Atomic Clocks - How well can we measure time?

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Over the last years atomic clocks have achieved better and better precision with remarkable results. By now the best atomic clocks loose less than a second over the whole age of the universe which corresponds to a relative time uncertainty of the order of 10^{-18}. This article will briefly describe two research fields of time and frequency metrology. In addition, the history of atomic clocks together with the newest generation of optical clocks is outlined.

With the invention and development of atomic clocks scientists can test the big theories such as the Standard Model or General Relativity. In 2010 the National Institute of Standards and Technology (NIST) reported a frequency measurement of a certain atomic transition of two Al^{+} optical clocks [1]. One clock was raised by 33 cm within the earth gravitational field. As a result a change of the relative frequencies of $(4.1 \pm 1.6) \times 10^{-17}$ was measured. This effect can be explained by the gravitational time dilation which is a consequence of General Relativity. The Standard Model (SM) can also be tested. For example, researchers can now investigate a possible variation of the fine-structure constant α over space and time. Based on astronomical observations, theories „Beyond the SM“ predict a shift of the order of $\dot{\alpha}/\alpha \approx 10^{-19}\,\mathrm{yr}^{-1}$ for earthbound experiments [2, 3, 4]. To verify this prediction certain atomic transitions of atoms or ions with different α-sensitivities can be probed. Due to their low relative uncertainties, atomic clocks are used to compare the frequency measurement. In an experiment, Rosenband *et al.* [5] compared two atomic clocks based on mercury and aluminium ions over a year. No significant deviation of α to the order of $10^{-17}\,\mathrm{yr}^{-1}$ was found. To overcome this limit and to finally test the prediction, highly charged ions (HCI) are used which have an enhanced α-sensitivity [6].

The beginning of the era of atomic clocks started with the so-called Essen clock [7]. 1995 Louis Essen and Jack Perry developed the first accurate caesium (Cs) based atomic clock with a relative uncertainty of the order of 10^{-10} (see figure 1). In 1967 the International Bureau of Weights and Measures defined the second with respect to the unperturbed caesium-133 atom. According to this definition, a second equals to the time duration of 9 192 631 770 periods of the radiation corresponding to the hyperfine-transition of the groundstate [8]. In the 90s atomic fountain clocks were invented. This setup has improved the application of the Ramsey Resonance Method obtaining much narrower spectroscopic linewidths [9]. With the development of the optical frequency comb [10] around 2000 scientists started to use optical transitions (red markers) rather than microwave transitions (blue markers). Together with lasercooling and new trapping techniques, optical clocks reached lower relative uncertainties. In 2019 NIST reported an optical clock based on quantum logic spectroscopy with a trapped aluminium ion with stunning 9.4×10^{-19} uncertainty [11] which is at the moment one of the best achievable precisions. However, the workhorses generating the International Atomic Time (TAI) and Universal Coordinated Time (UTC) are still Cs based atomic clocks. Nevertheless, the advantage of optical transitions might lead to a redefinition of the second.

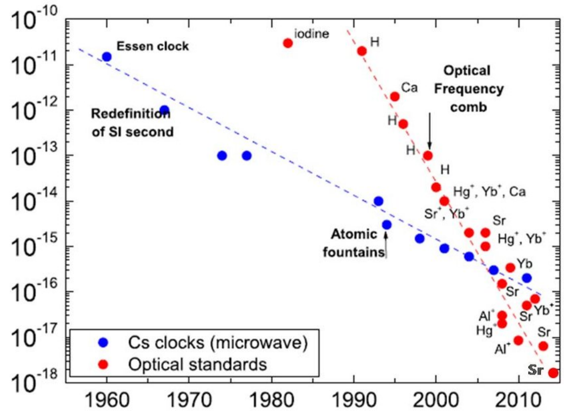

Figure 1: Atomic clocks with their relative uncertainties and their year of invention [12].

To answer the question of this article, atomic clocks can be used for high precision measurements with relative uncertainties of the order of 10^{-18} or even below, making them suitable for testing our well known physical theories.

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