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Referee report on the doctoral thesis „Development of an optical frequency standard" by Domagoj Kovačić

The dissertation was prepared on the basis of the work done during a three year stay of Mr. Kovačić at the National Laboratory FAMO in Toruń (Poland). The supervisors of the thesis are Dr. sc. Ticijana Ban from the University of Zagreb in Croatia and Prof. Dr. Habil. Michał Zawada from Nicolaus Copernicus University in Toruń (Poland). The main scientific activity was focused on an atomic optical strontium clock. Another scientific activity of the Ph.D. candidate was cooling of rubidium atoms using an optical frequency comb. The latter field is formally not part of the dissertation, and according to the rules, it is not under evaluation here.

Structure and contents of the thesis:

The main part of the dissertation consists of an abstract, table of contents, list of figures, seven chapters, curriculum vitae, a copy of four scientific articles coauthored by the Ph.D. candidate, and a list of 131 references. In total, the thesis has 140 pages and its main text is on 90 pages.

Chapter 1 is a short introduction to the field of optical atomic clocks and the evaluation of their stability. Chapter 2 is devoted to the description of the physics that governs clock operation – from Doppler cooling through bosonic and fermionic strontium cooling to fundamentals of optical lattices. Two crucial concepts are also introduced, namely the Lamb-Dicke regime and magic wavelength. In Chapter 3 the Author focusses on blue magic wavelength, considering the horizontal as well as the vertical case. Due to presence of the gravity, both cases differ significantly and the Author uses the formalism of Wannier and Wannier-Stark states to describe the behavior of atoms in the lattice. The presence of the probe light (necessary to perform the interrogation of the clock transition) is also taken into account. Results for the common red-detuned lattice and the new blue-detuned lattice at the magic wavelength are shown. Next, the important issue of a single-photon photoionization induced by a blue-detuned lattice is investigated experimentally and numerically for $^1P_1$

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and $^3S_1$ states, which are crucial for the measurement cycle in the optical clock. The results (acquired with the participation of the Author) show that the blue-detuned lattice, although beneficial in some aspects, is very demanding from the perspective of atom losses. Chapter 4 is devoted to the description of the experimental setup of the existing bosonic strontium clock (based on a red-detuned lattice) and its development (carried with the participation of the thesis' Author) towards the operation with fermionic strontium atoms. The Author's activity concerned the stages up to the so called single frequency red MOT. In Chapter 5 we find results of the preliminary measurements done by the Author on the fermionic blue and red MOTs. Chapter 6 summarizes the accuracy budget of the bosonic strontium clock, operating on the red-detuned optical lattice. The two effects of highest contribution were measured during the 2022 international campaign, and the rest of the results in Chapter 6 come from the 2015 campaign. Chapter 7 contains a very short and general summary of the work.

The main scientific goal, formulated as the development an optical frequency standard, has been achieved. The Ph.D. candidate had an important role in the calculation of the photoionization parameters for strontium atoms kept in the field of blue-detuned laser light. This light, at the magic wavelength of about 390 nm, is a new possible candidate to generate the optical lattice. The Author also developed the existing setup of bosonic strontium clock towards fermionic strontium clock and characterized its parameters at the level of a single frequency red MOT.

Advantages of the dissertation:

The topic undertaken by Mr. Kovačić is not only very interesting but also advanced, ambitious, and timely. The article presenting measurements of the photoionization cross sections was published in May 2022.

The experimental setups in the field of optical atomic clocks are extremely complicated and demanding with respect to their handling. A convincing proof of this statement is the fact that there are only a few operating optical atomic clocks in the world. The dissertation shows that the Ph.D. candidate gained experience in advanced techniques of atomic physics. He also proved that is able to perform necessary calculations – here they were the basis for loss rate measurements.

The language side of the dissertation is good – the reader does not have any problems understanding the content. Besides a few exceptions, there are no language mistakes (there are, however, some typos, omissions, duplications, etc. which do not impede reading in any way).

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Although this is not directly under evaluation here, I would like to stress that Mr. Kovačić is a coauthor of four scientific articles in very good journals (Optics Express, 4th author out of seven; JOSA B, 3rd author out of 6; Phys. Rev. A, 2nd author out of 7; Sci. Rep., 3rd author out of 6).

