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Re: **Referee report on the doctoral thesis of Mr. Domagoj Kovačić**
"Development of an optical frequency standard"

I was asked to write a report on the doctoral thesis of Mr. Domagoj Kovačić titled "Development of an optical frequency standard". The topics addressed in the thesis are optical clocks and experiments exploring interactions of cold rubidium atoms with a frequency comb. The work done on optical clocks was performed at Nicolaus Copernicus University of Toruń in Poland, where Mr. Kovačić upgraded the already existing bosonic optical clock, such that it was able to operate both in the bosonic and in the fermionic mode of operation. The fermionic clock is fully operational up to the single frequency red MOT stage. This type of work involving development of a very sophisticated experimental setup requires dedicated scientific focus, solving many technical problems, and is in general very demanding; scientific paper arising from the setup are expected in the future. The work exploring cooling ^{85}Rb and ^{87}Rb in a magneto-optical trap (MOT) and frequency-comb-induced radiation pressure force in dense atomic clouds was performed at the Institute of Physics in Zagreb, Croatia, and it resulted in several publications presented in the thesis. After reading the thesis, I conclude that the presented work done by Mr. Domagoj Kovačić deserves to be rewarded with a doctoral degree. Let me now elaborate in more detail the contents of the thesis.

Chapter 1 is an introduction into atomic optical clocks.

Chapter 2 contains the theoretical background of optical clock operation including a fairly detailed description of the Doppler cooling mechanism, details of the energy levels of the Strontium atom that is being used in the optical clock, and cooling of bosonic ^{88}Sr and fermionic ^{87}Sr, optical lattices (including the description of the Lamb-Dicke regime), and the magic wavelengths at which atomic polarizabilities in specific different atomic states attain identical levels thereby enabling the clock operation. Although there are some discrepancies between the calculated magic values from previously reported red-detuned optical lattice, the candidate was able to explain it. Finally, there is a subsection devoted to high-precision spectroscopy of $^1S_0 \rightarrow {}^3P_0$. From this Chapter it is evident that the candidate is well acquainted with the steps that need to be taken for an atomic clock to be operational.

Chapter 3 is focused on assessing the feasibility of blue magic wavelength optical lattice, including measurements of photoionization cross sections of $^1P_1$ and $^3S_1$ states in ^{88}Sr, and calculations of photoionization induced losses in the blue magic wavelength optical lattice clock, and discussion of potential ways to avoid them.

Chapter 4 describes the work performed by Mr. Kovačić on the Strontium optical clock experiment in the National Laboratory of Atomic, Molecular and Optical Physics (KL FAMO) in Toruń. The distinction from the previous and this implementation of the bosonic ^{88}Sr clocks, the experimental setup explained in the thesis allows both the operation of the bosonic ^{88}Sr and/or the fermionic ^{87}Sr clock. Because of the hyperfine structure of the fermionic ^{87}Sr energy levels, the experimental requirements for the ^{87}Sr optical clock are more demanding compared to its bosonic counterpart. Additional lasers and magnetic coils had to be introduced in the setup to mitigate losses.

In Chapter 5 Mr. Kovačić presented the experimental results of florescence spectroscopy of ultracold ^{87}Sr atoms in blue and red MOTs, and a comparison with the ^{88}Sr isotope. The key goal here was to optimize the experimental parameters to obtain maximal number of atoms, which was measured in dependence of the cooling and capture time of atoms in the trap.

Chapter 6 contains estimate of the accuracy of the operation of this optical clock (represented in the form of accuracy budget presented as a table in the thesis). The accuracy can be compromised due to many effects including the Zeeman effect, AC Stark effect, black-body radiation, probe light shift etc.

Finally, Chapter 7 contains main conclusions.

Appendices are simply reprints of the published articles co-authored by Mr. Kovačić, which also include his work on cooling ^{85}Rb and ^{87}Rb in a magneto-optical trap (MOT) and frequency-comb-induced radiation pressure force in dense atomic clouds.

In conclusion, original contributions of this thesis include: (i) proposal for the optimal experimental conditions for the use of blue magic wavelength optical lattices for optical atomic clocks, (ii) upgrade of the ^{88}Sr optical clock experimental setup such that it can operate with fermionic ^{87}Sr, (iii) systematic measurement of ^{88}Sr clock frequency shifts during international campaign of optical clock comparison in March of 2022. Thus, this work deserves to be awarded with a doctoral degree.

Zagreb, January 28th 2023

Hrvoje Buljan

Prof. Hrvoje Buljan