An Improved Value of the Atomic Mass of the Proton

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The electron, the proton and the neutron are the basic building blocks of atomic matter. The precise knowledge of their properties, e.g. their masses, is of utmost importance for tests of fundamental physics and the current revision of the SI base units.

In this context an experiment dedicated to the determination of the atomic mass of the proton and the neutron has been designed, assembled and commissioned. It is based on the former g-factor experiment for highly charged ions, which provided most stringent tests of bound-state QED by studying the bound-electron g-factors of $^{28}\mathrm{Si}^{13+}$ [1], $^{28}\mathrm{Si}^{11+}$ [2] and the g-factors of the calcium isotopes $^{40}\mathrm{Ca}^{17+}$ and $^{48}\mathrm{Ca}^{17+}$ [3]. Moreover, it delivered the most precise value of the atomic mass of the electron [4]. The new experiment consists of a stack of five individual cylindrical Penning traps, enclosed in a vacuum vessel operated at liquid helium temperature. Various single ions can be trapped at different locations for months.

For the high-precision measurement of the atomic mass of the proton the cyclotron frequency ratio of a single proton, $\nu_c(\mathrm{H}^+)$, and a single highly-charged carbon ion, $\nu_c(^{12}\mathrm{C}^{6+})$, is measured:

$$m(\mathrm{H}^+) = \frac{1}{6}\frac{\nu_c(^{12}\mathrm{C}^{6+})}{\nu_c(\mathrm{H}^+)} m(^{12}\mathrm{C}^{6+}),$$

where the relative uncertainty of $m(^{12}\mathrm{C}^{6+})$ due to the missing electrons and their binding energies is sufficiently small ($\delta m/m = 9\cdot 10^{-14}$).

In order to measure both cyclotron frequencies in the same electric and magnetic field configuration, both ions are transported alternately into a Penning trap, the Measurement Trap (MT), consisting of seven cylindrical electrodes. These electrodes serve to produce an extremely harmonic quadrupole trapping field by cancelling out to a large extent higher orders electric field contributions by properly chosen voltages. By applying exactly the same electric field configuration for both ions with different charge/mass ratio, requires two separate, precisely tuned axial resonators for non-destructive frequency detection. The modified cyclotron frequency is detected via the phase sensitive measurement technique PnA [5].

Aiming for relative precisions of less than $1\cdot 10^{-11}$, magnetic field fluctuations which limit the statistical uncertainty have to be overcome. For this purpose, the simultaneous PnA technique has been developed. Here, the modified cyclotron frequency of a highly-charged ion, $\nu_+(\mathrm{HCI})$, placed in an adjacent Penning trap, the Reference Trap (RT), and the modified cyclotron frequency of the ion of interest in the MT, e.g. of the proton or the carbon ion, are measured simultaneously, which enables dramatically longer phase evolution times. Thus, the two ultra-precise cyclotron frequency ratios: $R_1 = \nu_c(\mathrm{H}^+)/\nu_+(\mathrm{HCI})$ and $R_2 = \nu_c(^{12}\mathrm{C}^{6+})/\nu_+(\mathrm{HCI})$ can be determined and combined to finally derive the desired frequency ratio: $R_1/R_2 = \nu_c(\mathrm{H}^+)/\nu_c(^{12}\mathrm{C}^{6+})$.

At this conference, the new setup will be introduced and the latest results on the atomic mass of the proton will be discussed [6].

References

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