Criticism:

It is my duty to point out some weaknesses of the dissertation. My main criticism concerns two general issues.

The first one is the way the topic is presented. In section 2.1 (part of Chapter 2), the description of the Doppler cooling is not far from a popular science level introduction to the topic. Also, this field has been introduced in hundreds of Ph.D. and M.Sc. theses for many, many years. So, in my opinion, it would be far more beneficial to devote this place in the dissertation to specific and interesting issues concerning optical clocks. For example, a systematic comparison of bosonic and fermionic clocks is missing from the experimental and theoretical point of view. Some information is scattered in the text, but the reader has to somehow build the comparison by himself,, and I have a feeling that this image is quite incomplete. Similarly, a short review of current state-of-the-art of strontium, ytterbium or mercury lattice clocks is a must-have.

In the same spirit, in Chapter 7 (entitled "Conclusion") the scientific conclusions and some outlook are definitely missing. The reader would like to receive a summary of the results and their tangible influence on the future clock operation.

In other words, there is no "guide" in the dissertation, helping the reader to go from the formulation of the goals and the motivation, through their realization, to solid conclusions. For example, the description of the Zeeman slower, ready well before the Ph.D. candidate started his work, is by far less interesting here than the (actually missing) information about the reasons of extending the machinery with fermionic strontium clock.

The second issue is a relatively high number of various mistakes, including the editing ones. My general impression is that the dissertation was prepared in a hurry. This is definitely a common situation, but it was probably the main reason for this high "mistake density".

In particular, there are many mistakes regarding the appearance of the equations, inline equations, and inline mathematical symbols. The LaTeX environment is a perfect tool here, allowing us to prepare texts that not only meet the editorial standards but are also reader-friendly. This is obviously not of the greatest importance from the scientific point of view, nevertheless it may facilitate or (unfortunately) impede understanding of the content. For the

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convenience of the Author I collected a few advices in a kind of "appendix" at the end of my report.

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A list of some of the specific issues connected with the presentation of the equations, concepts, etc. is as follows:

- In the introductory section 2.6 entitled "Optical lattices" (mentioned above), the information on some of the assumptions (simplifications) is omitted. These are: a) neglecting the magnetic part of the Lorentz force, b) neglecting the size of the induced dipole with respect to the wavelength, and c) assuming low saturation (far detuning) in the Eqs. (2.13) and (2.14).
- Explanations of the acronyms used in the figures that present the experimental setups are sometimes missing in the captions. Examples are Fig. 4.1 (missing PL, PD, LO, BS, FI) or Fig. 4.7 where the less common HCL acronym is not explained (is it a hollow cathode lamp?). Also, judging by the schemes of the experimental setups, AMP is presumably a power amplifier (or in general, a whole device), not a pure single "operational amplifier".
- Similarly, some symbols used in equations are not defined. Some of the examples are k in Eq. (2.17), $\sigma_{^1P_1}$ in Eq. (3.11) or $\tilde{E}$ in the first line below Eq. (2.10). In the latter case I don't know what is the origin of the factor of "2" (being here instead of the common "1/2" factor). Presence of both E and E_0 in Eqs. (2.23) and (6.3) is unclear to me.
- In Eqs. (2.19) and (2.22) there is a notational collision – in the first case ω_r is the recoil frequency and in the latter case it is the radial trap frequency. Also, I am quite convinced that in Eq. (2.22) the denominator and nominator (excluding ω_z) are swapped, plus w_0 should read w_0.
- There is a minus sign missing in the exponent in Eq. (3.10). Just above this equation, the units should read cm^{-3} for the density of atoms and cm^2 for the cross section.
- A few sentences in the thesis should be devoted to explaining some of the concepts only mentioned in the text, such as the tight-binding approximation, autoionization resonance, the ξ correction factor in Table 2.4. or UTC(AOS)—UTC in Table 6.1.
- The angular frequency ω and frequency ν seem to be mixed up at some places. The commonly accepted notation is: $\omega = 2\pi \cdot 0.8$ MHz or $\omega = 5.03{\cdot}10^6$ 1/s or $\nu = 0.8$ MHz. For example, in the case of $\omega = 0.8$ MHz the presence (or absence) of 2π is unclear, as is the true value of the frequency ν.

