Letters

Apparent Power-Dependent Frequency Shift Due to Collisions in a Cesium Fountain

K. Szymaniec, W. Chalupczak, S. Weyers, and R. Wynands

***Abstract*—We describe a situation where a varying collisional frequency shift in cesium fountain primary frequency standards can be misinterpreted as a power-dependent shift. This misinterpretation may affect analyses of fountains test-operated at multiple $\pi/2$ microwave pulse areas. Such tests are typically performed in the search for microwave- and cavity-related systematic frequency biases.**

I. Introduction

Primary Frequency Standards (PFS) operate by interrogating atomic absorbers upon their passage through a resonant microwave cavity. In modern PFS, laser-cooled cesium atoms move along fountain-like trajectories passing the cavity twice, thus permitting the Ramsey-type spectroscopy of the clock transition [1]. There are a number of potential systematic biases of the clock frequency, which depend on the power of the microwave field inside the cavity. These effects are associated with, for example, microwave leakage, spurious components in the microwave spectrum, and cavity phase gradients. As the accuracy of cesium fountain PFS continues to improve, uncertainties related to the power-dependent biases become an important part of the overall PFS uncertainty budgets. Efforts are currently being made to provide a better understanding of these effects, needed for their correct estimation or calibration [2]–[5].

In order to search for the potential power-dependent effects, fountains are operated at elevated microwave field amplitude, typically at odd multiples of the $\pi/2$ pulse area (to optimize the contrast of Ramsey fringes, and hence the signal-to-noise ratio). In general, these effects may depend on the microwave power in a complex way, but in some special cases the dependence exhibits an oscillating signature, with the amplitude of the oscillations increasing with the field amplitude [2]–[5].

It has been pointed out that, as an atom cloud in a fountain expands during its ballistic flight, the average collision energy decreases rapidly [6]. This is especially the case for an initially small cloud, e.g., when atoms are released from a magneto-optical trap ($e^{-1/2}$ radius ≤ 1 mm) [7]. If the collision energy (divided by the Boltzmann constant) is well below 1 μK, the collision rate coefficients for the two clock states $|\mathrm{F}=3, m_\mathrm{F}=0\rangle$ and $|4, 0\rangle$ differ significantly [8]. This difference in the collision rates leads to a variation of the total collisional frequency shift as the fractional clock state populations ρ_{30} and ρ_{40}, established after the first Ramsey interaction, are varied ($\rho_{30}+\rho_{40}=1$) [9]. For example, depending on the number of launched atoms, the shift in NPL-CsF1 may vary by 0.1–0.2 mHz (1.2×10^{-14} in fractional frequency) for ρ_{40} in the range of 0.4 to 0.6.

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II. Operation of a Fountain at Elevated Microwave Power

We first note that the amplitude of the microwave field in the cavity varies significantly with position in both the radial and axial directions. We also note that, due to the velocity spread of the atom cloud, the atoms have various passage times through the cavity. Finally, the atoms will, on average, experience a lower pulse area on the way down than on the way up because, due to the spreading of the cloud, more atoms sample the weaker cavity field away from the central axis [3]. As a result, the average effect of the microwave excitation will vary depending on whether the atoms are ascending or descending in the fountain. The effect is evident when comparing excitation curves (population ρ_{40} as a function of the microwave amplitude, initially $\rho_{40}=0$) observed in the following cases (Fig. 1): (i) microwave field *on* when atoms are ascending and *off* when descending (full grey circles); (ii) field *off* for ascending atoms and *on* for descending atoms (open grey circles). As shown in Fig. 1, the two curves dephase with respect to each other as the field amplitude increases. The third curve, for the oscillations of ρ_{40} in the case of the Ramsey configuration ((iii) field continuously on, black circles), also dephases from (i). Note that choosing the microwave power for maximum transfer to $|4, 0\rangle$ in case (iii) results in $\rho_{40}\neq0.5$ after the first Ramsey interaction (case (i)). The deviation from $\rho_{40}=0.5$ increases with the field amplitude and changes sign for subsequent odd multiples of $\pi/2$.

