the electric field generated by the electrodes on the top and the bottom wafer define trapping sites in between the two wafers of 1 eV, exceeding the confinement of conventional surface traps. Furthermore, the glass spacer between top and bottom of the trap offers the opportunity to tackle problems introduced by free space optics.

We are working on the integration of optics into the spacer wafer of the microfabricated 3D ion traps, using waveguides imprinted in the spacer wafer to route the light to trapping sites [5], [6]. Integrating optics in quantum processors eliminates vibrations between optics and the ion trap and obviates a precise alignment of lasers. In the future, integrated waveguides are expected to realize complex light routing to multiple trapping sites and to make quantum information processors more robust and parallelizable.

[1] P. W. Shor, “Polynomial-time algorithms for prime factorization and discrete logarithms on a quantum computer,” 1997. doi: 10.1137/s0097539795293172.
[2] T. Monz et al., “Realization of a scalable shor algorithm,” 2016. doi: 10.1126/science.aad9480.
[3] K. Wright el al, “Benchmarking an 11-qubit quantum computer,” 2019. doi: 10.1038/s41467-019-13534-2.
[4] P. C. Holz et al., “2d linear trap array for quantum information processing,” vol. 3, doi: 10.1002/qute.202000031.
[5] M. L. Day et al., “A micro-optical module for multi-wavelength addressing of trapped ions,” 2021. doi: 10.1088/2058-9565/abdf38.
[6] K. K. Mehta et al., “Integrated optical multi-ion quantum logic,” 2020. doi: 10.1038/s41586-020-2823-6.

Quantum Information & Computing II / Wednesday 11:45 - 12:07

Signal Generation for Trapped Ion Quantum Gates

Author: Norman Krackow[1]

Co-author: Robert Jördens [2]

[1] *QUARTIQ*

[2] *QUARTIQ GmbH*

Corresponding Author: nk@quartiq.com

In order to manipulate quantum information in trapped ion systems it is necessary to mediate the interaction between qubits with electromagnetic fields in a precisely controlled fashion. As ion crystals become larger and enhanced fidelities demand increasingly sophisticated pulse schemes, dynamic signal generation for quantum gates becomes a difficult task.

The talk discusses various digital signal processing (DSP) techniques for signal generation using field programmable gate arrays (FPGAs) and data converters (DACs). Some basic signal processing concepts and modern techniques based on recent advances in telecommunications are presented. They allow an interpretation of current challenges in the light of digital data transmission and potentially offer intriguing solutions for quantum gates and for scaling up the qubit count.

Quantum Information & Computing Session III

Quantum Information & Computing III / Thursday 11:00 - 11:22

Collaborative design of a trapped-ion quantum computer with fully interconnected qubits

Author: Celeste Torkzaban[1]

Co-authors: Tobias Pootz ; Lukas Kilzer ; Timko Dubielzig ; Christian Ospelkaus

[1] *Leibniz Universität Hannover*

Corresponding Author: celestecarruth@gmail.com

Research groups in a wide range of disciplines at the Leibniz Universität Hannover, the Physikalisch-Technische Bundesanstalt (PTB) Braunschweig, and the Technische Universität Braunschweig are working together in the newly-created Quantum Valley Lower Saxony to create a trapped-ion quantum computer with fully interconnected qubits. A pair of existing trapped-ion experiments, one at LUH and one at PTB, have already provided the proof-of-concept for most of the key aspects that we require in the next stage of our project. This talk will provide an overview of the project, discuss the techniques and designs that have already been proven to work, and then discuss our plan for developing a quantum computer capable of running quantum operations on 50 Beryllium ion qubits by 2025.

Quantum Information & Computing III / Thursday 11:23 - 11:45

A two-node trapped-ion quantum network with photonics interconnects

Authors: Bethan Nichol[1]; David Nadlinger [1]; Gabriel Araneda[1]; Chris Ballance[1]; David Lucas[1]; Dougal Main[1]; Peter Drmota[1]; Raghavendra Srinivas[1]

[1] *University of Oxford*

Corresponding Author: gabriel.aranedamachuca@physics.ox.ac.uk

Trapped ions are a leading platform for quantum computing due to the long coherence time, high-level of control of internal and external degrees of freedom, and the natural full connectivity between qubits. Single and multi-qubit operations have been performed with high fidelity (>99.9%), which has enabled the demonstration of small universal quantum computers (10 atoms). However, scaling up to bigger sizes remains a challenge. In our experiment we aim to demonstrate the first operational and fully controllable two-node quantum computer, where each node is small scale quantum processors (5 ions) connected via photonic entanglement. We use two ion traps systems separated by 2 m, where we confine mixed chains of Strontium and Calcium ions. Calcium-43 has excellent qubit coherence properties, while Strontium-88 has convenient internal structure for generating photonic entanglement. Single 422 nm photons emitted by the Strontium ion are used to generate remote entanglement. We recently have achieved a remote Strontium-Strontium entanglement fidelity of 96.0(2)% at a rate of 100 entangled events/s, and a average CHSH violation of 2.65..In this talk I will present our current work on the implementation of high-fidelity local Calcium-Strontium entangling gates, to swap the remote Strontium-Strontium entanglement into Calcium-Calcium remote entanglement. Thereafter, creating a second pair of remotely entangled ions will allow us to perform entanglement distillation to create high-fidelity remote entanglement, at the same fidelity of local entangling operations (>99%), which together with a a universal set of local gates will be use to demonstrate the first two-node quantum computer. Furthermore, I will present our preliminary results on the demonstration of secure quantum communications between the nodes of our network certified by continuous violation of the CHSH inequality.

Quantum Information & Computing III / Thursday 11:45 - 12:07

Device-Independent Quantum Key Distribution Between Two Ion Trap Nodes

Author: David P. Nadlinger[1]

Co-authors: Peter Drmota [1]; Bethan C. Nichol [1]; Gabriel Araneda [1]; Dougal Main [1]; Raghavendra Srinivas [1]; David M. Lucas [1]; Chris J. Ballance [1]; Kirill Ivanov [2]; Ernest Y.-Z. Tan [3]; Pavel Sekatski [4]; Rüdiger L. Urbanke [2]; Renato Renner [3]; Nicolas Sangouard [5]; Jean-Daniel Bancal [5]

[1] *University of Oxford*

[2] *École Polytechnique Fédérale de Lausanne*

[3] *ETH Zürich*

[4] *University of Geneva*

[5] *Université Paris-Saclay*

Corresponding Author: david@klickverbot.at

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 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.

[1] Gisin et al., Rev. Mod. Phys. 74, 145 (2002).
[2] Lydersen et al., Nat. Photonics 4, 686 (2010).
[3] A. K. Ekert, Phys. Rev. Lett. 67, 661 (1991).
[4] Mayers and Yao, Quantum Info. Comput. 4, 273–286 (2004).
[5] Nadlinger et al., arXiv:2109.14600 (2021).

Quantum Information & Computing Session IV

Quantum Information & Computing IV / Thursday 14:10 - 14:32

ABaQuS: A trapped-ion quantum computing system using $^{133}\mathrm{Ba}^{+}$ qubits

Authors: Ana Sotirova[1]; Fabian Pokorny[1]; Lee Peleg[2]; Chris Ballance[1]

[1] *University of Oxford*

[2] *Weizmann Institute of Science, University of Oxford*

Corresponding Author: ana.sotirova@physics.ox.ac.uk

Trapped atomic ions are one of the most promising quantum computing architectures. They exhibit all of the primitives necessary for building a quantum computer and have very few fundamental limitations to the achievable gate fidelities. While high-fidelity quantum logic has already been demonstrated on a small number of qubits, scaling up the system without compromising its performance remains challenging. Here we present the design and initial evaluation of a quantum system aimed at realising high-precision control over long chains of $^{133}\mathrm{Ba}^{+}$ ions.

Barium ions exhibit several features that are favourable for quantum computing experiments, including visible-light optical transitions and very long-lived metastable states. The $^{133}\mathrm{Ba}^{+}$ isotope is particularly interesting as it additionally offers a range of magnetically insensitive 'clock' qubit states in the ground level and in the metastable $D_{5/2}$ level, and optical 'clock' qubits spanning the $S_{1/2} - D_{5/2}$ manifolds [1]. Hence it opens a vast playground of novel qubit control schemes, including qubit hiding, partial projective measurements and mid-circuit measurements.

In our experiment we use a segmented monolithic 3D microfabricated trap [2] that provides a high degree of control of the trapping potential whilst maintaining a low heating rate. We show preliminary results on the trap characterisation performed with $^{138}\mathrm{Ba}^{+}$ ions.

The ground level qubit transition of $^{133}\mathrm{Ba}^{+}$ is driven by a two-photon Raman process using a 532 nm laser. We present the design and initial characterisation of our novel system for driving this 10 GHz transition with low phase and intensity noise. We further discuss the design of a laser-written waveguide device used for individual addressing of non-uniformly spaced ion crystals.

[1] J. E. Christensen, D. Hucul, W. C. Campbell, and E. R. Hudson. High-fidelity manipulation of a qubit enabled by a manufactured nucleus.npjQuantum Information, 6(1):35, 2020.

[2] P. See, G. Wilpers, P. Gill, and A. G. Sinclair. Fabrication of a monolithicarray of three dimensional si-based ion traps.Journal of Microelectrome-chanical Systems, 22(5):1180–1189, 2013.

Quantum Information & Computing IV / Thursday 14:33 - 14:55

Trapped Barium Ions at the United States Air Force Research Laboratory

Author: Zachary Smith[1]

Co-authors: William Grant [1]; David Hucul [1]; Paige Haas [2]; Michael Macalik [3]; Justin Phillips [2]; Harris Rutbeck-Goldman [1]; Kenneth Scalzi [2]; Boyan Tabakov [1]; Capt James Williams [1]; Carson Woodford [4]; Kathy-Anne Soderberg [1]

[1] *United States Air Force Research Lab (US)*

[2] *United States Air Force Research Lab (US); Technergetics (US)*

[3] *United States Air Force Research Lab (US); Booz Allen Hamilton (US)*

[4] *United States Air Force Research Lab (US); Griffiss Institute (US)*

Corresponding Author: zachary.smith.130@us.af.mil

Laser cooled and trapped atomic ions are promising platforms for quantum networking, sensing, and information processing because they are quantum systems well isolated from their surrounding environment. The species and isotope selected for trapping have different properties. Nuclear spin $I = \frac{1}{2}$ isotopes have long coherence times for a ground-state hyperfine qubit with robust manipulation capabilities. Other candidates have metastable excited states, enabling high-fidelity measurements via electron shelving. $^{133}\mathrm{Ba}^{+}$ uniquely combines both characteristics while also needing only visible wavelength lasers for cooling, trapping, and shelving operations. We will discuss the commissioning of a barium ion trapping experiment at the United States Air Force Research Laboratory [AFRL], including the work's context within broader quantum networking efforts at AFRL. Approved for Public Release [Case #AFRL-2021-2583] Distribution Unlimited.

Quantum Simulation Session I

Quantum Simulation I / Tuesday 11:00 - 11:22

Trapping and ground-state cooling of planar ion crystals in a novel linear Paul trap

Author: Dominik Kiesenhofer[1]

Co-authors: Helene Hainzer [2]; Tuomas Ollikainen [2]; Matthias Bock [2]; Christian Roos [2]

[1] *Institute for Quantum Optics and Quantum Information Innsbruck*

[2] *IQOQI Innsbruck*

Corresponding Author: dominik.kiesenhofer@uibk.ac.at

Trapped ions in RF traps are a well-established platform for analog and variational quantum simulation of quantum many-body systems. Up to now, ions in linear Paul traps allow for simulations of the 1D Ising model with up to 50 spins. In our project, we aim for extending this approach to the second dimension which will enable studies of 2D spin models with a larger particle number. Our new ion trap apparatus whose centerpiece is a novel monolithic micro-fabricated linear Paul trap allows for trapping planar crystals of up to 100 ions. For these crystals we observe only a small number of distinct crystal configurations by applying a cluster algorithm to an image series recorded over several hours. We also found stable elongated crystal configurations of up to 91 ions by choosing suitable voltage sets inhibiting any configuration changes. Furthermore, we successfully applied electro-magnetically induced transparency cooling to cool the out-of-plane modes of motion of two-dimensional Coulomb crystals to the ground state. Cooling dynamics were analyzed by sideband-resolved spectroscopy on the vibrational modes of motion. Stable crystal configurations as well as fast and simultaneous ground-state cooling of all out-of-plane modes are laying the foundation for high-fidelity interactions in the near future. Effective spin-spin interactions will be induced by laser fields coupling the ions' electronic levels to excitations of the crystal's out-of-plane modes of motion.

Quantum Simulation I / Tuesday 11:23 - 11:45

Digital quantum simulation of a topological spin chain

Authors: Claire Edmunds[1]; Martin Ringbauer[2]; Enrique Rico Ortega[3]; Philipp Schindler[2]; Rainer Blatt[2]

[1] *Universität Innsbruck*
[2] *University of Innsbruck*
[3] *University of the Basque Country UPV/EHU*

Corresponding Author: claire.edmunds@uibk.ac.at

The quantum properties underlying a wide range of natural materials, such as topological matter or interesting molecules, have proven too complex to understand using classical physics and standard computation. The field of digital quantum simulation has been developed in order to study the behaviour of quantum systems by replicating the energy dynamics in a controlled, gate-based manner. The high fidelities and long coherence times of trapped ion systems make them an excellent candidate to demonstrate digital quantum simulation.

Here I will demonstrate the quantum simulation of a topological spin chain on a trapped-ion quantum processor. The digital simulation approach enables us to combine the toolset of quantum information with high performance gate-based evolution to study not only condensed matter properties, but also quantum information properties of the system [1]. In particular, we study correlation and entanglement properties, as well as error-robust edge modes that arise due to topological symmetry in our material. In addition, I will discuss the integration of quantum control techniques to mitigate single- and two-qubit errors during quantum simulation [2, 3], a benefit of the gate-based approach of digital simulation.

