PROCEEDINGS OF SCIENCE

Towards g-factor measurements of (anti-)protons using techniques based on quantum logic spectroscopy

N. Poljakov,[a,b] **J. Schaper,**[a,b] **J.-A. Coenders,**[a,b] **J.M. Cornejo,**[a,b] **S. Ulmer**[c,d] **and C. Ospelkaus**[a,b,e]

[a] *Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany*
[b] *Laboratorium für Nano- und Quantenengineering, Leibniz Universität Hannover, Schneiderberg. 39, 30167 Hannover, Germany*
[c] *RIKEN, Ulmer Fundamental Symmetries Laboratory, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*
[d] *Institut für Experimentalphysik, Heinrich Heine Universität Düsseldorf, Universitätsstr. 1, 40225 Düsseldorf, Germany*
[e] *Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany*

E-mail: poljakov@iqo.uni-hannover.de

We present the latest upgrades of our cryogenic multi-Penning-trap stack to implement quantum logic cooling and detection techniques for g-factor measurements of (anti-)protons within the BASE collaboration. This updated trap system has been designed to cool single protons to their motional ground state, a key feature for the implementation of quantum logic spectroscopy on (anti-)protons in Penning traps. For this purpose, a double-well potential will be generated in our trap system in order to implement free Coulomb coupling between a single proton and a $^9Be^+$ ion, allowing sympathetic cooling of single protons, as well as a spin-motion SWAP gate for spin state detection. The application of these techniques to antiprotons later will allow to increase the sampling rates of current (anti-)proton g-factor measurements, and thus contribute to the search for CPT violating coefficients acting on baryons in the Standard Model extension.

International Conference on Exotic Atoms and Related Topics and Conference on Low Energy Antiprotons (EXA-LEAP2024)
26-30 August 2024
Austrian Academy of Sciences, Vienna.

https://pos.sissa.it/

PoS(EXA-LEAP2024)102

1. Introduction

The CPT theorem states that any Lorentz-invariant physical system should remain invariant under the combination of charge conjugation (C), parity inversion (P), and time reversal (T). High-precision measurements on particles and their antiparticles have proven to be an excellent way to test the CPT theorem [1, 2], a violation of which would indicate new physics beyond the Standard Model [3]. The BASE collaboration [4] aims to probe the CPT theorem by measuring and comparing elementary properties such as the g-factor and the charge-to-mass ratio [5] of proton and antiprotons to the highest precision. The g-factor is obtained by measuring the cyclotron frequency ω_c and the spin precession Larmor frequency ω_L, $\frac{g}{2} = \frac{\omega_L}{\omega_C}$, of the (anti-)proton. The current record precision of the antiproton g-factor is 1.5 parts-per-billion (ppb) [1] and 0.3 ppb for the proton g-factor [2]. To achieve such high precision, particles are captured in a cryogenic Penning trap at ultra high vacuum in a static magnetic field that ensures radial confinement of ions, while the axial confinement is achieved with static voltages applied to the trap electrodes.

In our experiment [6], we aim to implement quantum logic spectroscopy (QLS) based laser techniques [7] to (anti-)proton spin precession frequency measurements within the BASE collaboration [4]. Since the (anti-)proton spin cannot be accessed with lasers directly, we aim to couple it to the laser-accessible ^{9}Be$^+$ ion via free Coulomb interaction in a double well potential [8, 9]. The proposed scheme works as follows: first, both particles are brought into the ground state by applying resolved-sideband cooling to the ^{9}Be$^+$ ion [10] and sympathetically cooling the (anti-)proton [6]. The ^{9}Be$^+$ ion is prepared in the spin state $|\uparrow\rangle$. Applying a sideband radio-frequency pulse to the (anti-)proton, a quantum of motion is added only if the (anti-)proton spin state is $|\downarrow\rangle$ and spin is flipped [11]. If the quantum of motion was added previously, it will be transferred to the ^{9}Be$^+$ ion in a two-qubit SWAP gate. Then we drive a sideband laser pulse that flips the internal state of the ^{9}Be$^+$ ion only if the motional state was $|1\rangle$ previously. Finally, we apply a resonant laser beam and we observe fluorescence if the ion state was $|\uparrow\rangle$ indicating that the (anti-)proton spin was $|\uparrow\rangle$. Such measurement cycle is aimed to be performed in a sub-second regime allowing fast and precise g-factor measurements [6].

