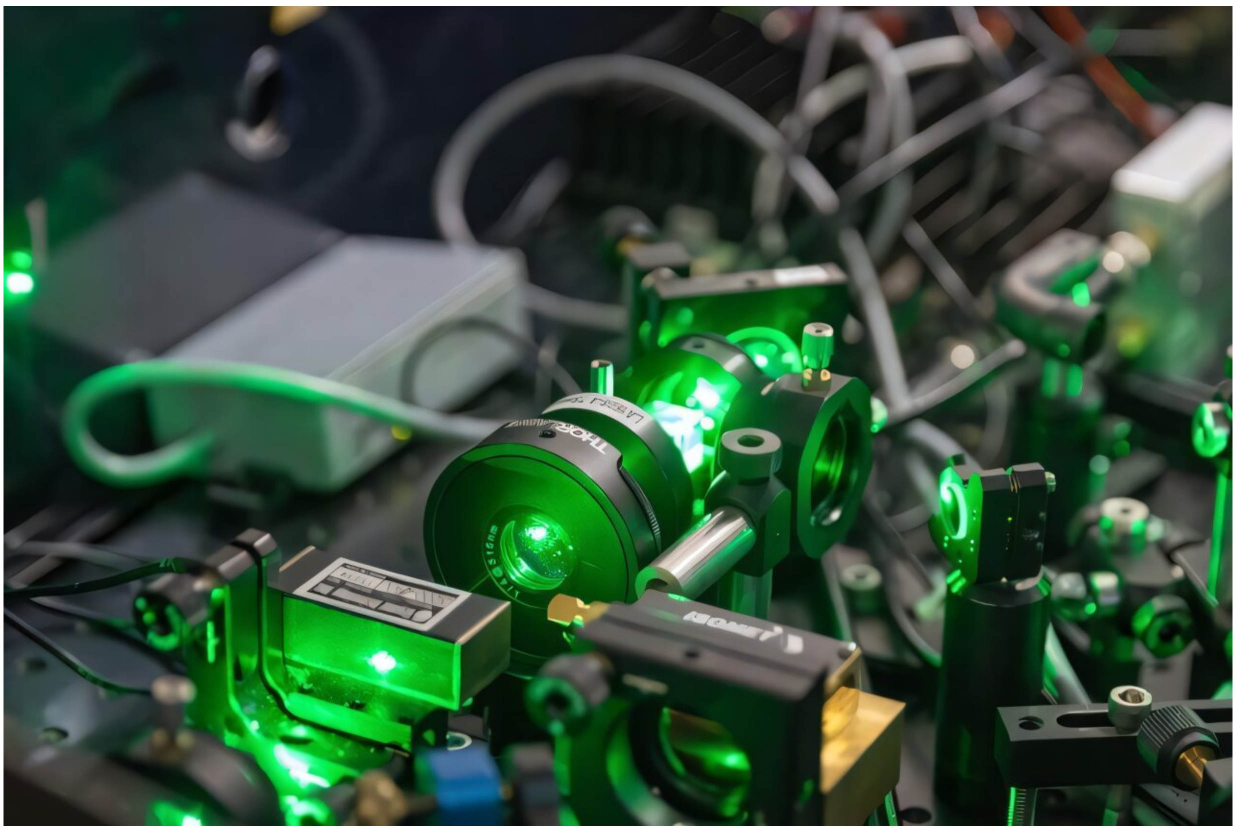
Physicists achieve record precision in measuring proton-to-electron mass ratio with H_2^+

September 9 2025, by Arne Claussen



Detailed view of the experimental setup. The hydrogen molecule ions are cooled by means of laser light to enable subsequent measurements to be taken using laser spectroscopy. Credit: Heinrich-Heine University Duesseldorf

The molecular hydrogen ion H_2^+ is the simplest molecule. This simplicity makes it a perfect study object for physicists, as its properties—for example, its energy levels—can be calculated precisely. In turn, this enables theoretical predictions to be compared with experimental measurements to determine whether the theories reflect reality correctly.