[1] Müller, M. et al., “Simulating open quantum systems: from many-body interactions to stabilizer pumping“, New J. Phys. 13, 085007 (2011)
[2] Edmunds, C. L. et al., “Dynamically corrected gates suppressing spatiotemporal error correlations as measured by randomized benchmarking”, Phys. Rev. Research 2, 013156 (2020)
[3] Milne, A. R. et al., “Phase-Modulated Entangling Gates Robust to Static and Time-Varying Errors”, Phys. Rev. Applied 13, 024022 (2020)

Quantum Simulation I / Tuesday 11:45 - 12:07

Fock state detection and simulation of sub- and superradiant emission with a single trapped ion

Author: Harry Parke[1]

Co-authors: Gerard Higgins [2]; Marion Mallweger [1]; Shalina Salim [1]; Robin Thomm [1]; Murilo Oliveira [3]; Celso Villas-Boas [3]; Romain Bachelard [3]; Markus Hennrich [1]; Nikolay Vitanov [4]

[1] *Stockholm University*

[2] *Austrian Academy of Sciences, Institute for Quantum Optics and Quantum Information Vienna*

[3] *Federal University of Sao Carlos*

[4] *Sofia University*

Corresponding Author: harry.parke@fysik.su.se

Quantum technologies employing trapped ion qubits are currently some of the most advanced systems with regards to experimental methods in quantum computation, simulation and metrology. This is primarily due to the excellent control available over the ion's motional and electronic states. By treating the ions as composite quantum systems, with qubit states that can be addressed by optical laser or microwave pulses and motional states that can be manipulated by driving sideband transitions, it is possible to engineer unique multi-qubit gate schemes for computation, simulate atom-cavity dynamics and study the boundary between classical and quantum behaviour.

In this work we make use of a single ion confined in a linear Paul trap and demonstrate how precise control over its motional state allows us to effectively probe the interface between the quantum and classical regimes. In the first experiment we trap a single ion, whose qubit state is coupled simultaneously to two motional modes via detuned laser pulses in order to simulate the dynamics of a single atom at the centre of a two-mode cavity. With such a set up the interaction between the atom and light field is governed by interference effects at the atom's position and leads to the formation of sub- and superradiant states when considering the system as a whole. It has been shown that the formation of these states can be attributed to a description of the atom-light interaction that is neither entirely classical (i.e. requiring a non-zero average electric field) nor entirely quantum (i.e. requiring a non-zero variance for the electric field). We adapt this set up to the analogous system of an ion confined in a radial quadrupole field and attempt to prepare specific superpositions of Fock states in order to observe sub- and superradiant emission.

In the second experiment we demonstrate and compare two techniques for detecting motional Fock states in trapped ion systems. These schemes rely on the Autler-Townes effect and composite pulse sequences respectively. We compare their effectiveness and efficiency in being able to discern between adjacent Fock states with high accuracy. During both detection sequences the state of the system is only disturbed when the correct Fock state is known. Thus it is not necessary to perform individual measurements on each phonon-number state; rather a single detection sequence efficiently checks each Fock state (from 0 upwards) non-destructively until the actual phonon number is reached.

Quantum Technologies Session I

Quantum Technologies I / Tuesday 9:00 - 9:22

Multi-tone RF generation for intermediate-scale trapped-ion control

Authors: Martin Stadler[1]; Vlad Negnevitsky[1]; Marco Stucki[1]; Roland Matt[1]; Robin Oswald[1]; Jeremy Flannery[1]; Luca Huber[1]; Utku Altunkaya[1]; Ilia Sergachev[1]; Cagri Oenal[1]; Jonathan Home[1]

[1] *ETH Zurich*

Corresponding Author: mastadle@student.ethz.ch

The increasing complexity of trapped-ion experiments requires more powerful classical control systems, in particular to work with many channels in parallel. I will present work on extending our in-house developed control system which is used on multiple setups across several research groups [1-3]. The latest development cycle is focused on the increased requirements of multi-channel, multi-frequency control. This will be described within the context of an experimental setup containing a cryogenic segmented ion trap with two junctions [4] with waveguide arrays used to address individual ions in parallel, with each fed from an independent fibre AOM. Our new platform can synthesize waveforms with up to 4 frequencies directly on the hardware and plays back arbitrary waveforms at 1 Gigasample/s. We have used this to compensate higher-order effects in AOMs when driven with two tones e.g. for a Mølmer-Sørensen gate. In order to ease implementation of complex circuits, we added an interface to Qiskit Pulse, which we modified to include branching behaviour. The API allows us to keep the memory footprint on the low-level hardware low without having to recompile the software running on the control system for every experiment. I will also describe a camera system which achieves low-latency, high-fidelity spatially resolved ion readout.

*This work is supported by IARPA and the EU Flagship under the project AQTION

[1]: I. Pogorelov, et al., Compact Ion-Trap Quantum Computing Demonstrator, PRX Quantum 2, 020343 (2021)
[2]: V. Negnevitsky, M. Marinelli, et al., Repeated multi-qubit readout and feedback with a mixed-species trapped-ion register, Nature volume 563, pages 527–531 (2018)
[3]: M. Malinowski, et al., Generation of a maximally entangled state using collective optical pumping, arXiv:2107.10374
[4]: Chiara Decaroli, et al., 2021 Quantum Sci. Technol. 6 044001

Quantum Technologies I / Tuesday 9:23 - 9:45

A laser-cooled ^{40}Ca^{+} ion and a ^{40}Ca^{+} - ^{40}Ca^{+} ion crystal for systematic investigations of motional quantum metrology

Authors: Francisco Domínguez[1]; Emilio Altozano[1]; Joaquín Berrocal[1]; Javier Cerrillo[2]; Daniel Rodríguez[1]

[1] *Universidad de Granada (ES)*

[2] *Universidad Politécnica de Cartagena (ES)*

Corresponding Author: frandominguez@ugr.es

At the Ion Traps and Lasers Laboratory of the University of Granada we have built a linear Paul trap apparatus as an assisted ion-trap system for a high-magnetic-field Penning trap experiment. The goal of this experiment is to generate and manipulate a qubit via the "clock" S1/2 -> D5/2 transition of ^{40}Ca^{+} to read out motional frequencies of a ^{40}Ca^{+} - ^{40}Ca^{+} crystal in the ground state of motion and to study metrological protocols to perform experiments beyond the standard quantum limit. The trap is fully characterized and, in 2021, a 729 nm laser system locked to a high-finesse cavity has been installed (measured finesse of 280000). The on-going work is devoted to properly address the S1/2 -> D5/2 transition in order to prepare the ion and ion crystal in their respective motional ground states and perform the first experiments on both systems in a very low magnetic field.

In this contribution, we will present the status of the linear Paul trap apparatus. We will underline the technical achievements of the experiment so far and describe the first experiment on a single ion and on the balanced ion crystal. The results are crucial for the measurements envisaged in the Penning trap apparatus and will allow for studies of systematic effects of such crystals in a high magnetic field.

Quantum Technologies I / Tuesday 9:45 - 10:07

Trapped ions in optical tweezers

Author: Matteo Mazzanti[1]

Co-authors: Rene Gerritsma [1]; Rima Xenia Schüssler [1]; Zhenlin Wu [1]; Juan Diego Arias Espinoza [1]; Zeger Ackerman [1]; Arghavan Safavi Naini [1]; Clara Robalo Pereira [1]; Thomas Feldker [2]

[1] *University of Amsterdam*

[2] *University of Innsbruck*

Corresponding Author: m.mazzanti@uva.nl

We present progress on our experimental setup where we will use novel optical tweezers – derived from spatial light modulators – to manipulate the phonon spectrum of a two-dimensional ion crystal in a Paul trap [1]. This allows us to control the effective spin-spin interactions between the ions in order to realize and study various Hamiltonians of interest [2]. In particular, the pinning of a single ion can be used to create short-range spin-spin interactions. In 2D crystals, this can be used to quantum simulate spin Hamiltonians on a kagome lattice [2].

In one dimensional ion chains optical tweezers can be combined with oscillating electric fields in order to realize two-qubit geometrical phase gates [3]. This novel approach, combined with other well-established techniques, can be used to realize a novel architecture for quantum computing using trapped ions.

Quantum Technologies I / Tuesday 10:08 - 10:30

Selective properties of a Paul trap with the asymmetrical power supply

Authors: Olga Kokorina[1]; Semyon Rudyi[1]; Vadim Rybin[1]

[1] *ITMO University (RU)*

Corresponding Author: kokorinaolga09@gmail.com

It is widely known that in a classical quadrupole Paul trap with endcap electrodes the localization of the particles with the narrow-defined charge to mass ratio realizes at fixed power supply parameters. If we consider a Coulomb crystal in a classical Paul trap, one can see the radial splitting of the crystal associated with the effective potential form at different voltages on the rod and endcap electrodes [1].

In the present work, we discuss an effective potential transformation in a linear Paul trap with an asymmetrical power supply system. Only the AC voltage is applied to the one pair of opposite rod electrodes and only the DC voltage is applied to the other pair of rod electrodes, also, we apply the DC voltage on the end cap electrodes as usual.

Performing the experiment with starch microparticles we observe an axial Coulomb crystal splitting (along the axis of the trap) at the asymmetrical power supply system. Also, we show that it is possible to obtain three groups of starch particles localized along the trap axis at fixed AC and DC voltages components on all electrodes. The central group of particles has one charge to mass ratio and for them, the single-well effective potential configuration is realized. Extreme left and right particles clouds have the distinctive charge to mass ratio. Due to this at the same time and voltages, for the extreme left and right particles clouds, the double-well effective potential configuration realizes. As a result, we observe three groups of trapped particles with different charge to mass ratios simultaneously.

Showed axial splitting effect in a linear Paul trap with the asymmetrical power supply system can be of service for precise measurements of particles characteristics, isotope separation and spatial selection, targeted laser cooling, and frequency standards [2 – 5]. The axial particle separation gives more opportunities for precise manipulations with trapped ions than the radial one because, generally, the length of the trap is several times larger than the trap's radius.

[1] Kokorina O., Rybin V., Rudyi S. Coulomb crystal splitting effect in a linear electrodynamic trap //Vibroengineering PROCEDIA. – 2020. – T. 32. – C. 212-215.
[2] Thompson R. C. Precision measurement aspects of ion traps //Measurement Science and Technology. – 1990. – T. 1. – №. 2. – C. 93.
[3] Doležal M. et al. Analysis of thermal radiation in ion traps for optical frequency standards //Metrologia. – 2015. – T. 52. – №. 6. – C. 842.
[4] Avice G. et al. High-precision measurements of krypton and xenon isotopes with a new static-mode quadrupole ion trap mass spectrometer // Journal of Analytical Atomic Spectrometry. – 2019. – T. 34. – №. 1. – C. 104-117.
[5] Fan M. et al. Laser Cooling of Radium Ions // Physical review letters. – 2019. – T. 122. – №. 22. – C. 223001.

Skills Session I

Skills session / Monday 16:45 - 18:45

Lecture: Making the most of your presentation

Author: Jean-luc Doumont

Corresponding Author: jl@principiae.be

Strong presentation skills are a key to success for researchers and other professionals alike, yet many speakers are at a loss to tackle the task. Systematic as they usually are in their work, they go at it intuitively or haphazardly, with much good will but seldom with an effective outcome. This lecture proposes a systematic way to prepare and deliver an oral presentation: it covers structure, slides, and delivery, as well as stage fright.

About the speaker:

An engineer (Louvain) and PhD in applied physics (Stanford), **Jean-luc Doumont** is acclaimed worldwide for his no-nonsense approach, his highly applicable, often life-changing recommendations on a wide range of topics, and Trees, maps, and theorems, his book about "effective communication for rational minds." For additional information, visit www.principiae.be.

Skills Session II

Skills session / Wednesday 16:45 18:15

Grant writing

Author: Pablo Garcia Tello

Corresponding Author: pablo.garcia.tello@cern.ch

Pablo Garcia Tello is currently section head of the CERN EU Office developing new EU funded projects and initiatives. He will offer his best tips on how to prepare a successful grant application.

Skills Session III

Skills session / Thursday 15:45 - 18:15

Career panel

We have invited early career CERN Alumni currently working in academia, governmental agencies and industry to discuss their inspiring professional journeys. They will tell us about their stories, how they got where they are and answer your most pressing career questions.

The panel will be composed by Silvia Zorzetti (Fermilab SQMS), Federica Mingrone (International Atomic Energy Agency), Mario Michan (Daphne Technology), and Ask Løvschall-Jensen (Hyme Energy, Seaborg Technologies), moderated by Rachel Bray (CERN Alumni Office).

Skills Session IV

Skills session / Friday 9:00 - 12:00

COMSOL workshop

Author: Roman Obrist; Sven Friedel

Corresponding Authors: roman.obrist@comsol.com, sven.friedel@comsol.com

In this introduction session to COMSOL Multiphysics® software you will get an overview of COMSOL® capabilities in modeling electromagnetic fields and the motion of particles therein.
In Unit 1 we will cover the basic modeling workflow for modeling stationary and time-dependent low frequency EM fields such as capacitive, resistive and inductive systems.
Unit 2 will give you an introduction into full wave modeling, e.g. for RF and microwave systems.
In Unit 3 you will learn the basics of particle trajectory simulation in EM fields.
All units will be a mix of lecture and diverse live demos.
We will also recommend tutorials for homework with a free trial license of the current COMSOL Multiphysics® software version.
The workshop is suitable for anyone with an engineering, physics, or science background. No previous experience with the COMSOL Multiphysics® software is required.

Skills session / Friday 9:00 - 12:00

LabVIEW workshop

Author: Odd Oyvind Andreassen; Patryk Dawid Jankowski; Adriaan Rijllart

Corresponding Authors: odd.oyvind.andreassen@cern.ch

In this workshop you will learn the basic steps of LabVIEW.

Antimatter Posters

Poster 1 / Antimatter

Improved precision on the measurements of low energy antimatter in the ALPHA experiment

Author: Edward Thorpe-Woods[1]

[1] *Swansea University (GB)*

Corresponding Author: edward.thorpe-woods@cern.ch

Antihydrogen is one of the most simple pure antimatter bound states, which can be synthesised and trapped for extended periods of time by the ALPHA collaboration since 2010 [1]. A consequence of CPT symmetry is that antimatter bound states will present the same energy spectrum as their matter equivalents, and over the last five years ALPHA have measured antihydrogen transitions as a direct test of this fundamental symmetry [2][3][4]. Through upgrading metrology instrumentation at ALPHA it will become possible to measure antihydrogen transition energies with the best precision yet. Specifically, the collaboration intends to improve the frequency reference precision by two orders of magnitude via the inclusion of a Caesium fountain clock and Hydrogen maser to replace the GPS-disciplined quartz oscillator reference. The metrology upgrades alongside the recent implementation of laser cooling antihydrogen [5] will signifiantly improve the precision on the measurement of the 1S-2S antihydrogen transition, in the bid to one day reach parity or surpass the precision of similar measurements made with hydrogen.

