COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK
DEPARTMENT OF PHYSICS

New York City, March 15th, 2024

Confirmation of Fellowship

To whom it may concern:

This letter is to confirm that Dr. Mateusz Borkowski has completed a *NAWA Bekker Programme* fellowship in my research group. The fellowship took place in my laboratory in Pupin Hall, at the Department of Physics at Columbia University of New York during the 24 months between March 15th, 2022 and March 15th, 2024. I can hereby confirm that during this time, Dr. Borkowski spent at least 90% of his time at Columbia University.

Dr. Borkowski divided his time in our group between theory and experiments. In the initial few months, he supported the efforts to demonstrate a clock transition in Sr_2 led by a senior graduate student, Dr. Kon Leung, and learned the operation of the experimental setup. In the meantime, he theoretically investigated the pathways towards creating molecules of different isotopologues and shown several pathways to produce Sr_2 molecules of all three bosonic isotopes. Interestingly, he also found a new improved pathway for strontium-88 molecules we used for the molecular clock demonstration, which improved the molecule signal twofold. At the same time, Dr. Borkowski started to design and build new laser systems for our experimental setup in an effort to increase the reliability of the molecule production and detection process.

The initial demonstration of the operation of the molecular lattice clock revealed that its precision is chiefly limited by the molecular lifetime, which in turn was limited to tens of milliseconds due to off-resonant scattering by lattice photons. At the time we had initial theoretical results from the Warsaw quantum chemistry group which suggested that for some pairs of vibrational states it may be possible to achieve near-magic trapping using a deeply infrared laser. This would enable us to prolong the molecular lifetimes and interrogation times and could lead to improved clock accuracy. I have tasked the group to investigate this possibility. To this end, Dr. Borkowski suggested that we use an extra infrared laser to measure ac Stark shifts directly for several molecular clock transitions. Fortunately, a 2-micron fiber laser was just purchased for my other experiment, so it could be borrowed. During winter 2022-23 Dr. Borkowski, together with graduate students Brandon Iritani and Emily Tiberi ran a measurement that revealed a vastly different behavior of polarizabilities than we initially predicted. Faced with this puzzle, Dr. Borkowski proposed a different approach to calculating polarizabilities, where instead of our initial sum-over-states method, dc and ac polarizabilities would be first calculated *ab initio* as a function of internuclear distance using linear-response coupled cluster theory. Then, polarizabilities of individual vibrational levels would be calculated as averages over numerical vibrational wavefunctions. He asked a fellow quantum chemist, Dr. Wojciech Skomorowski of Warsaw University, to run the LR-CCSD calculation and then used his own codes to calculate the polarizabilities for all vibrational levels. The results matched experimental data perfectly, without any fitting. While it turned out that there are no opportunities for off-resonant magic trapping that we hoped for at the start, Dr. Borkowski came up with another use for the theoretical model he developed: to constrain the blackbody radiation systematic shift for the molecular clock. To this end, he derived analytic formulas for the blackbody radiation shifts for ac polarizabilities expressed in the form of Cauchy coefficients and applied them to the numerically calculated vibrational state polarizabilities. This unique approach enabled us to determine blackbody radiation shifts for our molecular clock to the 10^{-16} level and has led to a paper now published in the prestigious *Physical Review Letters*. Dr. Borkowski wrote the majority of, edited, and handled the submission of this manuscript.

After the polarizability measurements were completed, I tasked the group with rebuilding the experimental setup such that it operated with a vertical lattice (rather than a horizontal one) and Dr. Borkowski has contributed mechanical designs to this effort. This effort is a large scale rebuild that required a redesign of large portions of the experimental setup. We also needed to replace the strontium sample in the effusive oven, as the previous sample has ran out. Dr. Borkowski helped in that regard. As of this writing, we have recovered our narrow-line second-stage magneto-optical trap (MOT) and are preparing to implement the vertical lattice beam. In parallel, the implementation of the ability to switch between isotopes of strontium is nearing completion. In the next few months, we hope to trap strontium-86 atoms in the vertical lattice and produce $^{86}Sr_2$ molecules.

Dr. Borkowski also spearheaded the effort to redesign the laser systems used to prepare and trap cold strontium molecules in the molecular clock experiment. To be specific, the experimental setup now has a new blue cooling laser at 461 nanometers, a new narrow-line Pound-Drever-Hall-stabilized reference and cooling laser at 689 nm, two new offset-locked 689 nm lasers for photoassociation and photodissociation of weakly-bound strontium molecules, a new repump laser at 707 nm, several infrared lasers for the spectroscopy of deeply-bound states of ultracold Sr_2, and finally, an upgraded pump laser for the lattice laser system. Dr. Borkowski also contributed to the design of the new vertical optical lattice. All of these upgrades should increase the stability and uptime of the molecular lattice clock, which could be used in the future to track oscillations of the proton-to-electron mass ratio, for

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example. Importantly, Dr. Borkowski designed and led the effort to enable the experiment to operate with the strontium-86 isotope. This functionality will be critical to our efforts to strengthen constraints on new gravity-like forces via isotope shift spectroscopy in the molecular lattice clock. Lastly, Dr. Borkowski implemented a galvo-based switch for our wavemeter.

