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Frequency Measure below the 10^{-11} Level in Few Microseconds for Antiprotonic Helium Spectroscopy

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Metastable antiprotonic helium is an exotic atom composed of a helium nucleus, an electron, and an antiproton in a Rydberg state. By measuring the transition frequencies of this atom by sub Doppler two-photon laser spectroscopy, the antiproton-to-electron mass ratio can be determined to high precision which can then be compared to the proton value [1]. Any deviation, however small, would indicate that this fundamental symmetry of nature is broken.

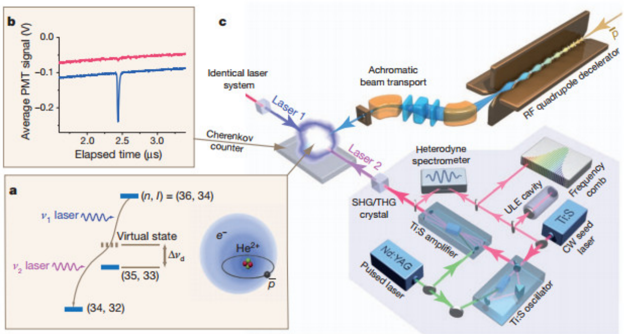

Figure 1. Frequency chain that is used to refer the probing lasers to a primary frequency standard. A Nd:YAG laser pumps the Ti:Sa laser; the ultrastable ULE cavity acts as flywheel and the frequency comb closes the gap with the local RF reference. The latter is disciplined by GNSS. The figure is from [1].

The ASACUSA collaboration at CERN will utilize the new ELENA storage ring [2] that has the potential to carry out these measurements at an improved level. The experiment synthesizes samples of antiprotonic helium by utilizing a pulsed beam of antiprotons that arrive from ELENA every 2 minutes; once formed, some of the long-lived states of the atom contain antiprotons for up to 10 μs, in the course of which they are probed by two Ti:Sapphire lasers. For proper spectroscopy, during the microsecond lifetime, it is necessary that the lasers have a frequency uncertainty as low as possible: at the level of 10^{-11} or better. This requirement, quite relaxed at first sight, is very stringent, since it corresponds to a time fluctuation of a few tens of attoseconds.

In this work, we will show how to approach this problem, how to analyze the frequency chain reported in Figure 1 and how to calculate its contribution to the frequency uncertainty. We will consider the role of the hard sampling induced by the very short lifetime together with the long repetition period; we will discuss which estimator between Allan and classical variances is more suitable; we will derive the formulae for calculating the contribution of each term in the polynomial-law model of the noise. Finally, we will use these tools to provide a noise budget for different configurations in order to understand which one is better for present and future needs.

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2. Gamba, D. et al. ELENA commissioning, in Proceedings of North American Particle Accelerator Conference NA-PAC2019, Lansing MI, USA (2019). https://doi.org/10.18429/JACoW-NAPAC2019-WEYBB1