2. Current status and Penning trap update

We have already built and commissioned a Penning trap apparatus, consisting of a 5-Tesla superconducting magnet and a cryo-mechanical structure incorporating laser access into the trap stack for manipulating single ^{9}Be$^+$ ions [12, 13]. Additionally, we have demonstrated key steps in the proposed quantum logic cooling and detection scheme [6], including control of the cooling ion [12, 13], a novel laser system for Raman transitions [14], sideband spectroscopy [13], fast adiabatic ion transport [15] and, most recently, ground state cooling of a single ^{9}Be$^+$ ion [10]. The next step is to demonstrate the quantum logic spectroscopy protocol first with a pair of ^{9}Be$^+$ ions [16] and then with a single ^{9}Be$^+$ ion and a proton [12]. A key feature for this is our ability to produce a double-well potential in our trap in order to implement free Coulomb coupling. Although this feature has already been studied in our macro-coupling trap of 8-mm inner diameter [12, 16], the large separation between the two potential minima produced by this large trap has prevented us from observing any coupling due to low coupling rates, which is given by

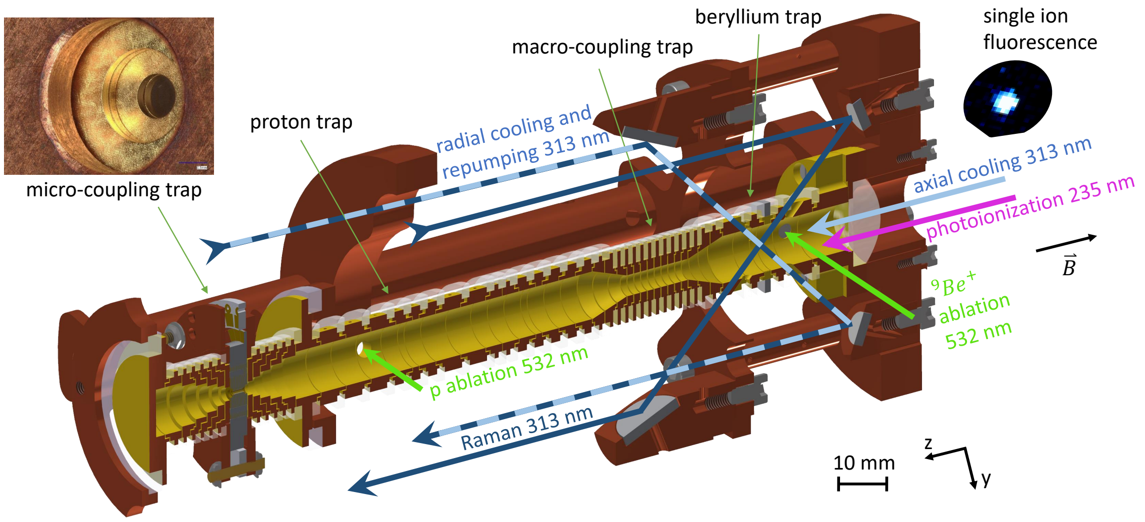

Figure 1: A cross-section view of our updated Penning trap stack. The trap stack consists of cylinder-shaped electrodes made of gold-plated oxygen-free high thermal conductivity (OFHC) copper, electrically insulated by sapphire rings. Beryllium ions are produced by ablation using a 532-nm laser (green arrow) in the beryllium trap. A 235-nm axial photoionization laser beam (dark purple arrow) is also guided into the trap for resonant ion production. $^9Be^+$ ions are cooled using intensity gradient with a radial Doppler laser beam (dashed light blue arrow) entering the trap at a 45° angle. An additional axial Doppler laser beam (solid light blue arrow) will allow to improve our cooling performance. At the top right, the fluorescence image of a single $^9Be^+$ ion in our CCD camera is shown. For this end, a lens at the end of the trap stack is used to collect the fluorescence photons. Four mirrors are used to guide the two Raman laser beams (dark blue arrows) into the trap. The Raman laser beams are guided in a 90° crossed-beam configuration resulting in an effective wave-vector difference along the axial direction in order to drive Raman transition of the $^9Be^+$ ion by coupling the axial mode to the internal modes of the ion [14]. Protons will also be produced by ablation using a 532-nm laser (green arrow) in the proton trap. The particles can be shuttled adiabatically through the trap stack during the measurement schemes by using our experimental control system [15]. At the top left, a photo of the micro-coupling trap is shown. Further details in the text.