[1] G. B. Andresen et al. (ALPHA-Collaboration). Trapped antihydrogen. Nature 468, 673 (2010)
[2] M. Ahmadi et al. (ALPHA-Collaboration). Observation of the 1S–2S transition in trapped antihydrogen. Nature 541, 506–510 (2017)
[3] M. Ahmadi et al. (ALPHA-Collaboration). Observation of the hyperfine spectrum of antihydrogen. Nature 548, 66–69 (2017)
[4] M. Ahmadi et al. (ALPHA-Collaboration). Observation of the 1S–2P Lyman- transition in antihydrogen. Nature 561, 211–215 (2018)
[5] C. J. Baker et al. (ALPHA collaboration). Laser cooling of antihydrogen atoms. Nature 592, 35-42 (2021).

Poster 2 / Antimatter

Sympathetic cooling of ^{9}Be$^+$ by laser-cooled ^{88}Sr$^+$ in an ion trap: an experimental simulation of the trapping and cooling of antimatter ions (GBAR experiment).

Authors: Albane Douillet[1]; Derwell Drapier[2]; Jean-Philippe Karr[1]; Jean-Pierre Likforman[3]; Laurent Hilico[4]; Luca Guidoni[3]; Théo Henner[5]

[1] *Laboratoire Kastler Brossel (FR)*

[2] *Sorbonne Université*

[3] *Laboratoire Matériaux et Phénomènes Quantiques, Université de Paris*

[4] *Université d'Evry - UPMC - CNRS*

[5] *Université de Paris*

Corresponding Author: derwell.drapier@lkb.upmc.fr

We develop an experiment to study the energy exchange during the *sympathetic cooling* of a light ion, ^{9}Be$^+$, by a set of laser-cooled heavy ions, ^{88}Sr$^+$. The objective is to simulate an important step of the GBAR (Gravitational Behavior of Antihydrogen at Rest) experiment installed at CERN which aims at studying the effect of the Earth's gravity on anti-matter by analyzing the free fall of anti-hydrogen atoms at rest [1]. In this experiment a Hbar+ ion (an anti-proton with two positrons) is produced and then slowed down before entering an ion trap with an energy of the order of 1eV. This ion is then cooled to about 10µK and then a laser beam photo-detach a positron. The antihydrogen atom, is only subjected to gravity and free falls on one of the detectors. The time between the photo-detachment of the positron and the detection allows to calculate the fundamental constant gbar which is the equivalent of g but between matter and antimatter. One of the essential steps of this experiment is the cooling of the Hbar+ ion. One of the crucial step of this experiment is the sympathetic cooling of the Hbar+ ion (light ions) by a reservoir of cold laser-cooled Be$^+$ ions (heavy ions).
Modeling the cooling of the Hbar+ ion is a process that involves an N-body problem, which makes numerical simulations very cumbersome and does not allow modeling the cooling dynamics over times longer than a few milliseconds. To understand the cooling dynamics over long times it is necessary to implement an experimental approach. We developed a setup to study sympathetic cooling of a light and hot ^{9}Be$^+$ ion (the equivalent of Hbar+) by a heavy laser-cooled ^{88}Sr$^+$ ion (the equivalent of ^{9}Be$^+$ in the GBAR experiment). Using the ^{88}Sr$^+$/^{9}Be$^+$ ion pair offers two advantages: (i) its mass ratio (88/9 9,78) is very close to the one in GBAR (9/1), (ii) and both species are laser addressable. This allows for optical diagnosis and thus provide insight into the cooling dynamics of the light ion.
I will present our experiment for which we have designed a surface-trap with two trapping zones, a Be$^+$ ion will be trapped in one zone and a set of Sr$^+$ ions in the other. Both species will be cooled by laser. Then, by varying the voltages of our segmented trap, the light ion will be transferred to the second trapping zone with a well-controlled energy up to 1eV. The analysis of the light ion fluorescence will allow us to know its velocity distribution and thus to determine its temperature. It will then be possible to follow the cooling dynamics of the ion and determine the optimal cooling parameters and protocols for the GBAR experiment.
Preliminary experiments have already been performed in a volume trap. The cooling of ^{9}Be$^+$ by a coulomb crystal of ^{88}Sr$^+$ has been demonstrated with a cooling time of several seconds.

[1] P Pérez et al. The GBAR antimatter gravity experiment. Hyperfine interactions, 233 :21–27, 2015.

Poster 3 / Antimatter

Towards observing anti-hydrogen fluorescence: Investigation of SiPMs in cryogenic environments

Author: Joos Danjeel Schoonwater[1]

Co-author: April Louise Cridland [2]

[1] *Eindhoven Technical University (NL)*

[2] *Swansea University*

Corresponding Author: joos.schoonwater@cern.ch

The 1S-2P transition has been measured to a precision of 5×10^{-8} in 2018 by the ALPHA collaboration[1]. This milestone was achieved by allowing a trappable 2P state to decay to a non-trappable 1S state causing it to annihilate with the inner wall of the trapping apparatus. The annihilation events were destructively measured using a silicon vertex detector. The next generation ALPHA-3 apparatus will be equipped with silicon photomultipliers (SiPM) in order to detect fluorescent light from antihydrogen atoms down to the single photon level. Detecting fluorescent light from anti-hydrogen offers the possibility to probe the inner structure of the anti-atom *in situ* and *non destructive* such that more precise spectroscopic measurements could be done. Furthermore, the use of SiPMs would be a great tool for the diagnostics of beryllium ion plasmas which will be used to sympathetically cool down positrons in order to obtain colder anti-hydrogen. There are however several engineering challenges to overcome: the SiPMs need to be tested in a similar environment as the trapping apparatus which operates at temperatures down to 4 K where limited space is available for the SiPMs to be installed. We will present methods to characterise the SiPMs in a cryogenic environment and feasibility studies of the use of SiPMs inside the ALPHA apparatus.

[1] M. Ahmadi et. al, (2018), Observation of the 1S–2P Lyman- transition in antihydrogen, *Nature, vol. 561, pp. 211-215*

Poster 4 / Antimatter

The Effects of Patch Potentials in Penning-Malmberg Traps

Authors: Andrew Jordan Christensen[1]; Joel Fajans[1]; Jonathan Syrkin Wurtele[1]

[1] *University of California Berkeley (US)*

Corresponding Author: a.j.c@cern.ch

Antiprotons created by laser ionization of antihydrogen are observed to quickly escape the ALPHA trap. Further, positron plasmas heat more quickly after the trap is illuminated by laser light for several hours. These unexpected phenomena are caused by patch potentials - variations in the electrical potential along metal surfaces. A simple model for the effects of patch potentials explains the particle loss, and an experimental technique is developed for measuring the magnitude of the electric field produced by the potentials. The model is validated by controlled experiments and simulations.

Poster 5 / Antimatter

Sympathetic cooling of positrons with laser-cooled beryllium ions

Author: Joanna Peszka[1]

[1] *Swansea University (GB)*

Corresponding Author: joanna.peszka@cern.ch

Precision measurements on antihydrogen allow for testing CPT symmetry. The ALPHA Collaboration at CERN performs laser spectroscopy of antihydrogen in a magnetic minimum trap in order to compare its energy level structure to that of hydrogen [1, 2, 3]. Antihydrogen atoms are produced by three-body recombination of an antiproton and two positrons [4]. Antiprotons are provided in the form of a beam by CERN's Antiproton Decelerator, while positrons are obtained from the Na-22 radioactive source and stored in a Surko-type accumulator. Due to our magnetic potential well depth, we can trap only H atoms of energy below 0.5K.

Decreasing the positron temperature could lead to an increase in the antihydrogen trapping rate [5]. Our proposed technique is sympathetic cooling of positrons with laser-cooled beryllium ions $^9\text{Be}^+$ [6, 7]. Ions are created by ablating a beryllium foil with a short laser pulse and are subsequently caught in the ALPHA-2 Penning Trap, which is superimposed with the antihydrogen magnetic trap. We Doppler cool 600k ions with a 313nm laser and merge them with about 3.5M positrons.

We have demonstrated sympathetic cooling of positrons to around 10K, which is half of the temperature that we normally use during antihydrogen production. We will present the experimental scheme and our latest results.

[1] ALPHA Collaboration, Nature 557, 71-75 (2018).
[2] ALPHA Collaboration, Nature 548, 66-69 (2017).
[3] ALPHA Collaboration, Nature 561, 211-215 (2018).
[4] W.A. Bertsche et al., Jour. Phys. B 48, 231001 (2015).
[5] ALPHA Collaboration, Nature Communications 8, 681 (2017).
[6] B. M. Jelenkovic et al., Phys. Rev. A 67, 063406 (2003).
[7] N. Madsen et al., New J. Phys 16, 063046 (2014).

Poster 6 / Antimatter

Non-Destructive Diagnostics for the PUMA Antiproton Trap

Author: Jonas Fischer[1]

[1] *TU Darmstadt*

Corresponding Author: jfischer@ikp.tu-darmstadt.de

The antiProton Unstable Matter Annihilation experiment (PUMA) is aimed at investigating nuclear haloes and neutron skins, that short-lived nuclei can exhibit [1]. Antiprotons are especially suited for this investigation as they probe the outermost tail of the nuclear density distribution [2]. When antiprotons and nuclei are brought together with low relative kinetic energies, an antiproton can annihilate with a nucleon. The energy of the annihilation is carried away mainly by pions. Since the total charge of the annihilation partners is conserved, measuring the total charge of the pions will reveal the annihilation partner (n or p) and therefore the neutron-to-proton ratio at the annihilation site. The experiment is set to take place at CERN, the only location world-wide where both low energy antiprotons and short-lived nuclei can be provided. As there currently is no way to transport antiprotons to the production site of the short-lived nuclei, up to 10^9 antiprotons will be stored in a transportable cryogenic Penning trap.

To gain control over the stored antiprotons behaving as an ellipsoid plasma, information about the antiproton plasma is crucial. Complete diagnostics of the plasma include the total number of antiprotons and their spatial distribution. Following a method developed at ATHENA [3], the PUMA experiment will use a vector network analyser to measure the dipole and quadrupole oscillation frequencies of the plasma and the power transmitted though the plasma to extract the number of stored antiprotons during accumulation and transport.

In this poster, the plasma conditions of PUMA will be presented as well as the foreseen diagnostic method to be implemented.

[1] PUMA Collaboration, “PUMA: antiprotons and radioactive nuclei”, Proposal SPSC P 361, CERN (2019).
[2] A. Trzcińska et. al., “Neutron Density Distributions Deduced from Antiprotonic Atoms”, Phys. Rev. Lett. 87, 082501 (2001).
[3] M. Amoretti et al., “Complete nondestructive diagnostic of nonneutral plasmas based on the detection of electrostatic modes”, Physics of Plasmas 10, 3056 (2003).

Poster 7 / Antimatter

Improving frequency resolution in BASE

Author: Julia Ines Jäger[1]

Co-authors: Matthias Joachim Borchert [2]; Jack Devlin [3]; Stefan Erlewein [1]; Markus Fleck [4]; Barbara Latacz [5]; Peter Micke [3]; Phil Nuschke [6]; Gilbertas Umbrazunas [7]; Frederik Volksen [8]; Elise Wursten [5]; Fatma Abbass [9]; Matthew Bohman [10]; Andreas Mooser [10]; Daniel Popper [11]; Markus Wiesinger [10]; Christian Will [12]; Klaus Blaum [12]; Yasuyuki Matsuda [13]; Christian Ospelkaus [14]; Wolfgang Peter Quint [15]; Jochen Walz [16]; Yasunori Yamazaki [5]; Christian Smorra [17]; Stefan Ulmer [5]

[1] *RIKEN, CERN, Max Planck Institute for Nuclear Physics*
[2] *RIKEN, Leibniz Universitaet Hannover, Physikalisch-Technische Bundesanstalt*
[3] *RIKEN, CERN*
[4] *RIKEN, University of Tokyo*
[5] *RIKEN*
[6] *RIKEN, Leibniz Universitaet Hannover*
[7] *RIKEN, ETH Zurich*
[8] *RIKEN, GSI-Helmholtzzentrum fuer Schwerionenforschung GmbH*
[9] *Institute for Physics, JGU Mainz*
[10] *RIKEN, Max-Planck-Institute for Nuclear Physics*
[11] *Johannes Gutenberg Universitaet Mainz*
[12] *Max-Planck-Institute for Nuclear Physics*
[13] *University of Tokyo*
[14] *Leibniz Universitaet Hannover, Physikalisch-Technische Bundesanstalt*
[15] *GSI - Helmholtzzentrum fur Schwerionenforschung GmbH*
[16] *Institut für Physik, JGU Mainz, Helmholtz-Institut Mainz*
[17] *RIKEN, Institute for Physics JGU*

Corresponding Author: julia.ines.jager@cern.ch

The BASE collaboration at the antiproton decelerator facility of CERN is testing the Standard Model by comparing the fundamental properties of protons and antiprotons at lowest energies and with highest precision. Several world-record measurements have been performed in BASE such as the comparison of the antiproton-to-proton charge-to-mass ratio with a fractional precision of 69 parts per trillion [1], and the comparison of the proton/antiproton magnetic moments with a fractional precision of 1.5 parts per billion [2].

With the recent implementation of direct cyclotron frequency measurements and phase sensitive detection methods, we've reached frequency resolutions with a shot-to-shot fluctuation on the level of about 300 parts per trillion [3]. These limits are imposed by drifts and fluctuations of environmental laboratory parameters such as the temperature, pressure variation in the cryoliquid recovery lines and fluctuations in the external magnetic field in the AD-hall.

The goal of this project is the implementation of advanced stabilization systems such as an active pressure stabilization for the superconducting magnet, for both the LN2 and LHe vessel. Moreover, a mechanical decoupling of the cryogenic experiment stage from the experiment cryostats and an interferometric stabilization of the experiment stage will be implemented. In addition, the laboratory temperature will be actively stabilized, with the goal to overcome the current limits in frequency measurements induced by fluctuations in the environmental conditions and to perform improved measurements of fundamental antimatter constants on the parts per trillion level.

