Title：

Progress on the precision spectroscopy study with ions

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Abstract:

With the development of cold atomic physics and laser technology, the study on atomic precision spectroscopy is greatly developed in the recent two decades. Constants with higher accuracy are obtained, and the fundamental physical laws are tested with higher precision. The above developments help us to better understanding the universe, or searching for new physics. Meanwhile, the performance and application of the time and frequency standards based on atomic precision spectroscopy are also greatly improved and extended.

This report describes our recent progress on ion-based precision spectroscopy.

(1) The Development of ion optical frequency standards and the implementation on precision measurements

By solving the problems such as the stable trapping and effective cooling of single ions, development of ultra-narrow linewidth lasers and experimental environmental control (including electric, magnetism, vibration, temperature, etc.), the Ca^+ ion optical frequency standard with systematic uncertainty of 5.5×10^{-17} and stability of 7×10^{-17} was developed in 2015[1]. Then, through further suppression of micromotion, blackbody radiation and servo error, the systematic uncertainty was improved to 2.2×10^{-17}, and the stability was improved to 6.3×10^{-18} at an averaging time of 500000 s in 2019[2]. Recently, a liquid-nitrogen-cooled cryogenic Ca^+ ion optical frequency standard has been developed, for further suppress the blackbody radiation, with a systematic uncertainty of 3×10^{-18} in 2021[3].

Meanwhile, a transportable Ca^+ ion optical clock with a systematic uncertainty of 1.3×10^{-17}, and an operating uptime rate of >75% has been developed, the clock has been successfully transported from Wuhan to the National Institute on Metrology (NIM) in Beijing, with a distance of > 1200 km[4].

The absolute frequency of the Ca^+ ion optical transition was measured by using the transportable Ca^+ ion optical clock, by both referenced to the SI s and a Cs fountain clock in NIM, with uncertainties at the 10^{-16} and 10^{-15} levels, respectively[4]. The measurements were adopted at the 22nd meeting of the Consultative Committee for Time and Frequency (CCTF), the International Bureau of Weights and Measures on March 19, 2021, at the meeting, the calcium ion optical transition was recommended as a new reference for the secondary representation of the SI s by the CCTF.

The frequency comparison of two Ca^+ ion optical frequency standards at different heights has been taken for the measurement of the gravitational shift. The tests on the Lorenz invariance with uncertainty at the 10^{-18} level have also been made with the frequency comparison of two Ca^+ ion optical frequency standards.

We have demonstrated experimentally the existence of magic wavelengths and have determined the ratio of oscillator strengths for a single trapped ion. Two magic wavelengths near 396 nm for the Ca^+ clock transition have been measured simultaneously with high precision and the ratio with a deviation of less than 0.5%. The measurement of these magic wavelengths paves the way to building all-optical trapped ion clocks [5].

(2) Precision spectroscopy on highly charged nickel ions and lithium ions (few electrons system)

With the combination of studies on both the experiments and the theory, the preliminary research on the optical frequency standards based on highly charged ions (HCI) has been made: a small-size high-temperature superconducting electron beam ion trap (EBIT) was developed, and the wavelengths of multiple clock transitions for highly charged nickel ions was measured, with uncertainties of 1-2 orders of magnitude smaller than the recommended values on the NIST database[6].

A stable ion beam source has been developed, and both the fine structure and the ultrafine structure splitting for 2S and 2P states of $^{7}Li^{+}$ ions have been accurately measured by the saturation absorption technique, with accuracies less than 100 kHz. The measurement accuracies have been improved by an order of magnitude compared to the early work [7]. Combined with the theoretic study, the Zemach radius of the lithium core has also been determined, confirming that "the Zemach radius of the lithium 6 core is 40% smaller than that of the lithium 7 core" [8].

References:

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