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Comment on "Ramsey spectroscopy, matter-wave interferometry, and the microwave-lensing frequency shift"

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The theory of a frequency shift in primary frequency standards due to microwave lensing in Gibble [Phys. Rev. A **90**, 015601 (2014)] contains a number of problems that undermine its validity. Furthermore, because the exposition of the theory has multiple errors and because the shift has never been experimentally observed, we believe this possible shift should not be included as a correction to primary frequency standards contributing to international atomic time. Although the theory may describe the basic mechanisms of a possible frequency shift, we argue it is not possible to use this theory to make reliable corrections to a primary frequency standard at the $\delta f/f \sim 10^{-16}$ level.

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Determination of the second in the International System of Units (SI) and realization of international atomic time (TAI) are among the most precise measurements of any kind and have some of the greatest impacts on technology and research, largely because the careful physical measurements are complemented by well-established and tested theories. Reference [1] describes the theory of a frequency shift from which the author calculates "corrections" to various primary frequency standards: the laser-cooled atomic microwave fountain clocks that are used to determine TAI and the SI second. According to Ref. [1], the magnitude of this frequency shift ($\delta f/f$) is on the order of the current frequency uncertainty of the best primary frequency standards $df/f \sim 1 \times 10^{-16}$. Corrections for this shift (microwave lensing) are currently applied to some (but not all) of the primary frequency standards that help determine TAI and the SI second [2–4]. The frequency shift described in Ref. [1], thus introduces a significant bias in TAI compared to TAI realized without the proposed shift applied. Our group has performed independent theoretical investigations into the theory of a microwave frequency shift from lensing [5], and our theory shows significantly different results than those claimed in Ref. [1].

The effect described in Ref. [1] is the result of "clipping" of the atomic wave function by limiting apertures in a primary frequency standard (PFS). It is postulated that differential clipping of the two dressed states of the atomic wave function occurs as a result of a very small transverse force on the atoms caused by a gradient in the microwave field during microwave interrogation. This small transverse force generates a displacement between the wave functions of the two dressed states on the order of a few nanometers, which is much less than the millimeter size of the wave packets after their trip through the frequency standard [1]. It is widely accepted that the atom's dressed-state wave function trajectories are affected by the resonant interaction. This effect was investigated some time ago [6,7] and predictions made regarding lensing (lensing refers to specific modifications to the atomic trajectories) that are identical to the much later work of Ref. [1]. Reference [1] and earlier works [2–4,8] go on to use the modified atomic trajectories and attempt to calculate a frequency shift from these trajectories. The theory of this frequency shift as presented in Ref. [1] (and earlier papers) is both incomplete and contains significant errors that undermine the validity of both the theory and any correction to primary frequency standards developed using it. Many of the comments here regarding fundamental issues with the theory apply to Refs. [2–4,8] as well.

If the theory in [1] were clearly stated, and without apparent errors, one could better evaluate it and the relatively large frequency shifts it predicts. The paper [1] includes problems in the mathematical and related discussions that make it difficult to confirm the validity of the conclusions. For example, the first line of Eq. (4) is identically zero at all times, yielding an exactly zero frequency shift. In another example, the units in the critical Eqs. (6) and (7) of Ref. [1] are flawed somehow as the units are physically inconsistent within different terms of the equations.

Next, in the paragraph of Ref. [1] following Eq. (5) we find the statement "... $\Delta_{x,y}$ *must be at least 30 nm and should be less than the 852 nm wavelength of the laser cooling light [20,21]...*" (in Ref. [1], $\Delta_{x,y}$ refers to the wave-packet size which describes the atom). The precise atomic size is a crucial parameter in the theory with the choice of initial atom-packet size markedly changing the size of the claimed frequency shift and therefore any correction to be applied. The lower limit of 30 nm presented in Ref. [1] presumably comes from the Heisenberg limit of a 1-μK Cs atom. First, the Heisenberg limit here is an approximation made by substituting the momentum P for the momentum uncertainty δP in $\delta P \delta x > \hbar/2$. Second, this is the one-dimensional (1D) limit, whereas the problem at hand is a two-dimensional (2D) one, leading to a Heisenberg limit of more like 43 nm than 30 nm. Although quibbling about the difference may seem like splitting hairs, calculating corrections to high-precision measurements where factors of $\sqrt{2}$ are highly significant means one must be certain that all such factors have been accounted for before applying any such calculated correction. In Ref. [5], the size of the frequency shift changes by more than a factor of 2 depending on the choice of initial wave-packet size within that range stated in Ref. [1] to be appropriate. We further note that, in the absence of experimental data on this shift, the appropriate wave-packet size, [e.g., Heisenberg limit ($\sim$30 μm for 1-μK Cs atoms in 1D or 43 nm in 2D), de Broglie wavelength (375 nm for 2D, 1-μK Cs atoms), or optical wavelength of 852 nm] is a matter of conjecture (along with whether or not minimum uncertainty wave packets are even appropriate) and greatly changes the size of any calculated correction. Never in Ref. [1] or previous Refs. [2–4,8], does the author ever explain what atom wave-packet size he is using for his calculations of corrections as used in Refs. [2–4]. This is critical; the magnitude of the effect is strongly dependent on this parameter, and there are a number of equally physically reasonable choices which predict very different magnitudes of any correction applied to frequency standards. In the absence of any experimental data on the effect, it is unclear what wave-packet size would be appropriate. Finally, in later parts of Ref. [1], the atom size is given as 30 μm, which is not a typographical error (this size is used to reduce wave-packet spreading over the atom's flight time) but has no physical basis in the reality of Cs fountains that operate with microkelvin atom temperatures ($\delta x = 30\,\mu$m corresponds to picokelvin atom temperatures).