[1] S. Ulmer et al., Nature 524, 196 (2015).
[2] C. Smorra et al., Nature 550, 371 (2017).
[3] M. Borchert, PhD Thesis (2021).

Poster 8 / Antimatter

Application of electron cyclotron resonance (ECR) magnetometry for experiments with antihydrogen

Author: Adam Powell[1]

[1] *University of Calgary Dep. of Phys. and Astronomy (CA)*

Corresponding Author: adam.michael.powell@cern.ch

The Antihydrogen Laser Physics Apparatus (ALPHA) is based at the European Centre for Nuclear Research (CERN) antiproton decelerator facility. Using low energy antiprotons we produce, trap, and study the bound state of an antiproton and positron, antihydrogen [1]. Given the long history of atomic physics experiments with hydrogen, spectroscopy experiments with antihydrogen offer some of the most precise tests of quantum electrodynamics and charge-parity-time symmetry [1]. A test of the weak equivalence principle is also on the horizon with a major addition to the ALPHA experiment, ALPHAg, aiming to measure the free fall of antihydrogen.

All experiments in ALPHA require precise measurements of the magnetic field inside the apparatus, this is especially relevant for ALPHAg [2]. A technique developed in ALPHA determines the in situ magnetic fields by measuring the cyclotron frequency of an electron plasma. Microwave pulses on resonance with the electron cyclotron frequency, which is magnetic field dependent, heat the plasma [3]. A campaign to characterize the precision and accuracy of this technique in a high magnetic field gradient is required before a successful measurement of the effect of Earth's gravity on antimatter can be made.

I will show recent progress made towards realising this goal including the first application of this technique in a strong magnetic field gradient and methods used to experimentally distinguish the cyclotron frequency from a sideband structure.

[1] Characterization of the 1S–2S transition in antihydrogen, ALPHA Collaboration, Nature, 557, 71, (2018)

[2] Description And First Application Of A New Technique To Measure The Gravitational Mass Of Antihydrogen, ALPHA Collaboration, Nature Communications 4, 1785 (2013)

[3] Electron Cyclotron Resonance (ECR) Magnetometry with a Plasma Reservoir, E. D. Hunter and A. Christensen and J. Fajans and T. Friesen and E. Kur and J. S. Wurtele Physics of Plasmas 27, 032106 (2020)

Nuclear Physics Posters

Poster 9 / Nuclear Physics

Development of a novel ion trap for laser spectroscopy

Authors: Jaspal Singh[1]; Giuseppe Lospalluto[2]

Co-author: Kieran Flanagan [1]

[1] *University of Manchester (GB)*

[2] *ETH Zurich*

Corresponding Authors: jaspal.singh@cern.ch, glospalluto@phys.ethz.ch

A novel radio-frequency (RF) ion trap based on planar printed-circuit board (PCB) electrodes was designed and simulated. This device would serve as a commercial ion cooler and buncher that delivers a low emittance ion bunch to laser spectroscopy experiments, such as the Collinear Resonance Ionisation Spectroscopy (CRIS) experiment in ISOLDE at CERN.

The ions inside the trap were cooled by collisions with a He buffer gas at a pressure of 10^{-2} mbar. The simulations included injection optics and extraction optics. The former consisted of an electric quadrupole triplet and a series of electrodes that decelerated and focused the ion beam inside the trap. The latter was an arrangement of cylindrical and conical electrodes used to deliver a pencil-like beam. The transmission efficiency and the emittance of the beam were computed at multiple stages of the beamline. It was found that, under certain conditions, the field due to planar electrodes successfully approximated an ideal quadrupole field and yielded nearly full transmission efficiency.

Lastly, the preliminary stage of the building and testing of such ion trap with printed-circuit boards is presented. The limits of this design are outlined as well as future improvements.

Poster 10 / Nuclear Physics

Bound Electron g Factor Measurements of Highly Charged Tin

Author: Jonathan Morgner[1]

Co-authors: Charlotte M. König [1]; Tim Sailer [1]; Fabian Heiße [1]; Bingsheng Tu [1]; Bastian Sikora [1]; Vladimir A. Yerokhin [2]; Zoltán Harman [1]; José Crespo López-Urrutia [1]; Christoph H. Keitel [1]; Sven Sturm [1]; Klaus Blaum [1]

[1] *Max Planck Institute for Nuclear Physics*

[2] *Center for Advanced Studies, Peter the Great St. Petersburg Polytechnical University*

Corresponding Author: jonathan.morgner@mpi-hd.mpg.de

Highly charged ions are a great platform to test fundamental physics in strong electric fields. The field-strength experienced by a single electron bound to a high Z nucleus reaches strengths exceeding 10^{18}V/m. Perturbed by the strong field, the g factor of a bound electron is a sensitive tool that can be both calculated and measured to high accuracy. In the recent past, g factor measurements of low Z ions reached precisions below $5 \cdot 10^{-11}$ [1, 2]. Following this route, the ALPHATRAP Penning trap setup is dedicated to precisely measure bound-electron g-factors of the heaviest highly charged ions [3].
In this contribution, our recent measurement of bound-electron g factors in highly charged tin will be presented. Over the course of multiple months, g factors for three different charge states have been measured, each allowing a unique test of QED in a heavy highly charged ion, probing different g factor contributions. Furthermore, progress on a new EBIT setup is presented. This will eventually allow ALPHATRAP to inject and measure even heavier highly charged systems beyond hydrogenlike lead (Pb^{81+}) in our Penning-trap apparatus.

References

1) S. Sturm et al, Nature 506, 467–470 (2014)
2) S. Sturm et al, PRA 87, 030501(R) (2013)
3) S. Sturm et al, EPJ 227, 1425–1491 (2019)

Poster 11 / Nuclear Physics

Characterization of a Multi-Reflection Time-of-Flight Mass Separator (MR-ToF MS) for the Offline Ion Source of PUMA

Authors: Moritz Schlaich[1]; Alexandre Obertelli[1]; Frank Wienholtz[1]

[1] *TU Darmstadt*

Corresponding Author: mschlaich@ikp.tu-darmstadt.de

The antiProton Unstable Matter Annihilation (PUMA) project aims at investigating the nucleon composition in the matter density tail of short-lived as well as stable isotopes by studying antiproton-nucleon annihilation processes. For this purpose, low-energy antiprotons provided by the Extra Low Energy Antiproton (ELENA) facility at CERN will be trapped together with the ions under investigation. While the unstable ions will be supplied by the Isotope mass Separator On-Line DEvice (ISOLDE) at CERN, the stable ions are taken from an offline ion source that should be able to provide a cooled and bunched as well as isotopically pure ion beam. It is used to benchmark the antiproton nuclear annihilation process as well as for development and reference measurements at ELENA. The ion source contains a radio-frequency quadrupole cooler-buncher for ion accumulation and bunching. In addition, an MR-ToF MS is used to clean the beam. In this respect, the poster gives an overview of the working principle of the MR-ToF MS designed for the PUMA offline ion source and provides first experimental results of reference measurements performed with stable nuclei.

Poster 12 / Nuclear Physics

Alkali-earth ions Confined for Optical and Radiofrequency spectroscopy for Nuclear moments (ACORN)

Author: Anais Dorne[1]

Co-author: Ruben Pieter De Groote [1]

[1] *KU Leuven (BE)*

Corresponding Author: anais.dorne@cern.ch

Nuclear moments have proved to be excellent probes for nuclear configurations and thus act as excellent benchmarks for nuclear theory. The magnetic octupole moment, which has for now only been measured for 19 stable isotopes, is very promising for the study of magnetization currents and the distribution of nucleons. We present the construction of the ACORN (Alkali-earth ions Confined for Optical and Radiofrequency spectroscopy for Nuclear moments) experiment, a new Paul trap experiment for the measurement of the nuclear magnetic octupole moment of alkali-earth ions. We discuss the trap and photocollection design, and their challenges in our aim to perform the first magnetic octupole measurements of stable and radioisotopes. We also discuss the choice of the first element the ACORN experiment will be performed on, and its corresponding laser system.

Precision Spectroscopy Posters

Poster 13 / Precision Spectroscopy

A compact penning trapped ion system for precision measurement

Authors: Jiang Zhuangde[1]; Yao Chen[2]

[1] *Xi'an Jiaotong University (CN)*

[2] *Northwestern University (US)*

Corresponding Author: yao.c@cern.ch

Here we described a compact penning trapped ion system. The traditional superconducting magnet is changed into permanent magnet. We did a simulation about the magnet system and the magnetic field uniformity is simulated. Experiment are under developing to measure the magnetic field uniformity. The penning trap geometry is also designed to compatible with the magnet. Laser cooling technic should be developed to cool the motions of the ions. The ion crystal should be construct for sensing. At the first stage of the design. Weak force will be measured and other physical quantities are also designed for sensing. Ca atoms are evaporated from a homemade oven under high vacume for ion loading. The Ca atoms are ionized by a pulsed laser beam.

Poster 14 / Precision Spectroscopy

Towards High Resolution Spectroscopy of Nitrogen Ions

Authors: Amber Shepherd[1]; Laura Blackburn[1]; Matthias Keller[1]

[1] *University of Sussex*

Corresponding Author: as2154@sussex.ac.uk

High resolution spectroscopy of molecules is a prime candidate to measure potential temporal changes in the proton-to-electron mass ratio, μ [1]. These potential changes can be detected by comparing vibrational or rotational transitions in molecules to optical atomic transitions.

In our experiment, a vibrational Raman transition in a nitrogen ion will be compared to a quadrupole transition in a calcium ion. The $N_2{}^+$ ion has systematic shifts better than the best optical atomic clocks to date. To perform precision spectroscopy, a single nitrogen ion will be co-trapped in a linear Paul trap with a $^{40}Ca^+$ ion. This calcium ion will act as a frequency reference and be used for the cooling and state detection of the nitrogen ion.

Prerequisite to this is the preparation of $^{14}N_2{}^+$ in a specific rovibronic state. Recently, a 2+1' resonance-enhanced multiphoton ionisation (REMPI) scheme was developed, using the $a^1\Sigma_g{}^+(=6) \leftarrow X^1\Sigma_g{}^+(=0)$ band in $^{14}N_2$ for the resonant excitation. This scheme demonstrated a fidelity of >99% for loading into the rovibronic ground state [2]. However, simulations show that the high amplitude and inhomogeneous electric fields of the ion trap broaden the ionisation threshold and prevent state-selective loading in many cases. Rapidly switching the trap off during loading can reduce the electric field and can mitigate this to allow state selective loading of the ion trap [3].

[1] M. Kajita et al., Physical Review A 89, 032509 (2014).

[2] A. Gardner et al., Scientific Reports 9, 506 (2019).

[3] L. Blackburn et al., Scientific Reports 10, 18449 (2020).

Poster 15 / Precision Spectroscopy

Towards the Threshold Photodetachment Spectroscopic studies of C_2^- and C_2H^-

Author: Sruthi Purushu Melath[1]

Co-authors: Christine Lochmann [2]; Markus Nötzold [2]; Robert Wild [2]; Roland Wester [2]

[1] *University of Innsbruck, Austria*

[2] *University of Innsbruck*

Corresponding Author: sruthi.purushu-melath@uibk.ac.at

Different neutral and charged interstellar molecules constitute the building blocks for a rich reaction network in the interstellar medium (ISM). Many complex molecules have been detected but many observed spectra still have unidentified features. The abundance of negative ions in the ISM and their role in the chemistry of these environments has been subject to long-standing discussions in astrochemistry. Photodetachment cross-section studies are crucial for predicting the abundance of anions in the ISM.

Absolute photodetachment cross-section studies of hydrocarbon anions C_nH^-, n = 2, 4, 6 above the detachment threshold were performed in 2011 [1]. The threshold photodetachment spectroscopy of CN^- was performed by our group at both 16 K and 295 K in a 22-pole ion trap and 295 K from a pulsed ion beam using crossed-beam velocity map imaging (VMI) setup [2]. In next experiments we aim to study the threshold photodetachment spectroscopy of C_2^- and C_2H^-, which are speculated to exist in the interstellar medium, in a 16-pole radiofrequency ion trap, which can be cooled down to 6 K to mimic conditions in the ISM. The status of the experiment will be presented.

Reference

1. Best, T., Otto, R., Trippel, S., Hlavenka, P., Von Zastrow, A., Eisenbach, S., Jezouin, S., Wester, R., Vigren, E., Hamberg, M. and Geppert, W.D., 2011. Absolute photodetachment cross-section measurements for hydrocarbon chain anions. The Astrophysical Journal, 742(2), p.63.
2. Simpson, M., Nötzold, M., Schmidt-May, A., Michaelsen, T., Bastian, B., Meyer, J., Wild, R., Gianturco, F.A., Milovanović, M., Kokoouline, V. and Wester, R., 2020. Threshold photodetachment spectroscopy of the astrochemical anion CN−. The Journal of Chemical Physics, 153(18), p.184309.

Poster 16 / Precision Spectroscopy

Gas-phase spectroscopic studies of $[dAMP\text{-}H]^-$ in cryogenic 16-pole wire trap

Author: Salvi Mohandas[1]

Co-authors: Franziska Dahlmann [2]; Eric Endres [3]; Sunil Kumar S [4]; Roland Wester [5]

[1] *IISER TIRUPATI, University of Innsbruck*

[2] *Univerity of Innsbruck*

[3] *University of Innsbruck*

[4] *IISER Tirupati*

[5] *Univerisity of Innsbruck*

Corresponding Author: salvi28anamika@gmail.com

Recent studies suggest that the pharmacological activity of biomolecular drugs associates with their gas-phase geometries but not with the aqueous-phase structures [1]. In this scenario, the gas-phase study of biomolecules becomes more relevant with emerging RNA and DNA-based drugs by contributing knowledge to their biologically active geometry. 2'-deoxyadenosine-5'- monophosphate(dAMP) is a monomer of the genetic material, deoxyribonucleic acid (DNA). UV photodamage of DNA occurs mainly due to the absorption of the UV radiation by the aromatic ring present in their nitrogenous bases (Adenine, Thymine, Guanine, and Cytosine) [2,3,4]. The photodissociation spectroscopy of deprotonated 2'-deoxyadenosine-5'-monophosphate anion is measured with UV laser light in the range 220-280 nm with a linewidth of 0.02 nm. Electrospray ionization (ESI) is a widely used technique for generating complex biomolecular ions in the gas phase with little or no fragmentation [5]. The study is carried out by confining the anions generated from electrospray ionization, in a cryogenic 16-pole wire trap maintained at 2.9 K [6]. He buffer gas collision is employed for thermalizing the trapped ions to this temperature.

