Multiple $\pi/2$ Pulse Area Operation of Caesium Fountains and the Collisional Frequency Shift

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***Abstract*— Typically, primary fountain frequency standards are tested at elevated microwave powers in order to check for potential frequency shifts due to, e.g., microwave leakage or cavity phase gradients. Usually such tests are performed at $n\pi/2$ microwave pulse area (n an odd integer), where the microwave power is set to these values typically by maximizing the contrast of the central Ramsey fringe. We have experimentally demonstrated that in this case for different n a varying clock state composition after the first Ramsey interaction can be obtained, if the average microwave power seen by the expanding atom cloud is different during the first and the second transition through the Ramsey cavity. In the presence of a clock state composition dependent collisional shift, this effect gives rise to different collisional shifts for operation at different $n\pi/2$ pulse area.**

I. Introduction

In atomic caesium fountains used as primary frequency standards the frequency shift due to cold collisions is one of the type B uncertainty contributions which requires particular consideration. Various techniques have been developed to determine both the actual shift itself and the corresponding uncertainty of the shift [1]. Recently it has been pointed out [2] that under certain conditions the overall collisional shift significantly depends on the clock state composition after the first interaction with the microwave field in the Ramsey cavity, i.e. the ratio of the atom numbers in the clock states $|F=4, m_F=0\rangle$ and $|F=3, m_F=0\rangle$. Notably in the case of a small initial atom cloud size associated with the use of a magneto-optical trap, the expansion of the cloud during its ballistic flight results in position-momentum correlations, which in turn lead to decreasing relative atom velocities in a collision. At these low collisional energies the collisional cross-section is markedly different for atoms in the two clock states [3] and can even change sign during the period of ballistic flight of the atom cloud [2]. The overall collisional shift therefore depends on the composition of the atomic state between the Ramsey interactions [2].

We have demonstrated this effect for two independent fountain clocks, NPL-CsF1 and PTB-CSF1. Figure 1 shows for the case of CSF1 the expected linear dependence of the output frequency of the fountain clock on the composition of the superposition state prepared during the first Ramsey interaction [2]. This composition can be changed by varying the microwave pulse area $p\pi/2$; for odd-integer p, for example,

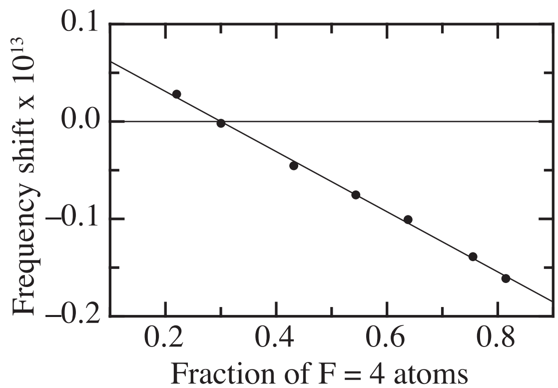

Fig. 1. Measurement of the collisional frequency shift in PTB-CSF1 as a function of population fraction in $|4,0\rangle$ during the time between the two parts of the Ramsey interaction.

states $|F=4, m_F=0\rangle$ and $|F=3, m_F=0\rangle$ are represented with equal weight in the superposition state under idealized conditions.

It has become a standard procedure to test primary fountain frequency standards at elevated microwave powers in order to check for potential frequency shifts due to, e.g., microwave leakage or cavity phase gradients. Usually such tests are performed at $n\pi/2$ microwave pulse area (n an odd integer), where the microwave power is set to these values typically by maximizing the contrast of the central Ramsey fringe. However, when the optimization is based on this criterion one summarily covers all details of the microwave excitation, including the influence of the field inhomogeneity of the microwave mode: Since the cloud is larger on the way down than on the way up, the atoms sample a different spatial region and therefore see (as an average over the cloud) a different effective Bloch rotation angle during ascent and descent when the microwave power fed to the cavity is held constant.

We have shown this experimentally for the fountain clocks in our laboratories (see Figure 2 for the CSF1 data) [4]. In the experiments the microwave power was varied over a wide range, covering nominal pulse areas up to $11\pi/2$. Three series of data were taken, depending on when the microwave power was actually switched on: during ascent only, during descent only, or continuously on. The vertical lines in the figure indi-

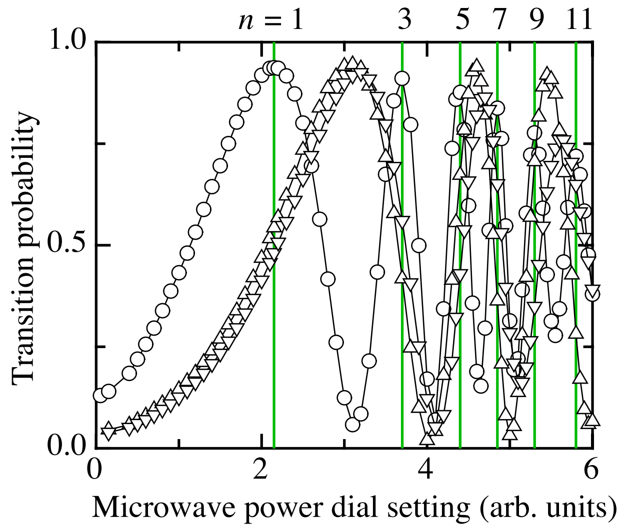

Fig. 2. Microwave power dependence of the transition probability in PTB-CSF1 when the microwave is switched on only part of the time. Upward-pointing triangles: power on during ascent only; downward-pointing triangles: power on during descent only; circles: power on during ascent and descent.