Finally we come to the physical nature of the differential clipping of the atomic wave functions by apertures. In the case of Ref. [1], the author seems to assume an initial wave-packet size much smaller than the de Broglie wavelength ($\lambda_{\text{dB}} \approx 375$ nm for 1-μK Cs atoms), likely 30 nm, but this is not absolutely clear. If the initial wave-packet size is chosen as approximately 30 nm, the final clipped wave-packet size approaches that of the apertures ($\sim$1 cm), resulting in essentially complete overlap of the two dressed-state wave functions as well as the majority of atoms having the wave functions for both of the dressed-state components clipped. The frequency shift is postulated to result from the differential clipping of both wave functions, that is, one of the dressed-state wave functions is clipped slightly more than the other. In order for the theory in Ref. [1] to be correct we must now be able to clip a sizable fraction ($\sim 10^{-5}$) off of the dressed-state wave functions without changing the internal superposition phase at the 10^{-8} radian level. However, it would not be unreasonable to expect that, if there was a phase shift in the dressed-state wave function as a result of this wall interaction, that that magnitude of that phase shift would depend on the fraction of wave function clipped: If that were the case, the frequency shift could be much larger than that predicted by Ref. [1] or, conversely, much smaller or even have the opposite sign. In Ref. [1], no investigation of the nature of the assumed clipping is attempted; rather, the clipping is assumed to have happened with no other effect on the atomic wave functions. Given that the two atomic states used in Ref. [1] as dressed states are themselves hyperfine superposition states and that the accuracy of the clock depends critically on the *phase* of exactly those superpositions, the nature of the clipping must be investigated. Any differential phase shift of the wave functions occurring during the clipping could easily and grossly change the size of the frequency shift or even its sign. We note that radian level phase shifts are observed in similar systems as a result of wall interactions [9]. We also note that this defect (no discussion of the nature of the clipping) is shared by our investigations into lensing [5], however, we do not use our theory to calculate numerical corrections to be applied to PFS measurements. The physics of atom-wall interactions is relatively well studied, and any such clipping must presumably be understood as an interaction between the atom and the adjacent wall. As pointed out in Derevianko *et al.* [10] "*As the separation z between an atom and a wall increases, the atom-wall interaction evolves through several distinct regimes: (i) chemical-bond region that extends a few nm from the surface, (ii) van der Waals (vdW) region, (iii) retardation [Casimir-Polder (CP)] region, and (iv) the thermal (Lifshitz) zone.*" It would seem that, at the least, all of these effects must be considered before calculations used to correct primary frequency standards are carried out and applied. In this case, applying a frequency correction based on a partial theory may very well cause a much larger bias than exists in the absence of the correction. The investigation of the details of the clipping is not a separate effect; it is part and parcel of any correction being made to the clock as a result of clipping of the wave function by wall interactions.

The authors of this Comment operate the primary frequency standards for the United States, National Institute of Standards and Technology (NIST)-F1, and NIST-F2. We are concerned that the microwave-lensing frequency shift as described in Ref. [1] and preceding similar papers [2–4,8] include significant problems in exposition and significant omissions in the physical theory. Simply put, the theory in Ref. [1] contains multiple mathematical errors, is physically incomplete, and is in significant disagreement with other theories of the same effect. However, this theory is being used to calculate corrections to some primary frequency standards used to realized the SI second and determine TAI. Since this proposed correction has never been experimentally observed, it is crucial that there be complete confidence and transparency in the details of all calculations and ideas involved in generating the proposed numerical correction for the frequency shift. The exact details (and their validity) matter very deeply in this case. Because of the significant concerns about the validity of this proposed frequency shift, we believe there should not be a correction included in the determination of the SI second nor in the realization of TAI for this frequency shift. We are concerned that, because a correction for this frequency shift is currently applied to some primary frequency standards [2–4], there is a resulting unjustifiable bias in TAI comparable to a significant fraction of the stated TAI uncertainty. Realization of TAI and determination of the SI second are among the most precise and highest impact measurements performed. Any corrections or shifts to these measurements should be applied only after thorough and convincing theoretical considerations and/or careful and repeatable experimental demonstrations.

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