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Quantum logic spectroscopy of the hydrogen molecular ion

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I will present our latest results [1], implementing pure quantum state preparation, coherent manipulation, and non-destructive state readout of the hydrogen molecular ion H_2^+.

H_2^+ is the simplest stable molecule, and its structure can be calculated ab initio with high precision using quantum electrodynamics. By comparing the calculations with experimental data, fundamental constants can be determined, and the validity of the theory itself can be tested. However, challenging properties such as high reactivity, low mass, and the absence of rovibrational dipole transitions have thus far strongly limited spectroscopic studies of H_2^+.

We trap a single H_2^+ molecule together with a single beryllium ion using a cryogenic Paul trap apparatus, achieving trapping lifetimes of 11 h and ground-state cooling of the shared axial motion [2]. With this platform we have recently implemented Quantum Logic Spectroscopy of H_2^+. The H_2^+ molecule is produced in a chosen rovibrational state using resonance-enhanced multiphoton ionization. We use quantum-logic operations between the molecule and the beryllium ion for the preparation of single hyperfine states and non-destructive state readout. In the lowest rovibrational state of ortho-H_2^+ (rotation $L = 1$, vibration $\nu = 0$), we achieve a combined state-preparation and readout fidelity of 66.5(8)%. We demonstrate Rabi flopping on several hyperfine transitions using stimulated Raman transitions and microwaves. Utilizing a magnetic field insensitive hyperfine transition driven with a microwave, we observe sub-Hz linewidths and statistical uncertainties in the mHz range.

We are now performing a systematic measurement of the hyperfine structure which will provide a stringent test of state-of-the-art molecular theory and might enable putting an improved bound on a possible tensor force between the two constituent protons of the H_2^+ molecule [3].

Our results pave the way for high-precision rovibrational spectroscopy of single H_2^+ molecules, which would enable tests of quantum electrodynamics, metrology of fundamental constants such as the proton-electron mass ratio, and the implementation of an optical molecular clock based on the simplest molecule in nature.

[1] D. Holzapfel et al., Phys. Rev. X 15, 031009 (2025).
[2] N. Schwegler et al., Phys. Rev. Lett. 131, 133003 (2023).
[3] N. F. Ramsey, Physica 96A, 285 (1979).

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