$$\Omega_{ex} = \frac{q_a q_b}{\pi \epsilon_0 s_0^3 \sqrt{m_a m_b} \sqrt{\omega_a \omega_b}}, \tag{1}$$

where ϵ_0 is the vacuum permittivity, s_0 is the distance between coupling potential minima, m_a and m_b are the masses of the oscillating particles, ω_a and ω_b are the oscillation frequencies, q_a and q_b are their charges.

In order to produce a double-well potential with a shorter separation of potential minima, smaller traps have become advantageous. For this reason, we have designed and manufactured two new coupling traps: a new macro-coupling trap with an inner diameter of 4 mm, that will enable us to halve the distance between the ions and hence increase the coupling rate by a factor of 8, and a micro-coupling trap with an inner diameter of 800 µm, that will increase the coupling rate by a factor of 1000. For the latter, microfabrication techniques have been used. The electrodes of the micro-coupling trap are made of fused silica substrate by selective laser-induced etching. To structure the electrodes, photolithography is used, and they are covered with a gold layer by electroplating techniques.

Figure 1 shows the upcoming iteration of our Penning trap stack with the two new coupling traps. To produce and trap protons, we will use the proton trap section. Here, we include a tantalum target in one of the electrodes since tantalum is a good hydrogen absorber [17]. To decrease single $^{9}\mathrm{Be}^{+}$ ion production time, we included an axial photoionization laser system along the imaging beam path. Currently, Doppler cooling is performed using intensity gradient cooling with a single Doppler beam going into the trap at a 45° angle, cooling all three motions at the same time. We also plan to include an axial cooling beam which will also be guided into the trap along the imaging beam path [18]. The upgrades and changes to the imaging system necessary to allow the access of the two new beams into the trap, including a new lens system, have been successfully implemented.

3. Coupling simulations

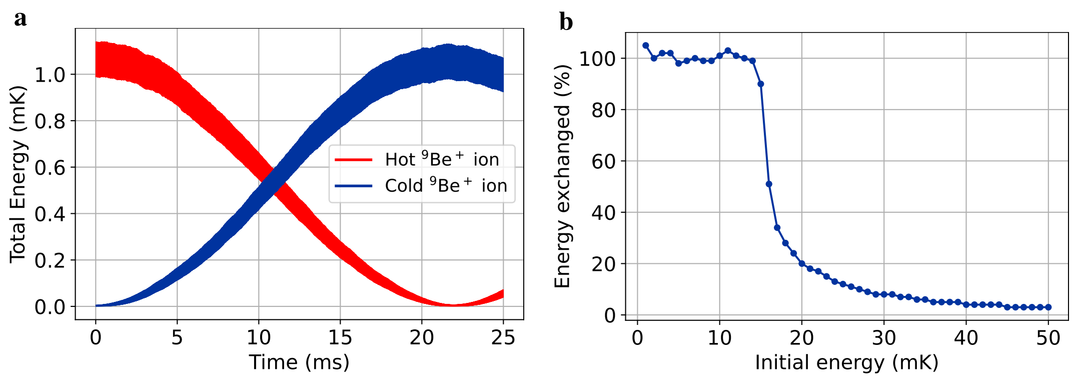

Figure 2: Coupling simulation results. **a**, The plot shows the evolution of the total energy of a $^{9}\mathrm{Be}^{+}$ ion initially near the Doppler limit (red) and a $^{9}\mathrm{Be}^{+}$ ion in the ground state (blue). The energy is completely exchanged after the expected exchange time of 22 ms, as described by equation 1. **b**, The blue dots show the maximum energy exchange for different initial energies of a $^{9}\mathrm{Be}^{+}$ ion, while the other $^{9}\mathrm{Be}^{+}$ ion is initially in the ground state. The dots are connected to guide the eye. Transfers above 100% are due to noise.

