

Effect of Helium Contamination on Rubidium Clocks – A Possible Error Source for Absolute Gravimeters and Kibble Balances

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Summary: When a Kibble balance is operated at highest accuracy level, often a Programmable Josephson Voltage Standard (PJVS) and a Free-Fall Absolute Gravimeter are located in the same room. The helium used in PJVS systems can evaporate into the laboratory air, potentially contaminating the rubidium clock used by the gravimeter. This contamination affects the absolute frequency of the clock and can lead to wrong measurements of the free-fall acceleration, and, as a consequence, wrong determination of the mass.

Keywords: Kibble balance, rubidium clock, frequency shift, mass determination, free-fall acceleration

Introduction

Since the re-definition of the SI unit kilogram in 2019, the Kibble balance [1] is one possible experiment to realize the unit at highest accuracy level. Because the Kibble balance compares the weight of a mass piece to an electro-magnetic force, the knowledge of the local acceleration due to free-fall (gravity) must be known to high accuracy. The accuracy of the most precise Kibble balances is at a relative level of 1×10^{-8} . For the force comparison a Kibble balance needs accurate timing, be it for velocity measurements or synchronization of data acquisition systems. Also, the absolute gravimeter requires accurate timing, as it measures the free-fall acceleration via laser interferometric length measurements, combined with accurate time stamps for all the measured positions along the free-fall trajectory. On the other hand, for measurements of voltage at the relative 1×10^{-9} level and better, a Programmable Josephson Voltage Standard (PJVS) is usually used in Kibble balance experiments. Those PJVS require liquid helium for cooling. An evaporation of some helium during operation or preparation of the measurement is unavoidable. The helium content in the laboratory room will thus increase, which can have significant negative effects on the frequency accuracy of a rubidium clock, as reported in the literature (see, e.g. [2]). Such clocks are usually used in free-fall absolute gravimeters, especially of kind FG5/X, from the company Microg-LaCoste, CO, USA. A helium-induced frequency shift has been observed and reported, e.g. in [3] or [4]. However, also for other components in the Kibble balance experiments, rubidium clocks can be used, e.g. for data acquisition systems or for the PJVS itself.

The Physikalisch-Technische Bundesanstalt (PTB), the German national metrology institute, is developing a compact Kibble balance, called

Planck-Balance [5], for industrial applications. To this end, a PJVS is run in the laboratory of the Planck-Balance. At the same time, an FG5X gravimeter is located in the same lab room. Recently, we noticed a rapid increase in the absolute frequency of the rubidium clock, which is integrated in the FG5X, while a PJVS was in operation. In this short article, we report on the observed details.

Effect of Helium Contamination on Rubidium Clocks

The impact of helium on rubidium clocks is known among specialists. For example, in [3] or [4] this issue was reported for gravimeters. In [2] the authors investigated this effect systematically for different kinds of noble gases. Therein, it is stated that the effect is a result of the collisions of the Rb atoms with the noble gas atoms. In the case of He (as well as for Ne) atoms this shift is always positive, while for other noble gases (Ar, Kr, Xe) it is negative. Measured cross sections agree very well with a pseudo-potential model, as the authors reported. Thus, the effect can be theoretically predicted and quantified.

Observations in the Laboratory

In the Planck-Balance laboratory at the PTB we regularly perform measurements of the local free-fall acceleration with our free-fall absolute gravimeter FG5X-263, or we make investigations of it. For those measurements we usually either use PTB's 10 MHz signal that is provided via an optical fiber to our lab room, or we lock the gravimeter's rubidium clock to a GPS. For our Planck-Balance we also have a PJVS in the same lab, but during the last few months, the PJVS was not in operation, so that no helium dewar was in the lab.