During the second half of his time in my group, Dr. Borkowski led a project to demonstrate how an ultra-precise isotope shift measurement could be used to constrain the magnitude of new Yukawa-type interactions (or "fifth forces") at nanometer ranges. This kind of research is important to fundamental physics: there are many theories extending the Standard Model with new particles, for example in an effort to explain the nature of dark matter, or solve the so-called hierarchy problem – the apparent smallness of the gravitational interaction as compared to the three remaining fundamental interactions. Constraining new interactions experimentally is a way of testing these theories. This work was done primarily by Dr. Borkowski and Dr. Emily Tiberi, then graduate student whose work he supervised. To show the sensitivity of molecular clock transitions to the new forces they calculated the energy shift to each vibrational level due to the new Yukawa interaction for two isotopes of strontium and calculated an extra isotopic shift due to this new interaction. Then, they considered a scenario where *ab initio* theory fully reproduces measured isotope shifts for selected molecular clock transitions at our current experimental accuracy. As it turns out, for Yukawa ranges comparable to the equilibrium distance of the strontium dimer the constraints that can be achieved surpass even the most stringent state-of-the-art constraints derived from neutron-scattering experiments or measurements of Casimir interactions. Encouraged by this promising result, we are submitting the manuscript describing it to *Physical Review Letters*.

Dr. Borkowski is involved in the theory research with our collaborators in the Warsaw group, as mentioned above. Aside from the engineering and experimental work done in the laboratory, Dr. Borkowski has supported the lab with theory input. Early on, he proposed a new pathway towards producing strontium-88 molecules which improved our molecule numbers by a factor of two. This helped demonstrate the operation of the molecular clock. He has also found photoassociative pathways for producing molecules of other isotopes of strontium. Furthermore, in collaboration with Dr. Wojciech Skomorowski and Prof. Robert Moszynski of Warsaw University, he has constructed an accurate, quantitative model of static and dynamic polarizabilities of the ground state strontium molecule. He applied this model to develop a quantitative understanding of blackbody radiation shifts in the strontium molecular lattice clock which allowed us to reduce the uncertainty of this systematic shift to the 10^{-16} level. It must be stressed that this was the first analysis of its kind and as such was published in the prestigious *Physical Review Letters*. He also led the effort to demonstrate the potential of isotope shift spectroscopy for constraining new Yukawa-type forces and was able to show that molecular lattice clocks could beat the state-of-the-art constraints derived from neutron-scattering experiments. Currently, he is involved in two theory projects: one deals with the quadratic Zeeman shift in a molecular lattice clock due to variations in the magnetic susceptibility of the strontium molecule with the internuclear distance. The other is concerned with the development of a next-generation beyond-Born-Oppenheimer interaction model for the strontium molecule.

During his time in New York, Dr. Borkowski co-authored three journal articles. The first, titled *Terahertz Vibrational Molecular Clock with Systematic Uncertainty at the 10^{-14} Level* [K. Leung *et al.*, *Phys. Rev. X* **13**, 011047 (2023)] reports on the observation and characterization of the systematic effects of the molecular clock transition between the most weakly bound state and the rovibrational ground state of the strontium dimer. This work was also featured in popular science outlets, such as *Phys.org* and *Physics*. The second, *Accurate Determination of Blackbody Radiation Shifts in a Strontium Molecular Lattice Clock* [B. Iritani, *et al.*, *Phys. Rev. Lett.* **131**, 263201 (2023)] is the first accurate determination of an important systematic effect for a molecular lattice clock. The last, titled *Searching for New Fundamental Interactions via Isotopic Shifts in Molecular Lattice Clocks*, is being submitted to *Physical Review Letters*. It must be stressed that both *Physical Review X* and *Physical Review Letters* are premier physics journals with top impact factors of 12.5 and 8.6, respectively, and both are extremely selective in the research that they publish. I am confident that future collaborations can bring more papers of similar impact. Finally, Dr. Borkowski has presented his work at several international conferences, including invited talks at SPIE Photonics West in San Francisco and the Workshop on Ultracold Molecules in Warsaw, as well as in seminars at the National Institute of Standards and Technology in Boulder, Colorado, the University of Amsterdam, and University of Strathclyde in Glasgow.

There are many opportunities for future collaborative research; the investigation of quadratic Zeeman shifts and beyond-Born-Oppenheimer effects is already underway. Another possible theoretical project is related to the use of tensor polarizabilities for engineering far-off-resonant optical traps for Sr_2. Dr. Borkowski could also continue to support our effort to produce strontium-86 molecules, an effort that he has already begun to implement in our current experimental setup. Lastly, he could provide theory support for our efforts to measure isotopic shifts in the molecular lattice clock and derive new constraints on new Yukawa-type interactions.

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All told, this has been a successful collaboration which has already resulted in two publications in top scientific journals. A third manuscript is now being submitted for publication and further works are anticipated in the near future.

Sincerely,

Tanya Zelevinsky,
Principal Investigator
Professor of Physics
Columbia University in the City of New York

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