References
[1] Pereverzev, Aleksandr Y., and Oleg V. Boyarkin. Phys. Chem. Chem. Phys. 19(5), 3468-3472, 2017.
[2] Sunil Kumar, S., Pérot-Taillandier, M., Lucas, B., Soorkia, S., Barat, M., & Fayeton, J. A. J. Phys. Chem. A 115(38), 10383-10390, 2011.
[3] Yang, X., Wang, X. B., Vorpagel, E. R., & Wang, L. S. PNAS 101(51), 17588-17592, 2004.
[4] Stokes, S. T., Grubisic, A., Li, X., Jae Ko, Y., & Bowen, K. H. J. Chem. Phys. 128(4), 01B621, 2008.
[5] Fenn, J. B., Mann, M., Meng, C. K., Wong, S. F., & Whitehouse, C. M. Mass Spectrum. Rev. 9(1), 37-70,1990.
[6] Geistlinger, K., Fischer, M., Spieler, S., Remmers, L., Duensing, F., Dahlmann, F., Endres, E. and Wester, R. Rev. Sci. Instrum., 92(2), 023204, 2021.

Poster 17 / Precision Spectroscopy

Correlation spectroscopy with multi-qubit-enhanced phase estimation

Author: Helene Hainzer[1]

Co-authors: Florian Kranzl ; Matthias Bock ; Dominik Kiesenhofer ; Tuomas Ollikainen ; Manoj Joshi ; Tuvia Gefen ; Rainer Blatt ; Alex Retzker ; Christian Roos

[1] *Austrian Academy of Sciences*

Corresponding Author: helene.hainzer@uibk.ac.at

Precision spectroscopy on trapped ions 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 linear and planar Coulomb 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.

Poster 18 / Precision Spectroscopy

Precision measurement of electron g-factor in highly charged ions at ARTEMIS

Author: Kanika Kanika[1]

Co-authors: Khwaish Kumar Anjum [2]; Patrick Baus [3]; Gerhard Birkl [3]; Manasa Chambath [2]; Jeffrey William Klimes [4]; Wolfgang Quint [5]; Manuel Vogel [2]

[1] *Universität Heidelberg and GSI Helmholtzzentrum für Schwerionenforschung GmbH*

[2] *GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt*

[3] *Institut für Angewandte Physik, TU Darmstadt, Darmstadt*

[4] *GSI - Helmholtzzentrum fur Schwerionenforschung GmbH (DE)*

[5] *GSI Helmholtzzentrum für Schwerionenforschung GmbH*

Corresponding Author: kanikawadhwa12@gmail.com

The ARTEMIS (AsymmetRic Trap for the measurement of Electron Magnetic moment in IonS) [1] experiment at the HITRAP facility in GSI, Darmstadt, aims to measure magnetic moment of the electron bound to highly charged ions using the laser-microwave double-resonance spectroscopy [2] technique. The ARTEMIS Penning trap consists of two parts, the creation part of the trap which allows for *in-situ* production of the ions and the capture of ions, when connected to an external ion source, and the spectroscopy part of the trap where the measurements are performed. In the spectroscopy trap, laser-microwave double-resonance technique will be used to determine the electron's Larmor frequency, where a Zeeman transition is induced by microwave radiation, and the success of the transition is determined by the corresponding drop in the fluorescence light generated by a closed optical cycle transition. Ion clouds with 10^3 to 10^4 ions are stored and cooled in the Penning trap [3]. These large ion clouds are stored up to several weeks due to the high vacuum of about 10^{-15} mbar in the trap at cryogenic temperatures of 4 K. Due to the presence of electric and magnetic fields, the ions oscillate in the axial direction with frequency ω_z, the radial motion has a reduced cyclotron frequency ω_+ and the drift motion with frequency ω_-. These oscillating charges induce image currents on the electrodes, which are detected non-destructively using resonators. Currently, ARTEMIS is working toward a commissioning measurement of Ar^{13+} using ions created directly inside the trap chamber. Work is also underway to prepare the experiment for capture of heavy, HCIs from HITRAP such as Pb^{81+} and Bi^{82+}.

References

1) W. Quint et al., Phys. Rev. A 78, 032517 (2008)
2) D. Lindenfels et al., Phys. Rev. A 87 023412 (2013)
3) M. S. Ebrahimi et al., Phys. Rev. A 98 023423 (2018)

Poster 19 / Precision Spectroscopy

Feshbach resonances in a hybrid atom-ion system

Authors: Joachim Welz[1]; Fabian Thielemann[1]; Wei Wu[1]; Thomas Walker[1]; Pascal Weckesser[2]; Daniel Hönig[1]; Amir Mohammadi[1]; Tobias Schaetz[1]

[1] *University of Freiburg (DE)*

[2] *Max-Planck-Institut für Quantenoptik (DE)*

Corresponding Author: joachim.welz@physik.uni-freiburg.de

We present the first observation of Feshbach resonances between neutral atoms and ions. [1,2] While Feshbach resonances are commonly utilized in neutral atom experiments, however, reaching the ultracold regime in hybrid traps is challenging, as the driven motion of the ion by the rf trap limits the achievable collision energy. [3] We report three-body collisions between neutral ^{6}Li and ^{138}Ba^{+}, where we are able to resolve individual resonances. We demonstrate the enhancement of two-body interactions through an increase in the sympathetic cooling rate of the ion by the atomic cloud measured by spatial thermometry of Ba in the ODT; and molecule formation evidenced by subsequent three-body losses. This paves the way to new applications such as the coherent formation of molecular ions and simulations of quantum chemistry. [4]

[1] WECKESSER, Pascal, et al. Observation of Feshbach resonances between a single ion and ultracold atoms. *arXiv preprint arXiv:2105.09382*, 2021.
[2] SCHMIDT, J., et al. Optical traps for sympathetic cooling of ions with ultracold neutral atoms. *Physical review letters*, 2020, 124. Jg., Nr. 5, S. 053402.
[3] CETINA, Marko; GRIER, Andrew T.; VULETIĆ, Vladan. Micromotion-induced limit to atom-ion sympathetic cooling in Paul traps. *Physical review letters*, 2012, 109. Jg., Nr. 25, S. 253201.
[4] BISSBORT, Ulf, et al. Emulating solid-state physics with a hybrid system of ultracold ions and atoms. *Physical review letters*, 2013, 111. Jg., Nr. 8, S. 080501.

Quantum Information & Computing Posters

Poster 20 / Quantum Information & Computing

Coherent control of ion motion via Rydberg excitation

Author: Marion Mallweger[1]

Co-authors: Harry Parke [1]; Shalina Salim [1]; Chi Zhang [2]; Markus Hennrich [1]

[1] *Stockholm University (SE)*

[2] *Imperial College London (GB), Stockholm University (SE)*

Corresponding Author: marion.mallweger@fysik.su.se

Trapped Rydberg ions are a novel approach to quantum information processing [1, 2]. This idea combines qubit rotations in the ions' ground states with entanglement operations via the Rydberg interaction [3]. Importantly, the combination of quantum operations in ground and Rydberg states requires the Rydberg excitation to be controlled coherently. In the experiments presented here a trapped strontium ion was excited from the metastable 4D to Rydberg states.

While for the ground state of the ion, the polarizability is negligible, for Rydberg ions it increases as $\sim n^7$. Thus, the high polarizability of the Rydberg states with respect to the ground state will lead to a displaced trapping field during the Rydberg excitation if the ion experiences an offset electric field [4]. Until now, these changes in the trapping potential were compensated for, to enable coherent sub-microsecond entangling gates between trapped ions [6]. We propose that the trapping field displacement can be employed for coherent control of the ions' motion.

Repeated transitions between the ground and the Rydberg states will displace the ion due to the change in trapping potential and in this way can induce geometric phases accumulation via the ion motion. We investigate this effect by performing coherent Rydberg excitation using stimulated Raman adiabatic passage (STIRAP). This excitation of motional modes via Rydberg excitation could be utilized for realizing a fast quantum phase gate between multiple ions.

Polarizability dependent trapping field changes can recreate a Conical Intersection (CI) which normally appears in large molecules. The commonly applied Born-Oppenheimer approximation breaks down for this non-adiabatic process, hence other simulations need to be found. Rydberg ions with their well-controlled trapping and interaction properties can allow for studies of the phenomena of CIs [7].

[1] M. Müller, et al., NJP, 10, 093009 (2008).
[2] F. Schmidt-Kaler, et al., NJP, 13, 075014 (2011).
[3] W. Li, and I. Lesanovsky, APB, 114, 37 (2014).
[4] G. Higgins, et. al., Phys. Rev. X 7, 021038 (2017).
[6] C. Zhang, et. al., Nature 580, 345 (2020).
[7] F. Gambetta, et. al., Phys. Rev. Lett. 126, 233404 (2021).

Poster 21 / Quantum Information & Computing

Photon statistics from a large number of independent single-photon emitters.

Authors: Artem Kovalenko[1]; Daniel Babjak[1]; Lukáš Lachman[1]; Lukáš Podhora[1]; Petr Obšil[1]; Tuan Pham[2]; Adam Lešundák[2]; Lukáš Slodička[1]; Ondřej Čip[2]; Radim Filip[1]

[1] *Department of Optics, Palacký University,17. listopadu 12, 771 46 Olomouc, Czech Republic*

[2] *Institute of Scientific Instruments of the Czech Academy of Sciences, Královopolská 147, 612 64 Brno, Czech Republic*

Corresponding Author: artem.kovalenko@upol.cz

The coherence of light provides a paramount resource in modern physics. At the atomic scale, its source and properties can be often mimicked by different phenomena. We present the experimental characterization of coherence properties of light emitted from ensembles of trapped Ca^+ ions with a number of contributing particles ranging from a single ion up to the Coulomb crystals with several hundred trapped ions.

The radiofrequency linear Paul trap where confined ions scatter the light from the exciting 397 nm laser beam was used. The light was collected using a lens in the radial position and focal point carefully optimized for maximizing the fluorescence detection efficiency.

We study the dependence of the second-order coherence on the number of independently contributing ions in the Coulomb crystal in the single-mode detection regime. We observe unambiguous evidence of indistinguishable emission from ion crystals by measurement of photon bunching. The $g(2)(\tau = 0)$ gradually increases from a single-ion sub-Possonian value to approximately 1.5 for a large number of contributing ions. The observed phenomena correspond to a first controllable and scalable demonstration of a finite coherence between a large number of independent single-photon emitters. It provides a testbed for further experimental studies of the generation of complex nonclassical states of light and atoms.

Poster 22 / Quantum Information & Computing

Dielectric Properties of Plasma Oxides for Microfabricated Ion Traps

Authors: Alexander Zesar[1]; Clemens Rössler[2]; David Seebacher[2]; Michael Sieberer[2]; Elmar Aschauer[2]; Helmut Schönherr[2]; Klemens Schüppert[2]; Oliver Blank[2]; Peter Hadley[3]

[1] *Graz University of Technology*

[2] *Infineon Technologies Austria AG*

[3] *Graz University of Technology, Institute of Solid State Physics*

Corresponding Author: alexander.zesar@student.tugraz.at

The upcoming revolution in computation - quantum computing - will open up new avenues to efficiently solve classically hard problems, like quantum simulation and optimization tasks. A leading implementation of a feasible quantum processor is realized by trapped ions, where electronic states in stored ions represent physical quantum bits (qubits) [1]. The microfabrication of ion traps [2, 3] is a necessary step towards upscaling of qubit numbers, which will ultimately enable error corrected quantum computing.

Microfabricated ion traps employ structured metal layers isolated by dielectrics that are deposited via plasma enhanced chemical vapor deposition (PECVD). Surface electrodes produce an electromagnetic stray field, which confines the ions a few tens of micrometers above the trap. During trap operation involving radiofrequency (RF) fields of about 20 MHz, the charging of parasitic capacitances inside the metal-oxide structure causes heat dissipation by two major mechanisms. First the RF field in the dielectrics leads to dipole relaxation losses, which is quantified by the dielectric loss tangent. Second the currents needed for capacitor charging cause Ohmic losses in the metal leads. This effect is proportional to metal resistivity and to the total capacitance between RF electrodes and RF ground.

This work investigates dielectric properties of various dielectrics available at Infineon, both in the regime of optical- and radio frequencies. On the one hand, chemical and structural properties are quantified via infrared spectroscopy. Ellipsometry provides additional information on the refractive index in the visible spectrum. On the other hand, the radio frequency responses of capacitor test structures were evaluated in a wafer probing setup at frequencies from 1 to 100 MHz. The main structural influencing factors on the permittivity, measured via infrared spectroscopy, are found to be the Si-OH peak height, the Si-O-Si peak width, as well as the time of thermal tempering and fluorine content. Within our experimental resolution, we determine an upper bound for dielectric losses in plasma oxides of $\tan < 0.001$.

In a further analysis we find that replacing standard PECVD-deposited silane oxide with fluorosilicate glass would provide a reduction of dissipated power of up to 25% in future 1000 qubit ion traps. Finally, additional paths towards a lower overall power dissipation in large microfabricated ion traps are discussed.

[1] C. Bruzewicz et al., Trapped-Ion Quantum Computing: Progress and Challenges, Applied Physics Reviews (2019)
[2] P. Holz et al., 2D Linear Trap Array for Quantum Information Processing, Advanced Quantum Technologies (2020)
[3] R. J. Clark et al., A two-dimensional lattice ion trap for quantum simulation, Journal of Applied Physics (2009)

Poster 23 / Quantum Information & Computing

Feasible enhancement of collection efficiency of light from trapped ions

Author: Thuy Dung Tran[1]

Co-authors: Babjak Daniel [2]; Radek Šmíd [1]; Artem Kovalenko ; Petr Obšil [1]; Lukáš Podhora [1]; Lukáš Slodička [1]

[1] *Department of Optics, Palacký University, 17. listopadu 12, 77146 Olomouc, Czech Republic*

[2] *Department of Optics, Palacký University,17. listopadu 12, 77146 Olomouc, Czech Republic*

Corresponding Author: tran@optics.upol.cz

We present a theoretical analysis of optimisation of detection efficiency of optical signal scattered from dipole emitters using a far-field interference. These calculations are motivated by previous experimental demonstrations of coherent interaction of light with long strings of trapped ions [1,2,3]. For our models, we consider an ion string containing up to 10 ions, stored and laser cooled in a linear Paul trap [4].