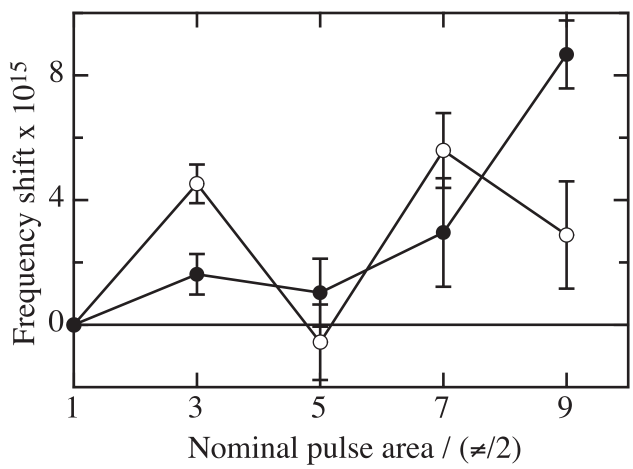

Fig. 3. Open circles: Output frequency of PTB-CSF1 when a nominal pulse area of $n\pi/2$ is set, based on a maximization of the fringe contrast. Full circles: Output frequency of PTB-CSF1 when near the nominal pulse area $n\pi/2$ the microwave power is adjusted such that the state composition after the first Ramsey interaction is the same as for $1\pi/2$ pulse area.

cate the microwave power dial settings for which the overall contrast of the Ramsey fringe is at its local maximum. For example, for these power values the fraction of $|F = 4\rangle$ atoms is $\{54\%, 42\%, 67\%, 36\%, 71\%, 28\%\}$ for nominal pulse areas of $\{1, 3, 5, 7, 9, 11\}\pi/2$ when the cloud sees the microwave only during ascent. It is clear from Figure 1 that in this case the clock output frequency must depend on the pulse area scaling factor n.

This effect is easily detected (open symbols in Fig. 3). On the other hand, when the microwave powers are adjusted near the nominal $n\pi/2$ areas such that the resulting state composition (Fig. 2) is the same as for $n = 1$, the frequency shifts for $n \neq 1$ are generally reduced (full symbols in Fig. 3).

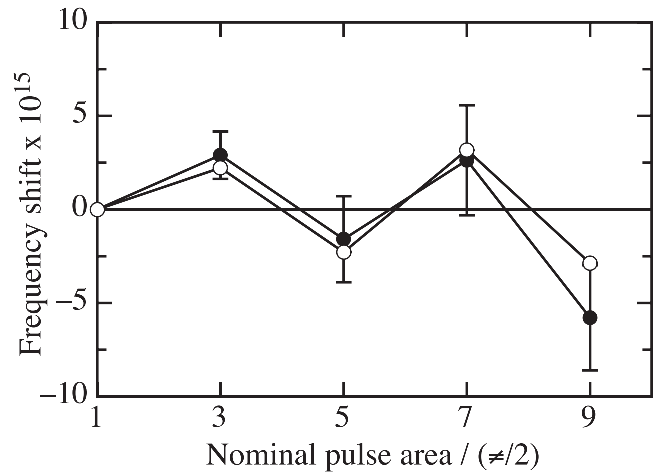

Fig. 4. Full circles: the difference of the curves in Figure 3. Open circles: Expected frequency variation with nominal pulse area when the state composition of Figure 2 is used to extract the corresponding frequency shift from the data in Figure 1. This data has been scaled by a factor of 0.52 to account for the difference in atom density chosen for the experiments of Figures 1 and 3.

Using the slope of the shift curve in Figure 1 with the state composition data (Fig. 2) we arrive at the expected values of the collision-induced power dependence (open circles in Fig. 4). On the other hand, we can read off the size of the effect as the difference (full circles in Fig. 4) of the two data sets in Figure 3. Since the shift-vs-nominal pulse area experiment was run at a density lower by a factor of 0.52 than the shift-vs-composition experiment, the data for the open circles in Figure 4 have been scaled by that factor of 0.52. The very good agreement between the two curves in Fig. 4 indicates that the residual pulse area dependence (full circles in Fig. 3) does not contain the collision-induced contributions anymore.

II. Conclusion

We have experimentally demonstrated the collision-induced pulse-area dependence of the clock output frequency for caesium fountain clocks. Based on Monte-Carlo simulations [2] one can expect this effect to be particularly strong when the cloud expansion is strong, for instance for fountain clocks collecting atoms in a magnetooptic trap. Power-variation tests for the presence of phase gradients in the cavity or for spurious frequency components in the microwave spectrum therefore need to take the collisional contribution into account, in order not to overestimate or underestimate the systematic uncertainty of a caesium fountain clock.

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