As a proof of principle, we started simulating the coupling dynamics of two $^{9}\mathrm{Be}^{+}$ ions in our 4-mm macro-coupling trap. For the target coupling potential $\Phi(z)$, we considered an analytical expression for which we expected a complete energy exchange. We considered a separation of potential minima of $s_0 = 0.7\,\mathrm{mm}$ and oscillation frequencies of $\omega_a = \omega_b = 100\,\mathrm{kHz}$. To find electrode voltages $V_1, V_2, ..., V_n$ that generate a coupling potential that approaches $\Phi(z)$ at positions $z_1, z_2, ..., z_k$, we solved the following matrix equation,

$$\begin{pmatrix} \phi_1(z_1) & \phi_2(z_1) & \dots & \phi_n(z_1) \\ \phi_1(z_2) & \phi_2(z_2) & \dots & \phi_n(z_2) \\ \vdots & \vdots & \ddots & \vdots \\ \phi_1(z_k) & \phi_2(z_k) & \dots & \phi_n(z_k) \end{pmatrix} \begin{pmatrix} V_1 \\ V_2 \\ \vdots \\ V_n \end{pmatrix} = \begin{pmatrix} \Phi(z_1) \\ \Phi(z_2) \\ \vdots \\ \Phi(z_k) \end{pmatrix}, \tag{2}$$

where $\phi_i(z)$ are potentials of individual electrodes i with the voltage set to 1 V. These values were obtained by simulating the trap using COMSOL [19]. Using the coupling potential generated by the trap voltages, we calculated the evolution of oscillating particles in the coupling potential using the Runge-Kutta method. At each timestep, the electrostatic forces due to the Coulomb interaction and the coupling potential acting on the oscillating point charges were calculated. Additionally, electric white noise was simulated as a random force acting on the ions, with an estimated standard deviation of $\sigma_E = 10^{-4}\,\mathrm{V\,m^{-1}}$ [10]. We initialized the simulation with one ion at 1 mK, near the theoretical Doppler limit, and the other ion in the ground state. Figure 2a shows the energy transfer between the two ions. As shown in figure 2b, we also tested the same potential for larger initial energies of the hotter $^9\mathrm{Be}^+$ ion. Due to increasing anharmonicities at larger oscillation amplitudes, a sharp drop from the complete energy transfer was observed for initial energies above 14 mK. We are also currently investigating the effects of anharmonicities on the coupling of a $^9\mathrm{Be}^+$ ion to an (anti-)proton, initially in equilibrium with the trap temperature of 4 K.

4. Summary and acknowledgments

We have discussed the (anti-)proton g-factor measurement techniques using the QLS approach that would allow to increase the sampling rates of the current g-factor measurements. Furthermore, we have presented our new Penning trap stack and our laser systems upgrades that will allow us to trap and couple a proton and a single $^9\mathrm{Be}^+$ ion in a double well potential. Finally, we discussed $^9\mathrm{Be}^+$-$^9\mathrm{Be}^+$ coupling simulations and determined parameters to perform coupling experiments.

We are grateful for discussions with J.J. Bollinger, R.C. Thompson and P.O. Schmidt. This work was supported by PTB, LUH, and DFG through the clusters of excellence QUEST and QuantumFrontiers as well as through the Collaborative Research Center SFB1227 (DQ-mat Project-ID 274200144) and ERC StG "QLEDS". We also acknowledge financial support from the RIKEN Pioneering Project Funding and the MPG/RIKEN/PTB Center for Time, Constants and Fundamental Symmetries.