Considering realistic trapping parameters and dipole radiation patterns, the distances between ions have been optimised to maximise a signal in the axial trapping direction. We compare these results to the case of equidistant positions and to the case of ions in a harmonic trap where the individual scattering phases can be tailored by an application of addressable phase shift to ions.
Crucially, our simulations predict that the overall gain of detection efficiency in the feasible case of a harmonic trap with non-equidistant positions of ions and tuneable solely by the axial potential strength is better than the idealised case of equidistant emitters. The optimal number of ions for feasible trapping parameters and large feasible numerical apertures is 6. The optimisation can be significantly beneficial for very small numerical apertures. The relative intensity of the optimised case can be approximately two orders of magnitude higher than the relative intensity of the non-optimised case. We further evaluate the effect of the thermal motion of ions on detection efficiency.

We present our progress towards the realisation of Paul traps focused on the experimental implementation of such directional emission and efficient collection of light from trapped ion strings [5,6].

References

[1] G. Araneda et al., Phys. Rev. Lett., 120(19), 193603 (2018).
[2] P. Obšil et al., New J. Phys., 21(9), 093039 (2019).
[3] S. Wolf et al., Phys. Rev. Lett., 116(18), 183002 (2016).
[4] D. F. V. James, Appl. Phys. B 66, 181-190 (1997).
[5] T. Lauprêtre et al., Phys. Rev. A 99(3), 031401 (2019).
[6] Ł. Kłosowski et al., J. Mass Spectrom. 53(7), 541-547 (2018).

Poster 24 / Quantum Information & Computing

A multi-qubit gate zone for use in a large scale ion shuttling architecture

Authors: Alex Owens[1]; Sam Hile[1]

[1] *University of Sussex*

Corresponding Author: a.owens@sussex.ac.uk

The field of quantum computing with trapped ions has seen many milestone achievements, the challenge for the future lies in scaling ion processors to qubit numbers capable of tackling interesting problems – without forgoing the high fidelities seen in smaller prototypes. One class of large-scale ion trapping architecture comprises dedicated regions for trapping, measurement, storage and interaction between the qubits, combined with the ability to shuttle ions between regions.

We encode qubits in the hyperfine ground state manifold of trapped $^{171}\mathrm{Yb}^+$ ions. Quantum control utilises global microwave fields provided via in-vacuum antennae and a static magnetic field gradient [1]. Ions are off resonant with the global fields until shuttled to interaction zones at designated positions in the gradient, altering their Zeeman splitting accordingly. In addition to providing individual qubit addressability, the magnetic field gradient couples the spin and motional degrees of freedom of the ions, allowing use of the motional state as a quantum bus. The strength of the gradient dictates the strength of the spin-motion coupling, which further determines the speed and fidelity of quantum gates. The microwave scheme seeks to address some of the challenges associated with scaling up laser-based schemes, only a fixed number of global fields are required independent of system size in contrast to a number of lasers that scales with the qubit number. In addition the scheme benefits from the relative maturity of commercially available microwave technology.

Previous work has relied on permanent precisely aligned magnets to produce the required magnetic field gradient for the microwave gate scheme. We generate a strong on-chip gradient utilising wires beneath the chip surface, which allow the gradient to be switched on and off, not possible with permanent magnets. Without switching of the gradient idle ions must be shuttled through regions of large magnetic field, rendering them susceptible to dephasing – problematic for realizing quantum algorithms. Furthermore, the buried wire layer can be incorporated as a step in chip production using standard micro-fabrication processes, suitable for use in large-scale ion trap arrays.
We present work towards realising a multi-qubit 'interaction' region, designed to be easily integrated as a repeating unit in micro-fabricated ion trapping chips, in line with the road map to a large-scale quantum computer as outlined in [2].

[1] S.Weidt et al. Phys. Rev. Lett. 117, 220501 (2016)
[2] Bjoern Lekitsch et al. Science Advances 3.2 (2017)

Poster 25 / Quantum Information & Computing

Simulating Potentials and Shuttling Protocols on an X-Junction Surface Trap

Author: Sahra Kulmiya[1]

[1] *University of Sussex*

Corresponding Author: sk790@sussex.ac.uk

Trapped ion qubits achieve excellent coherence times and gate fidelities, well beyond the threshold for fault tolerant quantum error correction. One route towards scalability is the coherent control and shuttling of ions between different zones on a microfabricated surface trap. A current challenge in shuttling is speed and fidelity. The shuttling operations should be as fast as possible to speed up quantum computation, as well as slow (adiabatic) in order to preserve the internal qubit state. Through simulation of trapping potentials and ion dynamics, we can observe the effects of static and dynamic potentials on the ions motional state and investigate various shuttling protocols on an X-junction surface trap. We introduce a new software called 'Realpot' which is easy to use and specifically designed to simulate BEM potentials, and also import and visualize FEM potentials. The software package is designed for ease of use and can calculate voltage solutions subject to specific constraints that are then applied to the simulated electrodes. The software package also provides detailed visualization and interactive plotting of potentials and ion dynamics.

Poster 26 / Quantum Information & Computing

Microwave-driven quantum logic in ^{43}Ca^{+} at 288 Gauss

Authors: Andrew Steane[1]; Clemens Löschnauer[1]; David Lucas[1]; Jochen Wolf[1]; Joe Goodwin[1]; Mario Gely[1]; Marius Weber[1]; Ryan Hanley[1]; Tom Harty[1]

[1] *University of Oxford*

Corresponding Author: mario.gely@physics.ox.ac.uk

Magnetic field gradients, generated by microwave circuitry in the proximity of trapped ions, can couple the ions internal and motional degrees of freedom to implement two-qubit gates [1,2]. This approach presents many advantages with respect to laser-driven gates: the hardware is cheaper and more readily scalable, phase control is facilitated, and photon scattering errors are eliminated.

In the past, we have demonstrated gate fidelities of 99.7% [3], approaching the state of the art for laser-based gates. Critically, this number is above the minimum threshold of 99% required for implementing quantum error correction. But the drawback of microwave-driven quantum logic is that gate durations are orders of magnitude longer than their laser-driven counter-parts.

Here, we present a novel ion trap design and qubit, which aims to improve both gate fidelity and speed. The chip features a simple single-electrode microwave geometry which passively minimizes the field amplitude whilst producing a large gradient. Operating ^{43}Ca^{+} at 288 Gauss detunes transitions to “spectator” states, whilst offering a π-clock transition which is more sensitive to magnetic fields. Finally, by cooling the trap to cryogenic temperatures, we are able to reduce anomalous heating of the ions motion, allowing a reduced distance between the microwave electrode and the ions and hence a more effective delivery of microwaves.

References:
[1] C. Ospelkaus et al., Phys. Rev. Lett. 101, 090502 (2008)
[2] C. Ospelkaus et al., Nature 476, 181 (2011)
[3] T. P. Harty et al., Phys. Rev. Lett. 117, 140501 (2016)

Poster 27 / Quantum Information & Computing

High-Fidelity Entanglement Gates on Microfabricated Ion-Traps

Author: Petros Zantis[1]

[1] *Ion Quantum Technology group - University of Sussex*

Corresponding Author: petroszantis@gmail.com

Trapped ions have proved to be a promising way of realising a large-scale quantum computer, due to their long coherence times and reproducibility, while also allowing for modular architectures which is key for a scalable, universal quantum computer. A blueprint for a trapped-ion based quantum computer outlines operating with global microwave fields to dress the ground-state hyperfine manifold of $^{171}\mathrm{Yb}^{+}$ ions, and demonstrates a maximally entangled state using a Mølmer-Sørensen type gate with fidelity 0.985(12) [1].

Building on that work, we present novel approaches to performing entanglement gates, which feature microfabricated ion traps with current-carrying wires (CCWs) embedded in the chips to provide a controllable magnetic field gradient [2]. A great obstacle for high-fidelity gates is voltage noise, current noise from the CCWs and anomalous heating, which couple to the qubits and lead to spin and motional decoherence.

We simulate and analyse these various noise sources, and use our models to optimise the experiment parameters for maximising fidelity, which in turn will allow for logic operations within the fault-tolerant regime. Current estimates of the threshold are around 1% for surface code [3], a quantum error correction scheme, thus guiding us towards the aim of achieving at least 99% fidelity on these new chips.

[1] B. Lekitsch, S. Weidt, A. G. Fowler, K. Mølmer, S. J. Devitt, C. Wunderlich, and W. K.Hensinger, “Blueprint for a microwave trapped ion quantum computer”, Science Advances 3 (2017).
[2] Romaszko, Z.D., Hong, S., Siegele, M. et al. “Engineering of microfabricated ion traps and integration of advanced on-chip features”, Nat Rev Phys 2, 285–299 (2020)
[3] A. G. Fowler, A. M. Stephens, and P. Groszkowski, “High-threshold universal quantum computation on the surface code”, Physical Review A. 80, (2009).

Poster 28 / Quantum Information & Computing

Technical challenges of quantum computing with radioactive ^{133}Ba^{+} ions

Authors: Ana Sotirova[1]; Fabian Pokorny[1]; Jamie Leppard[1]; Chris Ballance[1]

[1] *University of Oxford*

Corresponding Author: jamie.leppard@physics.ox.ac.uk

A large scale quantum simulator will provide the necessary tools for unparalleled scientific development. The challenges to build such a device are centered around the realization of a universal set of high fidelity quantum gates, that can be maintained in a system of many qubits. In the case of trapped ion devices of intermediate size, i.e. several tens of ions, the most natural approach to reach this goal is to realize long ions chains.

Here we provide the technical details of such an intermediate scale trapped ion quantum computer using ^{133}Ba^{+} qubits [1]. ^{133}Ba has nuclear spin $I = 1/2$ which allows for hyperfine "clock" qubits which are insensitive to magnetic fields and can be driven by Raman transitions. Additionally, the transition wavelengths are in the visible, allowing for off the shelf optics and fibre components.

However, ^{133}Ba is a radioisotope of Barium with a half life of 10.5 years. While this is not a limiting factor in terms of qubit lifetime, it requires careful considerations in terms of radiation safety. Primarily it is desirable to work with minimal quantities of the radioisotope. As such, loading with an oven is not appropriate. Instead, we load using laser ablation to provide short bursts of atomic flux from BaCl ablation targets of our own design. Additionally we give details of target fabrication and testing.

Secondly, the BaCl solution used in the target fabrication process only offers an abundance of synthetic ^{133}Ba on the order of $\sim 2\%$. Thus, loading long ion chains consisting of only ^{133}Ba must involve a process of isotope selection. We discuss the different techniques for achieving pure chains of order 50 ions, and present experimental work towards this with natural abundance samples. The required isotope selectivity is achieved by making use of the monolithic 3D microfabricated trap [2] in our experiment, which provides the necessary control to shuttle verified species from a loading zone to the trap centre.

[1] D. Hucul, J. E. Christensen, E. R. Hudson, and W. C. Campbell, "Spec-troscopy of a synthetic trapped ion qubit", Physical review letters, vol. 119, no. 10, 2017.

[2] P. See, G. Wilpers, P. Gill, and A. G. Sinclair, "Fabrication of a monolithicarray of three dimensional si-based ion traps", Journal of microelectrome-chanical systems, vol. 22, no. 5, 2013.

Poster 29 / Quantum Information & Computing

Towards measurement-based blind quantum computing with trapped ions

Authors: Bethan Nichol[1]; David Nadlinger[1]; Peter Drmota[1]; Chris Ballance[1]; David Lucas[1]; Dougal Main[1]; Gabriel Araneda[1]; Raghavendra Srinivas[1]

[1] *University of Oxford*

Corresponding Author: peter.drmota@physics.ox.ac.uk

In the framework of blind quantum computing, quantum computations can be delegated to an untrusted server while ensuring privacy and verifying their correctness [1]. For an experimental demonstration, we consider the practical case of measurement-based blind quantum computation (MBBQC) on a continuously rebuilding cluster state. This protocol involves sequential measurements and remote state preparation, necessitating real-time feedback from the client.

We present progress towards implementing MBBQC protocols in our trapped-ion quantum network [2]. In this network, $^{88}\text{Sr}^{+}$ is entangled with a spontaneously emitted photon whose polarisation can be manipulated and measured by the client, thus implementing remote state preparation. By adding mixed-species operations using additional $^{43}\text{Ca}^{+}$, we can create a continuously rebuilding cluster state with sufficient coherence time, as required for MBBQC.

[1] Private quantum computation: an introduction to blind quantum computing and related protocols, J. F. Fitzsimons, npj Quantum Information 3.1 (2017)
[2] High-Rate, High-Fidelity Entanglement of Qubits Across an Elementary Quantum Network, L. J. Stephenson, Physical Review Letters 124.11 (2020)

Poster 30 / Quantum Information & Computing

Quantum thermodynamics: Heat leaks and fluctuation dissipation

Authors: Oleksiy Onishchenko[1]; Daniël Pijn[1]; Janine Hilder[1]; Ulrich Poschinger[1]; Raam Uzdin[2]; Ferdinand Schmidt-Kaler[1]

[1] *QUANTUM, Institut für Physik, Universität Mainz, Mainz, Germany*

[2] *Fritz Haber Center for Molecular Dynamics, The Hebrew University, Jerusalem, Israel*

Corresponding Author: oonishch@uni-mainz.de

Quantum thermodynamics focuses on extending the notions of heat and work to microscopic systems, where the concepts of non-commutativity and measurement back-action play a role [1]. Our experimental system consists of one or multiple qubits implemented in the Zeeman sublevels of the ground electronic state of $^{40}\mathrm{Ca}^+$, and the ion register is held in a microstructured Paul trap [2]. Quantum logic gate operations implement coherent dynamics in the multi-particle quantum system. Additionally, we use optical pumping to initialize spin qubits in a statistical mixture of $|0\rangle$ and $|1\rangle$, thus emulating thermal states. We test the principle of passivity to set bounds on system evolution in the following way: we subdivide the register into the system and environment qubits and then reveal the amount of non-unitary evolution of the system qubits by measuring only in the computational basis and without accessing the environment. The concepts of global passivity, and passivity deformation set tighter bounds for detecting such a heat leak [3]. In addition, we apply non-commuting sequential operations on a single spin and observe the resulting work fluctuations, as suggested theoretically [4].

