Towards Sympathetic Cooling of Single (Anti-)Protons

Teresa Meiners · Malte Niemann · Johannes Mielke · Matthias Borchert · Nicolas Pulido · Juan M. Cornejo · Stefan Ulmer · Christian Ospelkaus

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Abstract We present methods to manipulate and detect the motional state and
the spin state of a single antiproton or proton which are currently under develop-
ment within the BASE (Baryon Antibaryon Symmetry Experiment) collaboration.
These methods include sympathetic laser cooling of a single (anti-)proton using a
co-trapped atomic ion as well as quantum logic spectroscopy with the two parti-
cles and could be implemented within the collaboration for state preparation
and state readout in the antiproton g-factor measurement experiment at CERN. In
our project, these techniques shall be applied using a single $^9$Be$^+$ ion as the atomic
ion in a Penning trap system at a magnetic field of 5 T. As an intermediate step,
a controlled interaction of two beryllium ions in a double-well potential as well as
sympathetic cooling of one ion by the other shall be demonstrated.

Keywords Penning traps · laser cooling · motional coupling · atomic ion ·
g-factor · antiproton

T. Meiners
Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany
Tel.: +49-511-7624656, Fax: +49-511-7622211, E-mail: t.meiners@iqo.uni-hannover.de

M. Niemann, J. Mielke, N. Pulido and J. M. Cornejo
Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany

M. Borchert
Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany
RIKEN, Ulmer Fundamental Symmetries Laboratory, Wako, Saitama 351-0198, Japan

S. Ulmer
RIKEN, Ulmer Fundamental Symmetries Laboratory, Wako, Saitama 351-0198, Japan

C. Ospelkaus
Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany
Physikalisch Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany
1 Introduction

Comparing the magnetic moment of the proton and the antiproton is a stringent test of CPT invariance [1]. The $g$-factor of the proton has been determined with a precision of 0.3 ppb [2] and that of the antiproton with a precision of 1.5 ppb [3]. The $g$-factor can be determined by measuring the free cyclotron frequency $\omega_C$ and the Larmor frequency $\omega_L$, because $g = \frac{2\omega_L}{\omega_C}$. These frequency measurements are performed in Penning traps. The free cyclotron frequency is commonly determined using image current detection and the Larmor frequency by applying the continuous Stern Gerlach effect [4]. An alternative method of determining the Larmor frequency following a proposal by Heinzen and Wineland [5] that enables full control of all motional degrees of freedom of the (anti-)proton is described subsequently. Related ideas could also be implemented using antihydrogen ions cooled by $^9\text{Be}^+$ [6].

2 State preparation and readout of a single (anti-)proton

The experimental sequence described in the following will be carried out in a trap stack composed of four different Penning traps: A laser cooling and detection trap, a Coulomb coupling trap, a spin-motion coupling trap, and a precision trap [7], [8].

For state preparation the $^9\text{Be}^+$ ion and the (anti-)proton are initialized to their motional ground states and at the same time the $^9\text{Be}^+$ ion is prepared in the “spin down” state of two defined (hyperfine) qubit states. For the $^9\text{Be}^+$ ion both is achieved by using laser Doppler cooling, followed by laser sideband cooling [9]. The (anti-)proton ground state is prepared by applying sympathetic cooling via the remote Coulomb interaction in a double-well potential through the beryllium ion. Afterwards, the initial internal spin state of the (anti-)proton is mapped to the motional state with a radio-frequency sideband pulse while at the same time preparing the spin in a known state, depending on the type (red or blue) of sideband used. This motional state is then transferred to the $^9\text{Be}^+$ ion via Coulomb interaction in the double-well potential [10] and mapped to one of the qubit states by applying a motional sideband pulse. Read-out of the qubit state using fluorescence detection reveals the initial spin state of the (anti-)proton [11].

To determine the Larmor frequency of the (anti-)proton the particle is irradiated with radio frequency pulses at different frequencies close to the Larmor frequency to drive a spin flip. After each attempt the spin state of the (anti-)proton is determined as described above. This measurement sequence results in a probability distribution from which the Larmor frequency can be calculated.

3 Current experimental setup for motional coupling of two ions

With our current experimental setup we are aiming for demonstration of motional coupling of two beryllium ions in a Penning trap. The main part of the experimental setup is a cylindrical Penning trap stack that consists of three individual Penning traps. This stack is fixed to a support structure placed inside a vacuum chamber and mounted to a superconducting magnet and a mechanical cryo-cooler.
The magnet provides a homogeneous magnetic field of 5 Tesla. The mechanical cryo-cooler provides two stages, one at a temperature near that of liquid helium to cool the trap stack and another at a temperature near that of liquid nitrogen for shielding the trap stack from thermal radiation.

The trap stack currently placed on the system contains the following individual Penning traps: a laser trap, a coupling trap, and a storage trap. With this system Doppler cooling of a single $^9\text{Be}^+$ ion can be achieved as well as sympathetic cooling of a second $^9\text{Be}^+$ ion via Coulomb interaction in the double-well potential.

For the purpose of Doppler cooling, the laser trap has been designed and built. This trap has optical access for production, manipulation, and imaging of the ion. For production, a pulsed laser operating at 1064 nm and a continuous wave (cw) laser system operating at 235 nm shall be used for ablation and photoionization of beryllium atoms, respectively. For Doppler cooling, repumping, and fluorescence detection a cw laser system operating at 313 nm will be used. Its output beam crosses the trap center at an angle of 45° with respect to the magnetic field direction. The description of the cw laser systems can be found in [8] and [12].

For coupling of the axial modes of motion of two beryllium ions a double-well potential has been engineered in the coupling trap. The axial trap frequency of the two ions, which needs to be equal to achieve efficient energy exchange, has been calculated to be 129 kHz for an ion-to-ion distance of 1.24 mm. Approximating the double-well potential with the potentials of two quantized harmonic oscillators, the energy exchange rate for the motional energy of the ions can be derived [13]:

$$\Omega_{ex} = \frac{q^2}{4\pi\epsilon_0 s_0^3 m \omega_0}$$  \hspace{1cm} (1)

where $q$ is the ion’s charge, $\epsilon_0$ the permittivity of free space, $s_0$ the ion-to-ion distance, $m$ the ion’s mass, and $\omega_0$ the ion’s axial trap frequency. In our case the exchange rate is $10\text{ s}^{-1}$ which results in an exchange time $t_{ex} = \frac{\pi}{2\Omega_{ex}} \approx 157\text{ ms}$ to swap the motional states of the two ions.

4 Summary and prospects

We have described the goals and the current status of an experimental setup to demonstrate quantum logic spectroscopy of (anti-)protons. As a first step, sympathetic cooling of one $^9\text{Be}^+$ ion by another one can be demonstrated using their Coulomb interaction in a double-well potential. In the future this technique shall be applied to single (anti-)protons with a single beryllium ion in its motional ground state prior to carrying out quantum logic spectroscopy.

In order to start experiments with protons, we have already designed and produced a proton source based on electron bombardment of an organic target material.

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