References

[1] Smorra C, Sellner S, Borchert M J *et al.* 2017 *Nature* **550** 371–374 ISSN 1476-4687 URL https://doi.org/10.1038/nature24048

[2] Schneider G, Mooser A, Bohman M *et al.* 2017 *Science* **358** 1081–1084 (*Preprint* https://www.science.org/doi/pdf/10.1126/science.aan0207) URL https://www.science.org/doi/abs/10.1126/science.aan0207

[3] Colladay D and Kostelecky V A 1998 *Phys. Rev. D* **58**(11) 116002 URL https://link.aps.org/doi/10.1103/PhysRevD.58.116002

[4] Smorra C, Blaum K, Bojtar L *et al.* 2015 *The European Physical Journal Special Topics* **224** 3055–3108 ISSN 1951-6401 URL https://doi.org/10.1140/epjst/e2015-02607-4

[5] Borchert M J, Devlin J A, Erlewein S R *et al.* 2022 *Nature* **601** 53–57 ISSN 1476-4687 URL https://doi.org/10.1038/s41586-021-04203-w

[6] Cornejo J M, Lehnert R, Niemann M *et al.* 2021 *New Journal of Physics* **23** 073045 URL https://dx.doi.org/10.1088/1367-2630/ac136e

[7] Schmidt P O, Rosenband T, Langer C *et al.* 2005 *Science* **309** 749–752 (*Preprint* https://www.science.org/doi/pdf/10.1126/science.1114375) URL https://www.science.org/doi/abs/10.1126/science.1114375

[8] Heinzen D J and Wineland D J 1990 *Phys. Rev. A* **42**(5) 2977–2994 URL https://link.aps.org/doi/10.1103/PhysRevA.42.2977

[9] Wineland D J, Monroe C, Itano W M *et al.* 1998 *J. Res. Natl. Inst. Stand. Technol.* **103**(3) 259–328 URL https://https://tf.nist.gov/general/pdf/1275.pdf

[10] Cornejo J M, Brombacher J, Coenders J A *et al.* 2024 *Phys. Rev. Res.* **6**(3) 033233 URL https://link.aps.org/doi/10.1103/PhysRevResearch.6.033233

[11] Nitzschke D, Schulte M, Niemann M, Cornejo J M, Ulmer S, Lehnert R, Ospelkaus C and Hammerer K 2020 *Advanced Quantum Technologies* **3** 1900133 (*Preprint* https://onlinelibrary.wiley.com/doi/pdf/10.1002/qute.201900133) URL https://onlinelibrary.wiley.com/doi/abs/10.1002/qute.201900133

[12] Niemann M, Meiners T, Mielke J *et al.* 2019 *Measurement Science and Technology* **31** 035003 URL https://dx.doi.org/10.1088/1361-6501/ab5722

[13] Cornejo J M, Brombacher J, Coenders J A, Von Boehn M, Meiners T, Niemann M, Ulmer S and Ospelkaus C 2023 *Physical Review Research* **5** 033226 ISSN 2643-1564

[14] Mielke J, Pick J, Coenders J A *et al.* 2021 *Journal of Physics B: Atomic, Molecular and Optical Physics* **54** 195402 URL https://dx.doi.org/10.1088/1361-6455/ac319d

[15] Meiners T, Coenders J A, Brombacher J *et al.* 2024 *The European Physical Journal Plus* **139** 262 ISSN 2190-5444 URL https://doi.org/10.1140/epjp/s13360-024-04936-3

[16] Meiners T, Niemann M, Mielke J *et al.* 2018 *Hyperfine Interactions* **239** 26 ISSN 1572-9540 URL https://doi.org/10.1007/s10751-018-1502-6

[17] Velardi L, Delle Side D, Krasa J and Nassisi V 2014 *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* **331** 20–22 ISSN 0168-583X 11th European Conference on Accelerators in Applied Research and Technology URL https://www.sciencedirect.com/science/article/pii/S0168583X1400113X

[18] Schaper J 2023 *A laser system setup for production and cooling of 9Be+ in a cryogenic Penning trap for precision measurements with (anti-)protons* Master's thesis Leibniz Universität Hannover

[19] 2024 COMSOL Multiphysics® version 6.2. COMSOL AB, Stockholm, Sweden.

PoS(EXA-LEAP2024)102