[1] S. Vinjanampathy and J. Anders, Contemporary Physics 57, 545-579 (2016).
[2] J.Hilder et. al., accepted in Physical Review X (2022), arXiv:2102.12047 (2021).
[3] D. Pijn et. al., arXiv:2110.03277v1 (2021).
[4] M. Scandi et. al., Physical Review Research 2 023377 (2020).

Poster 31 / Quantum Information & Computing

Multipartite entanglement of trapped ions by graph-based optimized global Raman beams

Authors: Arjun D. Rao[1]; Christophe Valahu [1]; Tingrei Tan[1]

[1] *The University of Sydney*

Corresponding Author: arao5721@uni.sydney.edu.au

Entangling gates are arguably the main ingredient of quantum information processing (QIP). Trapped ion systems have typically outshone other quantum hardware in preparing Bell states. Two ion entanglement has been extensively covered [1, 2, 3] and sequences of pairwise gates can be used to generate multipartite entanglement. Alternatively, global irradiation is faster, which is important as speed is essential for scaleable QIP and for quantum algorithms [4, 5]. As the ion number increases, more motional modes appear and the error increases. For example, crosstalk and fluctuations in the tightly focused individual addressing Raman beams can decrease the fidelity [6].

Modulation techniques are widely used to improve the gate fidelity by reducing residual spin-motion coupling, dealing with the complexity of clustered motional modes in large ion crystals. Also, optimizers are used to design pulses which solve theoretical gate constraints, but is limited when considering more ions as it is a NP-hard problem. To this end, we implement a modulated single global beam to illuminate all of the ions, creating a global entangling interaction and have single ion addressability provided by a 411nm shelving beam. Then by using graph-based optimization instead of solving constraints, we can quickly reach solutions for large ion crystal entanglement with faster gates. We show that our error scales better than pairwise entangling gates and that the gate duration is favourable.

References
[1] J. P. Gaebler et al. "High-Fidelity Universal Gate Set for 9Be+ Ion Qubits". In: Phys. Rev. Lett. 117 (6 Aug. 2016), p. 060505. DOI: 10.1103/PhysRevLett.117.060505. URL: https://link.aps.org/doi/10.1103/PhysRevLett.117.060505.
[2] C. J. Ballance et al. "High-Fidelity Quantum Logic Gates Using Trapped-Ion Hyperfine Qubits". In: Phys. Rev. Lett. 117 (6 Aug. 2016), p. 060504. DOI: 10.1103/PhysRevLett.117.060504. URL: https://link.aps.org/doi/10.1103/PhysRevLett.117.060504.
[3] T. R. Tan et al. "Multi-element logic gates for trapped-ion qubits". In: Nature 528.7582(2015), pp. 380–383. ISSN: 0028-0836. DOI: 10.1038/nature16186.
[4] A Yu Kitaev. "Quantum measurements and the Abelian Stabilizer Problem". In: arXiv(1995).
[5] Jungsang Kim et al. "Modular Universal Scalable Ion-trap Quantum Computer (MUSIQC)".In: AIP Conference Proceedings 1363.1 (2011), pp. 190–193. ISSN: 0094-243X. DOI:10.1063/1.3630178.
[6] Yao Lu et al. "Global entangling gates on arbitrary ion qubits". In: Nature 572.7769 (2019), pp. 363–367. ISSN: 0028-0836. DOI: 10.1038/s41586-019-1428-4

Poster 32 / Quantum Information & Computing

Single Ion Addressing for Reliable Isolation of ^{171}Yb^{+} Hyperfine Qubit States

Author: Maverick Millican[1]

[1] *The University of Sydney*

Corresponding Author: mmil4812@uni.sydney.edu.au

Single ion addressing provides a critical computational advantage for trapped-ion registers used for large-scale quantum simulation and computation [1][2]. Several schemes are currently used including arrays of mechanically positioned micro-optic fibers [3], holographic diffraction patterns produced by arrays of micromirrors [4], and beam splitting by AODs driven by multi-tone rf frequencies [5]. The last technique offers simplicity of experimental setup and electronic control of beam position via arbitrary injection of rf tones applied to the AODs.
Presented here is a system for single-ion addressing by multi-tone RF driven AODs with a single high-intensity 411 nm beam delivered through a high NA lens on ^{171}Yb^{+} ions. This scheme offers the ability to arbitrarily select ions in a large quantum register to exhibit an AC Stark shift on the hyperfine energy splitting of the electronic ground state, providing reliable isolation from global interactions [6]. Further, this system enables single-qubit-addressable high-fidelity readout via electron shelving in the 2D5/2 and 2F7/2 electronic states [7].

References

[1] Hempel, Cornelius. Digital quantum simulation, Schrödinger cat state spectroscopy and setting up a linear ion trap. Diss. 2014.
[2] NAÈgerl, H. Ch, et al. "Laser addressing of individual ions in a linear ion trap." Physical Review A 60.1 (1999): 145.
[3] Crain, S., et al. "Individual addressing of trapped 171Yb+ ion qubits using a microelectromechanical systems-based beam steering system." Applied Physics Letters 105.18 (2014): 181115.
[4] Shih, CY., Motlakunta, S., Kotibhaskar, N. et al. Reprogrammable and high-precision holographic optical addressing of trapped ions for scalable quantum control. npj Quantum Inf 7, 57 (2021)
[5] Pogorelov, Ivan, et al. "Compact ion-trap quantum computing demonstrator." PRX Quantum 2.2 (2021): 020343.
[6] Pernthaler, Lukas Falko. Single Ion Addressing of up to 50 Ions. Diss. University of Innsbruck, 2019.
[7] Edmunds, C. L., et al. "Scalable hyperfine qubit state detection via electron shelving in the 2 D 5/2 and 2 F 7/2 manifolds in 171 Yb+." Physical Review A 104.1 (2021): 012606.

Poster 33 / Quantum Information & Computing

Photonic integration for trapped-ion quantum information science

Author: Felix Knollmann[1]

[1] *MIT*

Corresponding Author: fwk@mit.edu

A major architecture for large-scale quantum computing with trapped ions relies on individual computational nodes that are linked via quantum networking. This multi-node architecture would also benefit hybrid networks between trapped ions and other quantum systems. Quantum networks of practical scales will require modularization of the quantum control hardware and reduction of the equipment and alignment overhead. To realize this vision, we are developing new methods of integrating light delivery and collection into photonic waveguides on-chip. To achieve qubit array addressing without free-space optics, we are integrating emission structures for light delivery at colors and polarizations necessary for ion cooling and qubit manipulation. By collecting emitted single photons into waveguides and combining them on a beamsplitter, ion qubits can be remotely entangled via heralded photon coincidence using solely integrated optical elements. This entanglement between nodes would allow many chains of trapped ions, functioning as small quantum computers, to be coherently interconnected via teleported gates. Thus, chip-integration of photonic elements can pave the way towards distributed quantum computing and quantum networking with trapped ions.

Poster 34 / Quantum Information & Computing

Improving robustness of laser-free entangling gates for a trapped-ion architecture

Authors: I. Apostolatos[1]; C.P. Knapp[1]; Christophe Valahu[1]; Madalina Mironiuc[1]

Co-authors: S. Weidt ; S.J. Hile ; W.K. Hensinger

[1] *Imperial College London*

The combination of the entangling Mølmer-Sørensen gate and single qubit rotations is a well-established way to realise a universal set of quantum gates with trapped ions. Additionally, implementing this gate scheme using global microwave fields can further the scaling prospects of this quantum computing platform.

In previous work, the demonstration of a 98.5% fidelity Mølmer-Sørensen gate [1] using global microwave fields and a static magnetic field gradient was a milestone in demonstrating key elements needed for large scale quantum computation as outlined in Ref.[2]. Furthermore, this gate scheme can be particularly robust to magnetic field noise when realised using the dressed-state protocol [3]. However the gate fidelity in this demonstration was limited by the heating of the ions' motional state. Recent developments in the experimental set-up led to a substantial reduction of motional heating, which will enable future demonstrations of position-dependent logic.

Here we are discussing methods which will not merely increase the gate fidelity, but deliver improvements on the overall gate robustness. The methods considered are: dynamical decoupling techniques, which directly influence the gate mechanism [4], automated calibration techniques [5] and empirically motivated simulations, which use experimental results to improve theoretical predictions for gate parameters [6].

[1] S Weidt et al. "Trapped-ion quantum logic with global radiation fields". In: Physical review letters 117.22 (2016), p. 220501.
[2] Bjoern Lekitsch et al. "Blueprint for a microwave trapped ion quantum computer". In: Science Advances 3.2 (2017), e1601540.
[3] SC Webster et al. "Simple manipulation of a microwave dressed-state ion qubit". In: Physical Review Letters 111.14 (2013), p. 140501.
[4] Anna E Webb et al. "Resilient entangling gates for trapped ions". In: Physical review letters 121.18 (2018), p. 180501.
[5] Julian Kelly et al. "Physical qubit calibration on a directed acyclic graph". In: arXiv preprint arXiv:1803.03226 (2018).
[6] Nicolas Wittler et al. "Machine-learning tools for rapid control, calibration and characterization of QPUs and other quantum devices". In: APS March Meeting Abstracts. Vol. 2021. 2021, pp. X32–015.

Quantum Technologies Posters

Poster 35 / Quantum Technologies

Quantum non-Gaussianity of multiphonon states of a single atom

Author: Lukas Podhora[1]

Co-authors: Artem Kovalenko [1]; Lukas Lachman [1]; Tuan Pham [2]; Adam Lesundak [2]; Ondrej Cip [2]; Lukas Slodicka [1]; Radim Filip [1]

[1] *Palacký University (CZ)*

[2] *Institute of Scientific Instruments of the Czech Academy of Sciences (CZ)*

Corresponding Author: podhoralukas@gmail.com

Generation and manipulation of non-classical states of motion has been of interest with motivation in quantum metrology, quantum enhanced sensing [1] and quantum thermodynamics. Fock states of motion with exactly defined discrete value of energy are experimentally achievable realizations of such non-classical states in ion trap. Although the significant progress in the Fock state preparation has been achieved [2], the optimal method to characterize their quantitative properties remains a subject of discussion.

We demonstrate the generation of motional Fock states up to 10 in a single $^{40}\mathrm{Ca}^{+}$ trapped ion oscillator, and we derive the set of quantum non - Gaussianity (QNG) criteria, to characterize the measured state's non-classicality. We further subject the generated state to the controlled interaction with thermal environment and evaluate the QNG depth and other quantitative parameters of the imperfect state with losses. We also demonstrate the metrological advantage of our states proving the ability for quantum enhanced sensing.

We further experimentally realize the novel method for Fock state generation from thermal motional states with high energies, based on pioneering work of Blatt et al. [3]. By unconditional repetitive accumulation of anti-Jaynes – Cummings interaction with fixed interaction time, we prove that it is possible to generate a chosen mixture of motional Fock states within the finite number of iterations, and for an ion initially prepared in a thermal motional state [4]. The non-classical properties of the states are again proved by several complementary measures, and in addition, we investigate the QNG depth. Finally, we demonstrate our recent work showing the non-classicality of states generated by the process of repetitive absorption of phonons from thermal motional state of a single ion.

[1] F. Wolf, C. Shi, J. C. Heip, M. Gessner, L. Pezze, A. Smerzi, M. Schulte, K. Hammerer, and P. O. Schmidt, Nat. Commun. 10, 1 (2019).

[2] K. C. McCormick, J. Keller, S. C. Burd, D. J. Wineland, A. C. Wilson, and D. Leibfried, Nature 572, 86 (2019).

[3] R. Blatt, J. I. Cirac, P. Zoller, Phys. Rev. A 1995, 52, 518.

[4] L. Podhora, T. Pham, A. Lešundák, P. Obšil, M.Čížek, O. Číp, P. Marek, L. Slodička, and R. Filip, Advanced Quantum Technologies 3, 2000012 (2020).

Poster 36 / Quantum Technologies

Automated optical inspection and electrical measurement of industrially fabricated surface ion traps

Authors: Fabian Anmasser[1]; Matthias Dietl[1]; Clemens Rössler[2]

Co-authors: Christian Utizi [2]; Elaine Sotacio [2]; Alexander Zesar [3]; Silke Auchter [1]

[1] *Infineon Technologies Austria AG, Villach, Austria; Institute for Experimental Physics, Innsbruck, Austria*

[2] *Infineon Technologies Austria AG, Villach, Austria*

[3] *Graz University of Technology; Infineon Technologies Austria AG, Villach, Austria*

Corresponding Author: fabian.anmasser@infineon.com

In 1995, Zoller [1] suggested the realization of a quantum computer by means of using ions in a linear trap. Since linear traps are only capable of storing a few tens of ions, the transition to 2D surface traps will be essential for useful quantum computers. Hence, plentiful research was done already about micro-fabricated 2D surface traps in an industrial environment [2,3,4]. To pave the way to scalable quantum information processors using ion traps, control over a high number of qubits will be needed. Therefore, complexity and possible error sources are suspected to rise. We present two key concepts to improve on the quality of ion traps. Both have been implemented successfully at the industrial fabrication facilities of Infineon-Technologies in Villach.

In the process of automated optical inspection (AOI), a CCD camera images the entire wafer and creates a so called golden sample as an average of all ion traps. Every chip exhibiting deviations to the golden sample in range of a given resolution, is inked and discarded automatically.

In the final screening test, all ion traps are tested for electrical functionality. To that end, a dedicated probe-card places probe needles on all bond pads in order to perform a Kelvin-contact and applies predefined currents and voltages. Every electrode gets probed against each other with respect to its isolation- and connectivity specifications.

This scheme of quality control helps to introduce a higher standard in the fabrication of ion traps, making them more reliable and therefore facilitating experimental research.

[1] J. I. Cirac and P. Zoller. Quantum computations with cold trapped ions. Phys. Rev. Lett., 74:4091
4094, May 1995.
[2] Philip C. Holz, Silke Auchter, Gerald Stocker, Marco Valentini, Kirill Lakhmanskiy, Clemens
Rössler, Paul Stampfer, Sokratis Sgouridis, Elmar Aschauer, Yves Colombe, and Rainer Blatt. 2d linear trap array for quantum information processing. Advanced Quantum Technologies, 3(11):2000031, sep 2020.
[3] J. Stuart, R. Panock, C.D. Bruzewicz, J.A. Sedlacek, R. McConnell, I.L. Chuang, J.M. Sage, and
J. Chiaverini. Chip-integrated voltage sources for control of trapped ions. Physical Review Applied,
11(2), feb 2019.
[4] K. K. Mehta, A. M. Eltony, C. D. Bruzewicz, I. L. Chuang, R. J. Ram, J. M. Sage, and J. Chiaverini.
Ion traps fabricated in a CMOS foundry. Applied Physics Letters, 105(4):044103, jul 2014.