Since the collisional frequency shift depends linearly on ρ_{40} [9], the varying collisional shift can be misinterpreted as a shift caused by one of the mechanisms mentioned above: microwave leakage, spurious components in the microwave spectrum, or cavity phase gradients. In Fig. 2 we plot the expected collision-induced shift versus the microwave field amplitude. The shift was not measured directly; rather, it was obtained by multiplying the measured deviation from $\rho_{40}=0.5$ and the experimental shift variation rate, as presented in [9]. The oscillating character of the shift is similar to that found for these other potential

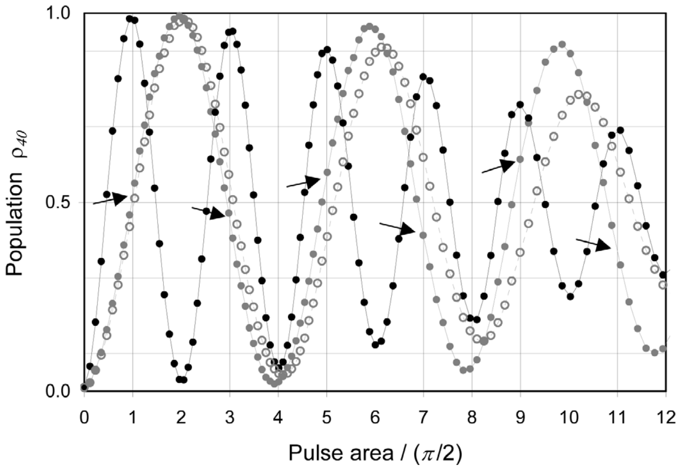

Fig. 1. Dephasing of the excitation curves as measured in NPL-CsF1. See text for description of the cases: (i) full grey circles, (ii) open grey circles, (iii) black circles. The experimental points are linked to guide the eye. The x-axis is scaled in the apparent pulse areas obtained by optimizing the Ramsey excitation. Arrows indicate the increasing deviation from $\rho_{40} = 0.5$ after the first Ramsey interaction.

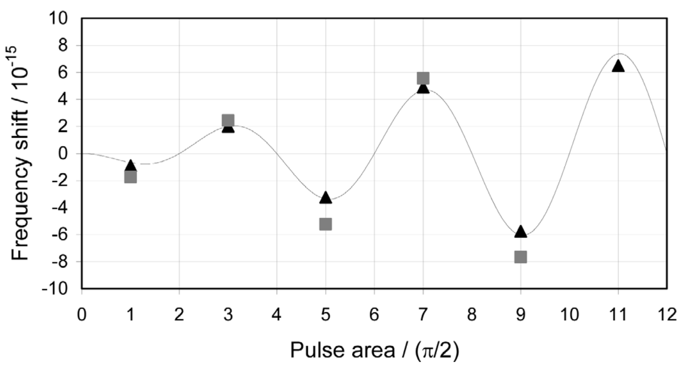

Fig. 2. Predicted oscillating collisional frequency shift as a function of apparent pulse area $n \times \pi/2$. The data points were obtained by multiplying the measured deviation from $\rho_{40} = 0.5$ and the shift variation rate, as presented in [9]; black triangles: NPL-CsF1, grey squares: PTB-CSF1 (corresponding error bars are smaller than the markers). The two sets of points are expected to differ owing to differences in the design and operating parameters of the two fountains. To illustrate the similarity to other potential frequency shifting systematic effects, we also plot a corresponding sinusoidal curve with linearly increasing amplitude matching one set of points, for the case that such shifts are in phase with the apparent shift (see text and [3]).

systematic effects [2]–[5]; these can be in phase or antiphase with the collision-induced shift. Mis-identification of the collision-induced shift may thus lead either to overestimation of these effects or, for example, in the case of microwave leakage present before or after the two Ramsey pulses [3], to a significant underestimation of the effect (i.e., when a null effect is observed as a result of destructive interference of the shifts). This is illustrated by the data points in Fig. 2, which suggest that the apparent effect can mask a real shift, at the optimum $\pi/2$ pulse area, of $1 - 2 \times 10^{-15}$.

In an experiment where the microwave amplitude is set by some nonlinear elements (i.e., amplifiers, attenuators), it might be tempting to use the optimum population transfer in the Ramsey process as an indication of the $n \times \pi/2$ setting. Instead, to avoid the misinterpretation, the test operation at elevated power has to be performed either such that the collisional shift correction is determined for each pulse area [10], or such that ρ_{40} (excitation after the first passage through the cavity) is not changed. The latter approach may require an increased temperature stability of the cavity, as the sensitivity of the ρ_{40} fluctuations to cavity resonance instabilities is proportional to n.

III. Conclusions

The variation of the collision-induced frequency shift has the potential to mask or at least alter any power dependence caused by imperfections in the setup, such as cavity phase gradients, microwave leakage fields, or spurious spectral components. In order to avoid such misinterpretation, the leverage tests for these effects require consideration of the collisional frequency shift, e.g., by assuring that the fractional populations of the clock states, defined after the first Ramsey interaction, are the same in all $n \times \pi/2$ measurements.

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