End of October this year, for reasons of high-accuracy voltage measurements of the Planck-

Balance, the PJVS was prepared with a dewar of liquid helium. During this time the gravimeter was running as well, however, with the rubidium clock still locked to a GPS. After the gravimeter measurements were finished, the GPS was disconnected from the gravimeter, and in the following an increase of the absolute frequency was observed (see fig. 1). In the beginning, we assumed that the clock was broken, as the relative drift was on the order of $5 \times 10^{-10} \text{ d}^{-1}$, a rate that is very high, when compared to the clock specifications. Note that a positive relative bias of 5×10^{-10} in the clock frequency results in an error of $-1 \mu\text{Gal}$ (or 1×10^{-9} relative) in the measured gravity.

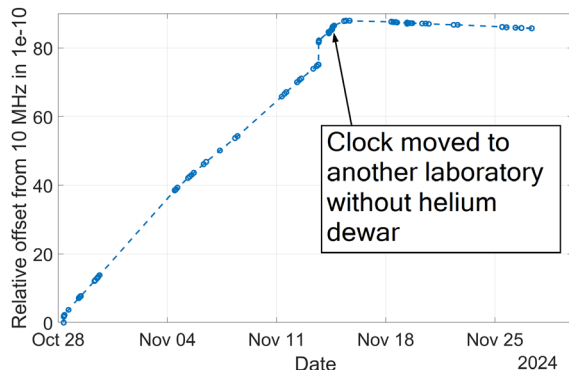


Fig. 1: The clock shows a rapid increase of its absolute frequency. The drift amounts to about $4 \times 10^{-10} \text{ d}^{-1}$. After the clock was moved to another room (see insert), the positive drift ceased, and a negative drift started, with an approximate rate of $-0.2 \times 10^{-10} \text{ d}^{-1}$.

Helium contamination was initially ruled out, as the dewar was connected to a silicone hose discharging the evaporated helium outside. It was assumed that this setup would prevent any significant helium concentration from accumulating in the room. But since the drift was positive, as the theory predicts, we decided to move the clock to another room to see if the effect diminishes or even reverses. In the following, first a further increase of the clock frequency was observed for one day, reaching a maximum of 87.9×10^{-10} of relative frequency offset (which is equivalent to a gravity error of about $-17.6 \mu\text{Gal}$ —resulting in a relative error of 17.6×10^{-9} in a mass determination with a Kibble balance). After that a constant, but very slow decrease by about $2 \times 10^{-11} \text{ d}^{-1}$ set in, which is lasting since then. This fact suggests that the rubidium clock was not contaminated by a sudden surge, but that the helium diffused into the glass cell at a steady rate. Assuming a linear drop in frequency, it will probably take over a year for the frequency to return to exactly 10 MHz. This rate, however, agrees quite well with a time constant of 90 to 100 days, as reported by [4]. For these reasons, we assume that the observed frequency devia-

tion actually comes from the helium.

Conclusion

Although helium contamination-induced frequency shifts of rubidium clocks is known in clock community, and partly also in gravity community, it might not be well known to groups working on Kibble balances. In such experiments, the effect is of great importance, as usually in the same laboratory, where the mass is determined, a PJVS is operated with liquid helium. This cannot only introduce a bias in the gravity determination with the gravimeter, but also to the velocity determination of the Kibble experiment, when in this case also a rubidium clock is used. In our case, a two-week contamination of the rubidium clock by helium, with normal operation of a PJVS and a room size of approx. 90 m^3 , led to a relative frequency error of 87.9×10^{-10} . If this error were to be disregarded in a mass determination with the Kibble balance, the relative error in the mass determination would be around 17.6×10^{-9} , i.e. more than the combined measurement uncertainties of the best Kibble balances worldwide. Moreover, the real amount of evaporated helium can easily be underestimated, as some tests with a helium leak detector at our PJVS showed us. Taking into account that 1 L of liquid helium converts into 750 L of gaseous helium, a daily rate of realistic 3 L of liquid helium can occupy a non-negligible part of the lab room. Therefore, it is recommended to use clocks that are not prone to helium contamination, or at least discipline the rubidium clock by a GPS signal.

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