Poster 37 / Quantum Technologies

Higher-order effects of electric quadrupole fields on a single Rydberg ion

Author: Shalina Salim[1]

Co-authors: Harry Parke [1]; Gerard Higgins [2]; Chi Zhang [3]; Fabian Pokorny [4]; Markus Hennrich [1]

[1] *Stockholm University*

[2] *AUSTRIAN ACADEMY OF SCIENCES, INSTITUTE FOR QUANTUM OPTICS AND QUANTUM INFORMATION VIENNA*

[3] *Imperial College London*

[4] *Department of Physics, University of Oxford*

Corresponding Author: shalina.salim@fysik.su.se

Abstract

Rydberg ions have large dipole and quadrupole polarizabilities which makes them extremely sensitive to external electric fields[1][2]. As a result, an ion in the Rydberg state experiences altered trapping potential which leads to motion-dependent Rydberg excitation energies[3]. Higher the Rydberg state more is the sensitivity to the electric quadrupole trapping fields. The oscillating trapping field induces an energy shift in these states which oscillates at the trap drive frequency and generates sidebands in the spectrum. Unwanted couplings to these field-induced sidebands reduces the fidelity of Rydberg ion quantum gate operations.

Here we study the higher order effects of the quadrupole electric filed on a single trapped Sr^+ Rydberg ion confined in a Paul trap, which arises due to the quadrupole polarizability of the Rydberg states. The effects were investigated on $nS_{\frac{1}{2}}$and $nP_{\frac{1}{2}}$ states and resonance shifts and spectral sidebands were observed experimentally. The Rydberg excitation energies depend quadratically on the trapping RF field amplitude. For the $nS_{\frac{1}{2}}$ state the first order spectral sidebands were much weaker whereas in the $nP_{\frac{1}{2}}$ state the spectrum showed a forest of sidebands. All results are in good agreement with theory[4].

References

[1] G. Higgins, *A single trapped Rydberg ion.* PhD thesis, Stockholm University and Innsbruck University, 2018.

[2] M. M"uller, L. Liang, I. Lesanovsky, and P. Zoller, *Trapped Rydberg ions: from spin chains to fast quantum gates,* New Journal of Physics, vol. 10, p. 093009, Sep 2008.

[3] G. Higgins, F. Pokorny, C. Zhang, and M. Hennrich, *Highly Polarizable Rydberg Ion in a Paul Trap*, Physical Review Letters, vol. 123, 2019.

[4] G. Higgins, C. Zhang, F. Pokorny, H. Parke, E. Jansson, S. Salim, and M. Hennrich, *Observation of second- and higher-order electric quadrupole interactions with an atomic ion*, Physical Review Research, vol. 3, no. 3, pp. 1-6, 2021.

Poster 38 / Quantum Technologies

Industrially microfabricated ion traps with low loss materials

Authors: Alexander Zesar[1]; Matthias Dietl[2]; Clemens Rössler[3]; Marco Valentini[4]; Oliver Blank[3]; Philip Holz[5]; Philipp Schindler[4]; Rainer Blatt[6]; Silke Auchter[7]; Thomas Monz[4]

[1] *Graz University of Technology*

[2] *Infineon*

[3] *Infineon Technologies Austria AG*

[4] *University of Innsbruck*

[5] *Alpine Quantum Technologies*

[6] *University of Innsbruck, Institute for Quantum Optics and Quantum Information*

[7] *University of Innsbruck, Infineon*

Corresponding Author: matthias.dietl@infineon.com

Quantum computers have the potential to revolutionize computation by making certain types of classically intractable problems solvable. There are several platforms, that might host a future quantum computer. Trapped ions enable quantum gate operations on quantum bits (qubits) by manipulating single or multiple ions. Trapped ion quantum computing offers advantages over other platforms like low error rates and long storage times [1]. The path towards a universal quantum computer unavoidably requires scaling up the number of qubits, which today poses a considerable engineering challenge. Pogorelov et al. [2] have recently managed to fully entangle 24 optical qubits in a 1-dimensional ion crystal by means of a linear Paul trap. To enable scalability, we employ an industrially microfabricated surface ion trap which features the ability to scale up to higher qubit numbers. However, by scaling up to higher qubit numbers the energy dissipation in the trap becomes an increasingly important obstacle. To address this problem, we promote the usage of wide bandgap dielectric materials as substrate and electrode materials with a high electrical conductivity.

We will present a surface ion trap capable of trapping 18 ions in two adjacent 1D crystals, arranged in an architecture suitable for further upscaling. In an ongoing research project, we investigate the usage of different electrode and substrate materials. In contrast to silicon, wide-bandgap (>6 eV) dielectric substrate, such as fused silica or sapphire, exhibits low radiofrequency (RF) absorption and is transparent to most lasers used in quantum computing with optical ions. These properties additionally opens up the possibility to remove a large metal layer, which shields the silicon from the RF fields and laser light. By restructuring our trap design, we are able to cut our trap capacitance nearly in half (Simulated old design: 38pF; new design: 22pF). To reduce the dissipated power resulting of Ohmic losses caused by capacitive charging currents, we investigate the usage of highly conductive materials. By using copper instead of aluminum together with the reduced overall trap capacitance, we will be able to reduce the power dissipation by at least one order of magnitude.

[1] C. Bruzewicz, Trapped-ion quantum computing: Progress and challenges, arXiv:1904.04178
[2] I. Pogorelov, A compact ion-trap quantum computing demonstrator, arXiv:2101.11390
[3] P. Holz, Two-dimensional linear trap array for quantum information processing, arXiv:2003.08085

Poster 39 / Quantum Technologies

A matter link for remote ion-trap modules

Authors: Falk Bonus[1]; Foni Raphaël Lebrun-Gallagher[2]; Mariam Akhtar[2]; Nicholas Johnson[2]

[1] *University College London*

[2] *University of Sussex*

Corresponding Author: falk.bonus.19@ucl.ac.uk

The number of qubits in quantum computing architectures must be increased dramatically in order to demonstrate an advantage over classical hardware [1]. This “scaling up” must be performed without experiencing reductions in the rate, or the fidelity of the qubit operations. Multiple ions can be confined within a single ion trap. However, qubit gate times and the motional mode density scale with the size of the trapped ion crystal and effectively put an upper limit on the crystal size [2]. Remote links between several trapping regions or modules offer a solution to scaling beyond this limit. These links have so far been demonstrated with photonic interconnects, where photons mediate entanglement between ion crystals in separate traps [3]. A different approach to modularity has been proposed where the trapped ions themselves form a matter link between remote modules [4]. This matter link is established by the deterministic and coherent transfer of ions between spatially separated modules, and has previously remained an unexplored area of research. Here we report on the recent developments in demonstrating a shuttling-mediated matter link.

[1] Brown, K.R., et al. “Co-designing a scalable quantum computer with trapped atomic ions.” npj Quantum Information 2.1 (2016): 1-10.
[2] Blakestad, R. B., et al. “Near-ground-state transport of trapped-ion qubits through a multidimensional array.” Physical Review A 84.3 (2011): 032314.
[3] Stephenson, L. J., et al. “High-rate, high-fidelity entanglement of qubits across an elementary quantum network.” Physical review letters 124.11 (2020): 110501.
[4] Lekitsch, B., et al. “Blueprint for a microwave trapped ion quantum computer.” Science Advances 3.2 (2017): e1601540.

Poster 40 / Quantum Technologies

TSV-integrated Surface Electrode Ion Trap for Scalable Quantum Information Processing

Authors: Chuan Seng Tan[1]; Hong Yu Li[2]; Jean-Pierre Likforman[3]; Théo Henner[4]; Jing Tao[1]; Luca Guidoni[3]; Wen Wei Seit[2]; Yu Dian Lim[1]; Peng Zhao[1]

[1] *School of Electrical and Electronic Engineering, Nanyang Technological University*

[2] *Institute of Microelectronics, Agency for Science, Technology and Research (A*STAR)*

[3] *Laboratoire Matériaux et Phénomènes Quantiques, CNRS - Université de Paris*

[4] *Université de Paris*

Corresponding Author: theo.henner@univ-paris-diderot.fr

Ion traps and their geometry have seen their complexity increase for several years. Examples of this trend are the integration of waveguides, photodetectors [1] and the design of array of trap [2][3][4]. To continue in this path, significant challenges for electric signal delivery must be solved. I will present a functional trap using Through Silicon Vias (TSV) electrodes connection (both Radio-Frequency (RF) and Direct Current (DC)) which is fully foundry compatible.

In this work, we report about design, fabrication and operation of a Cu-filled through silicon via integrated ion trap. With intrinsically small resistance, Cu-filled TSVs are used here as vertical connections between all the electrodes (including RF electrodes) and an interposer underneath. Besides, a standard CMOS process on a 12-inch wafer is used, facilitating high resolution and repeatability of trap fabrication. The integration of TSVs permit a significant reduction of electrode surfaces, decreasing the trap capacitance up to 90% in comparison to a wire bonded trap of same size. A low RF dissipation is achieved in spite of the absence of a screening layer. We evaluate the trap performances by loading and laser-cooling single 88Sr+ ions and by measuring the trap heating-rate using the technique of Doppler re-cooling [5]. The heating rate of the trap is evaluated at 250mK/s that corresponds to 17 quanta/ms for an axial frequency of 300 kHz. The lifetime of a laser-cooled ion in the trap is of the order of 30 minutes, compatible with the vacuum level.

This work pioneers the development of TSV-integrated ion traps, enriching the toolbox for scalable quantum computing. In particular the TSV approach is compatible with insertion of a ground screening layer to eliminate trap-heating, photonic circuit integration on which we are currently working, and in the future could be extended to glass substrates. In the future, further optimization of both TSV and multilayer metallization technologies (overlapping of alternate metal layers and dielectric materials beneath surface electrodes) is foreseen. However, a combination of the two techniques will be probably necessary to realize larger-scale ion traps with lower RF losses, and higher density of photonic components.

[1] Todaro *et al.* Phys. Rev. Lett. **126**, 010501 (2021)

[2]Mehta *et al.*, Nature nanotechnology **11**, 1066 (2016)

[3] Niffenegger *et al.*, Nature **586**, 538–542 (2020)

[4] Mehta *et al.*, Nature **586**, 533 (2020)

[5] Epstein *et al.*, Phys. Rev. A **76**, 033411 (2007)

Poster 41 / Quantum Technologies

Demonstrating a logical qubit on a surface ion trap

Authors: Daisy Smith[1]; Sahra Kulmiya[1]

[1] *University of Sussex*

Corresponding Authors: ds572@sussex.ac.uk, sk790@sussex.ac.uk

The Ion Quantum Technology group has proposed a scalable quantum computing design made up of modular surface ion traps which slot together. One of the main challenges in realizing this design is demonstrating fault-tolerant error correction on a surface trap. We use an X-junction trap which has designated zones for trapping, performing quantum gates and reading out results. It uses surface electrodes to 'shuttle' ions around the chip and embedded B-field gradient coils with global microwave fields to perform quantum gates. We are working towards good shuttling control of our ions and demonstrating high-fidelity qubit gates. However, to demonstrate quantum error correction, we also need to translate error-correction schemes into shuttling protocols which are achievable on our chip. We aim in the long-term to demonstrate the 17-qubit surface code.

The poster will discuss the implementation of the 5-qubit error-correcting code on an X-junction with a focus on compilation. We outline a set of compiler stages between the error-correction protocol and the physical implementation. The error-correction protocol will look like a set of quantum gates acting on physical qubits, and the physical implementation will look like a shuttling routine of ions around the chip interspersed with quantum gates. The compilation involves two main translation stages: from logical qubits to computational qubits, and from computational qubits to physical qubits. Crucially, our ion qubits are distinguishable only through their location, unlike the computational qubit which are simply labelled 0, 1, 2 etc. We will present our progress in tackling these compilation stages using the quantum framework ProjectQ, and the application of the generated routines on our X-junction chips.

Poster 42 / Quantum Technologies

Towards a fault-tolerant universal set of microwave driven quantum gates with trapped ions

Author: Hardik Mendpara[1]

Co-authors: Nicolas Pulido [2]; Markus Duwe [2]; Ludwig Krinner [2]; Amado Bautista-Salvador [2]; Giorgio Zarantonello [3]; Henning Hahn [2]; Christian Ospelkaus [2]

[1] *Leibniz-Universität Hannover*

[2] *Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany and PTB, Bundesallee 100, 38116 Braunschweig, Germany*

[3] *National Institute of Standards and Technology, 325 Broadway, Boulder, CO 80305, USA and Department of Physics, University of Colorado, Boulder, CO 80309, USA*

Corresponding Author: mendpara@iqo.uni-hannover.de

Single-qubit rotation operations and two-qubit entangling gates form a universal set of quantum operations capable of performing any quantum algorithm. Here, we consider the implementation of single- and two-qubit gates using microwaves as a scalable alternative to the more widely used laser-based addressing techniques, which have fidelities that are typically limited by photon scattering [1]. The control fields are generated by microwave conductors embedded directly into the trap structure. Using this fully integrated microwave approach, we obtain a preliminary infidelity of 10^{-4} for single-qubit gates and approaching 10^{-3} for two-qubit operations. The two-qubit gates are shown to be robust with respect to motional quantum bus noise as a result of a tailored amplitude modulation protocol [2]. Further, to better characterize the performance of two-qubit entangling gates, we will report on our recent progress in benchmarking our two-qubit quantum processor in a computational context [3,4].

[1] C. Ospelkaus et al., Phys. Rev. Lett. 101 090502 (2008)

[2] G. Zarantonello et al., Phys. Rev. Lett. 123 260503 (2019)

[3] A. Erhard \textit{et al.}, Nat. Commun. \textbf{10}, 5347 (2019)

[4] J. Gaebler \textit{et al.}, Phys. Rev. Lett. \textbf{109}, 179902 (2012)