Auto-Compensation of Collisional Shift in Atomic Clocks Based on Bosonic Atoms in an Optical Lattice

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***Abstract*—We propose a new approach to suppress the influence of collisional shift and its fluctuations on the long-term stability of optical clocks based on bosonic atoms (even isotopes) in an 1D or 2D lattice. The successful implementation of our auto-compensation method, in combination with the hyper-Ramsey spectroscopic schemes, will allow considering bosons as a real alternative to fermions while achieving the highest metrological characteristics of atomic clocks.**

Keywords—optical atomic clocks, collisional shift, optical lattice

I. INTRODUCTION

At present, optical clocks based on odd isotopes (fermions) of alkaline-earth atoms (Sr, Yb, etc.) trapped in an optical lattice at a magic wavelength have a leading position with record metrological characteristics at the level of 10^{-18}-10^{-19} for long-term stability [1-3]. Despite a number of advantages (the absence of Zeeman sublevels in the $^1S_0 \rightarrow {}^3P_0$ clock transition, high efficiency of trapping atoms in the lattice), even isotopes (bosons) still lose to fermions in long-term stability due to two main reasons: 1) large field shifts when using magnetically induced spectroscopy [4,5]; 2) significant collisional shifts for the trapped atoms in a 1D or 2D lattice. In this case, the problem of field shifts can be successfully solved using hyper-Ramsey methods [6-9], while the collisional shift can be eliminated in a 3D lattice if the average number of atoms per one potential well is less than one. However, the formation and stable operation of a 3D lattice is a rather difficult technical problem.

We propose an alternative approach that can allow suppressing the influence of collisional shift and its fluctuations on the long-term stability of atomic clocks using a 1D or 2D lattice.

II. GENERAL IDEA OF THE METHOD

Our method is based on the fact that the frequency shift of the clock transition due to interatomic collisions Δ_{coll} is proportional to the average density of atoms in the lattice, which, in turn, is determined by the number of trapped atoms N, i.e., $\Delta_{\text{coll}}=cN$ (where c is the proportionality coefficient for specific experimental conditions). If we have the information about the number of trapped atoms *before* the start of the spectroscopic measurement (e.g., using the fluorescence signal right before loading the atoms into the lattice or before clock transition spectroscopy), then we introduce an additional frequency shift $\Delta_{\text{art}}=\xi N$ of the clock laser, where ξ is a variable parameter. Thus, the quantity Δ_{art} plays the role of an artificial compensating anti-shift. In this case, the functional dependence of the error signal used to stabilize the frequency of the local oscillator ω_{LO} has the following form:

$$S_N(\delta+\Delta_{\text{art}}-\Delta_{\text{coll}}) = S_N(\delta+(\xi-c)N) \tag{1}$$

where $\delta=\omega_{\text{LO}}-\omega_0$ is the detuning from the unperturbed clock transition frequency ω_0. The result of frequency stabilization for ω_{LO} is determined from the zero condition of the error signal:

$$\begin{aligned} &S_N(\delta+(\xi-c)N)=0 \quad \Rightarrow \\ &\delta+(\xi-c)N=0 \end{aligned} \tag{2}$$

Hence it follows that the stabilized frequency ω_{LO} depends on the parameter ξ so that in the case of $\xi=c$ this frequency does not undergo a collisional shift, $\delta=0$. For the experimental realization of the condition $\xi=c$, we have developed a two-loop method using operating regimes with two significantly different average numbers of trapped atoms $\bar{N}_1$ and $\bar{N}_2$. In this case, condition (2) leads to an equation system with two unknown values δ and ξ:

$$\begin{aligned} &\delta+(\xi-c)\bar{N}_1=0 \\ &\delta+(\xi-c)\bar{N}_2=0 \end{aligned} \tag{3}$$

which has the following solution: $\xi=c$ and unperturbed (due to interatomic collisions) clock frequency, $\delta=0$ (i.e., $\omega_{\text{LO}}=\omega_0$).

We emphasize that our approach uses an active auto-compensation of the collisional shift in each individual spectroscopic measurement. This makes it possible to compensate not only the average collisional shift, but also its fluctuations caused by fluctuations in the number of trapped atoms N. Note that the proposed method is an analogue of the method [10,11], which makes it possible to effectively suppress field shifts in continuous-wave spectroscopy.

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III. Experimental scheme

The most important technical question is following: how to correctly obtain information about number of atoms in the lattice *before* spectroscopic measurement?

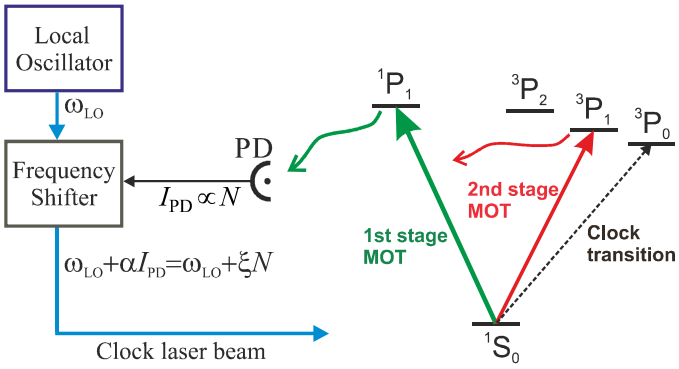

Fig. 1. The general scheme of the experimental implementation of the auto-compensation method.

For example, we can use the fluorescence signal from either first or second stage of the magneto-optical trap (MOT) (see Fig. 1). Also it is possible, in principle, to briefly illuminate with a laser for the 1st MOT the atoms already trapped in the lattice before the clock spectroscopy. In any case, we use the signal I_{PD} from the photodetector (see PD in Fig. 1), which is proportional (we assume this) to the number of trapped atoms, $I_{PD} \propto N$. Using the frequency shifter, we add an artificial anti-shift $\Delta_{art}=\alpha I_{PD}$ to the laser frequency (see Fig. 1), where the coefficient α is variable parameter. In the context of above theoretical analysis, it is equivalent to the anti-shift $\Delta_{art}=\xi N$, with variable coefficient ξ.

IV. Conclusions

We believe that the use of the auto-compensation method will significantly improve the accuracy and long-term stability of lattice atomic frequency standards based on even isotopes. The successful implementation of this method, in combination with the hyper-Ramsey spectroscopic schemes [6-9], will allow considering bosons as a real alternative to fermions while achieving the highest metrological characteristics of atomic clocks. In addition, it can significantly improve the parameters of the transportable frequency standards. Besides bosonic alkaline-earth atoms, our method can be applied for any clocks where the collisional shift has significance (e.g., for a molecular clock [12]).

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