Other issues I noticed:

- Page 23: The sentence "The recoil frequency, defined earlier in section 2.3., is the frequency of photons of the probe beam" is definitely not true,

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however the definition in section 2.3 is more or less correct (but still there remains the problem with 2π factor).

- Page 82: In part of the sentence "…the nuclear quantum number I for bosons is zero…" – I understand that the Author had in mind a particular case of strontium isotopes being composite bosons since, in general, this is not true.

Some of the questions I would like to ask during the defense:

1) The Ti:Sa 813 nm laser (Fig. 4.10) works in a closed-loop scheme. How is its frequency modulated in this case and what is approximately the bandwidth of the loop? Is the laser spectral width of 420 kHz narrow enough for the presented experiments?
2) The loading curves in Fig. 3.9 have barely distinguishable amplitudes. On the other hand, the well-known description in the form of Eq. (3.10) suggests (with the numbers provided in the text for both γ) that the amplitudes (that is, in the stationary regime) should differ by 10%. What may be the reason for this situation?
3) There is no information in the text or I missed it: what is the real time necessary to swap between bosonic and fermionic MOT?
4) What is the period of laser frequency modulation in the broadband (BB) phase of bosonic strontium cooling?
5) What limits the lifetime of atoms in the lattice to 1.5 s (right part of Fig. 2.7)?
6) I am curious, how the international clock campaigns (mentioned in Chapter 6) are organized.
7) What is the current status of the fermionic clock in KL FAMO?

Conclusions:

Despite the criticism I presented above, I think the Ph.D. candidate demonstrated a good understanding of the underlying theory and computational methods. Also, the thesis establishes that the Mr. Kovačić mastered the technical skills necessary to develop advanced experimental setups in the field of atomic physics. Similarly, he has data analysis skills that are needed in the formulation of scientific conclusions. The thesis also shows that the author understands the strengths, but also the limitations of the experimental setup and methods he has used.

Formal statements:

In my opinion, the presented thesis demonstrates that Mr. Domagoj Kovačić satisfies the requirements laid down by the Polish law (ustawa Prawo o szkolnictwie wyższym i nauce 2018, art. 187, ust. 1 i 2, z późniejszymi zmianami) for candidates for the degree of Doctor of Philosophy in Physics. In particular, the doctoral dissertation demonstrates the general theoretical knowledge of

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the Ph.D. candidate in physics and the ability to carry out research independently. The latter is also supported by the fact that he is co-author of four scientific articles in journals of very high reputation. Also, the subject matter of the doctoral dissertation is an original solution to a scientific problem.

I recommend the admission of Mr. Domagoj Kovačić for the subsequent stages of the procedure, including the public defense.

Tomasz Kawalec

Tomm Kaw

Podpisany elektronicznie przez
Tomasz Adam Kawalec
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Appendix: LaTeX-specific methods to meet the common editorial standards of scientific publications in physics and other disciplines (examples simulated in Word):

- All the variables should look exactly the same in the equations and in the text, so in the latter case they should be placed between dollar signs: x, w, etc. This consistency is important, as we have such a huge "zoo" of symbols (like w, ω, *w*).
- The vector, tilde, and other signs placed above symbols: \vec k_x instead of \vec {k_x}.
- To distinguish the elementary functions in equations from something looking like a product of a few variables, backslash has to be used as a leading sign: \sin, \cos, \exp, etc.

  Example: $\frac{\sin(sin)}{sin}$
- Each pause sign is generated from two (or three) short dashes: -- or ---.

  Example: IF -- interference filter $\Rightarrow$ IF – interference filter
- To avoid separation of values and units by line breaking, it is recommended to use nonbreaking spaces with tilde: 10~kg.
- The "times" symbol, depending on the convention, should be generated in one of the following ways: 10\times10^{-5} or 10\cdot10^{-5} instead of 10 x 10^{-5}.

  Example: 10×10^{-5} or $10 \cdot 10^{-5}$ instead of $10\ \mathrm{x}\ 10^{-5}$
- The brackets in the equations should have an automatically controlled size: \left(...\right) or \left[...\right] and so on.

  Example: $\left(e^{-\frac{x^2}{2\sigma^2}}\right)$ instead of $(e^{-\frac{x^2}{2\sigma^2}})$

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