At the Institute for Experimental Physics at HHU, the research group headed by Professor Stephan Schiller Ph.D. is striving for ever greater measurement accuracy. Professor Schiller explains why: "We are searching for 'new physics,' i.e., phenomena, which the widely successful Standard Model of particle physics cannot explain. We are comparing ultra-precise theoretical predictions for H_2^+ with similarly precise experimental measurements to search for the tiniest discrepancies."

Dr. Soroosh Alighanbari, postdoc in the research group and lead author of a new study published in *Nature*, adds, "Any variances we find could point to a new 'fifth force,' which might exist beyond the four fundamental forces we know. Or we could probe the existence of hidden extra dimensions, which could influence gravity at small scales."

The HHU research team uses quantum technologies—ion trapping, laser spectroscopy and laser frequency metrology—to measure H_2^+ transition frequencies. Alighanbari states, "In earlier work, we demonstrated the first-ever direct laser spectroscopy of a vibrational transition in H_2^+. However, the measurement accuracy was limited by the so-called Doppler effect, which broadens spectral lines."

The HHU physicists have now succeeded in vastly improving on the laser spectroscopy results they achieved in the past. Using a special "Doppler-free laser spectroscopy" method developed in Düsseldorf, they were able to eliminate the Doppler effect, which caused distortions in an earlier experiment. They also eliminated other distorting effects caused by external electric and magnetic fields.

"We trap both the molecular ions and laser-coolable atomic ions together," says Alighanbari, explaining the Düsseldorf approach. "The cold atoms sympathetically cool the molecules, slowing their motion dramatically. However, as this was not yet enough to eliminate the Doppler broadening in full, we selected a special spectroscopy geometry, which made this possible."

The physicists can use the measured vibration frequency to calculate fundamental natural constants. These numbers can be found in the equations of quantum mechanics, where they determine, e.g., the energy levels of atoms and molecules. Accordingly, they also determine the frequency of absorbed or emitted light when an atom or molecule transitions between two levels.

The Düsseldorf experiment can be used to determine the ratio of proton mass (mp) to electron mass (me), as the proton mass (mp) is particularly relevant for molecules. Schiller says, "The molecule spectroscopy is particularly well suited for the extremely precise determination of the proton-to-electron mass ratio (mp/me). This dimensionless constant sets the scale for particle-mass effects in molecular vibration and rotational energies."

The researchers determined the mp/me ratio at an uncertainty of just 26 parts per trillion, improving accuracy by three orders of magnitude compared with the earlier measurements. Alighanbari says, "This result not only agrees with Penning-trap mass spectrometry, another leading technique, but even surpasses it in precision."

"Our result is not just about mp/me. It is a stepping stone toward probing fundamental symmetries of nature, especially CPT (charge, parity, time) invariance," says Professor Schiller. "Our approach could eventually enable a much more sensitive CPT test in which we can compare a transition in H_2^+ with its antimatter counterpart. To achieve this, however, 'anti-H_2^+' will need to be synthesized successfully at the European Organization for Nuclear Research (CERN) in Geneva."

Background: Physics beyond the Standard Model

The Standard Model of particle physics describes fundamental particles and forces remarkably well, but profound mysteries remain unsolved: for example, the nature of dark matter—the mass of which makes up the majority of the universe—and dark energy—the effect of which drives the accelerating expansion of the universe. Further unanswered questions include: Why is gravity so weak? Why do neutrinos have mass? And why is the universe overwhelmingly made up to matter and not anti-matter?

In the future, it will be possible to compare H_2^+ with its antimatter counterpart in order to investigate matter-antimatter asymmetry in the universe. If the molecules do not behave in exactly the same way spectroscopically—physicists refer to this as a violation of CPT invariance, which predicts that matter and antimatter should behave identically—this may permit conclusions to be drawn about why a universe filled solely with matter remained after the Big Bang.

More information: S. Alighanbari et al, High-accuracy laser spectroscopy of H_2^+ and the proton–electron mass ratio, *Nature* (2025). DOI: 10.1038/s41586-025-09306-2

Provided by Heinrich-Heine University Duesseldorf