Sympathetic Cooling of Trapped Protons

M. Bohman[a,b], V. Grunhofer[c], C. Smorra[b,c], M. Wiesinger[a], C. Will[a], M. J. Borchert[a,d], J. A. Devlin[b,f], S. Erlewein[b,f], M. Fleck[b], S. Gavranovic[c], J. Harrington[a,b], B. Latacz[b], A. Mooser[a], D. Popper [c], K. Blaum[a], Y. Matsuda[g], C. Ospelkaus[d,e], W. Quint[h], J. Walz[c,i], S. Ulmer[b]

[a] *Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, D-69117 Heidelberg, Germany*
[b] *RIKEN, Fundamental Symmetries Laboratory, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*
[c] *Institut für Physik, Johannes Gutenberg University, Staudingerweg 7, D-55128 Mainz, Germany*
[d] *Institute für Quantenoptik, Leibniz Universität Hannover, D-30167 Hannover, German*
[e] *Physikalisch-Technische Bundesanstalt, D-38116 Braunschweig, Germany*
[f] *CERN, 1211 Geneva, Switzerland*
[g] *Graduate School of Arts and Sciences, University of Tokyo, Tokyo 153-8902, Japan*
[h] *GSI Helmholtzzentrum für Schwerionenforschung GmbH, D-64291 Darmstadt, Germany*
[i] *Helmholtz-Institut Mainz, D-55099 Mainz, Germany*

Efficient cooling of trapped charged particles is essential in fundamental physics experiments, high-precision metrology, and quantum technology. Some of the most precise measurements performed with matter-antimatter pairs rely on particles prepared far below typical 4.2 cryogenic temperatures [1, 2]. Even these low temperatures limit the precision of experiments with single, trapped protons and antiprotons [3] and novel experimental techniques have long been pursued that would extend sympathetic laser cooling to the (anti)proton and other systems with inaccessible laser cooling transitions [4] such as highly charged ions or molecular ions. Here we demonstrate the first sympathetic laser cooling of a trapped proton by coupling to laser cooled Be^+ ions via an LC circuit that resonantly increases the energy exchange time. Using two coaxial Penning traps separated by over 9 cm, this work simultaneously constitutes the first realization of sympathetic cooling via image current interactions and the first cooling of a mode of a macroscopic resonator by laser cooled ions. We demonstrate these results in three independent measurements that show the unique frequency response of the coupled ion-proton-resonator system, energy exchange far beyond thermal equilibrium, and the reduction in the total energy of the system when the resonant Be^+ ions are laser cooled. Using only a single laser, our technique can be extended to cool an arbitrary number of particles of any species, stored in far distant traps and can easily improve precision in matter-antimatter comparisons [3] and searches for axion-like dark matter [5, 6].

---

[1] G. Schneider, A. Mooser, M. Bohman, et al. Double-trap measurement of the proton magnetic moment at 0.3 parts per billion precision. Science, 358(6366):1081–1084,2017. ISSN 0036-8075. doi:10.1126/science.aan0207.

[2] C. Smorra, S. Sellner, M. J. Borchert, et al. A parts-per-billion measurement of the antiproton magnetic moment. Nature, 550(7676):371–374, 2017. doi:10.1038/nature24048.

[3] M. Bohman, A. Mooser, G. Schneider, et al. Sympathetic cooling of protons and antiprotons with a common end-cap penning trap. Journal of Modern Optics, 65(5-6):568–576, 2018. doi:10.1080/09500340.2017.1404656.

[4] D. J. Heinzen and D. J. Wineland. Quantum-limited cooling and detection of radio-frequency oscillations by laser-cooled ions. Phys. Rev. A, 42(5):2977, 1990.

[5] C. Smorra, Y. V. Stadnik, P. E. Blessing, et al. Direct limits on the interaction of antiprotons with axion-like dark matter. Nature, 575(7782):310–314, 2019. doi:10.1038/s41586-019-1727-9.

[6] J. A. Devlin, M. J. Borchert, S. Erlewein, et al. Constraints on the coupling between axion-like dark matter and photons using an antiproton superconducting tuned detection circuit in a cryogenic Penning trap. Phys. Rev. Lett., 123:123001, Sep 2019.doi:10.1103/PhysRevLett.123.123001.