Title

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Journal

Berkeley Scientific Journal, 28(2)

ISSN

1097-0967

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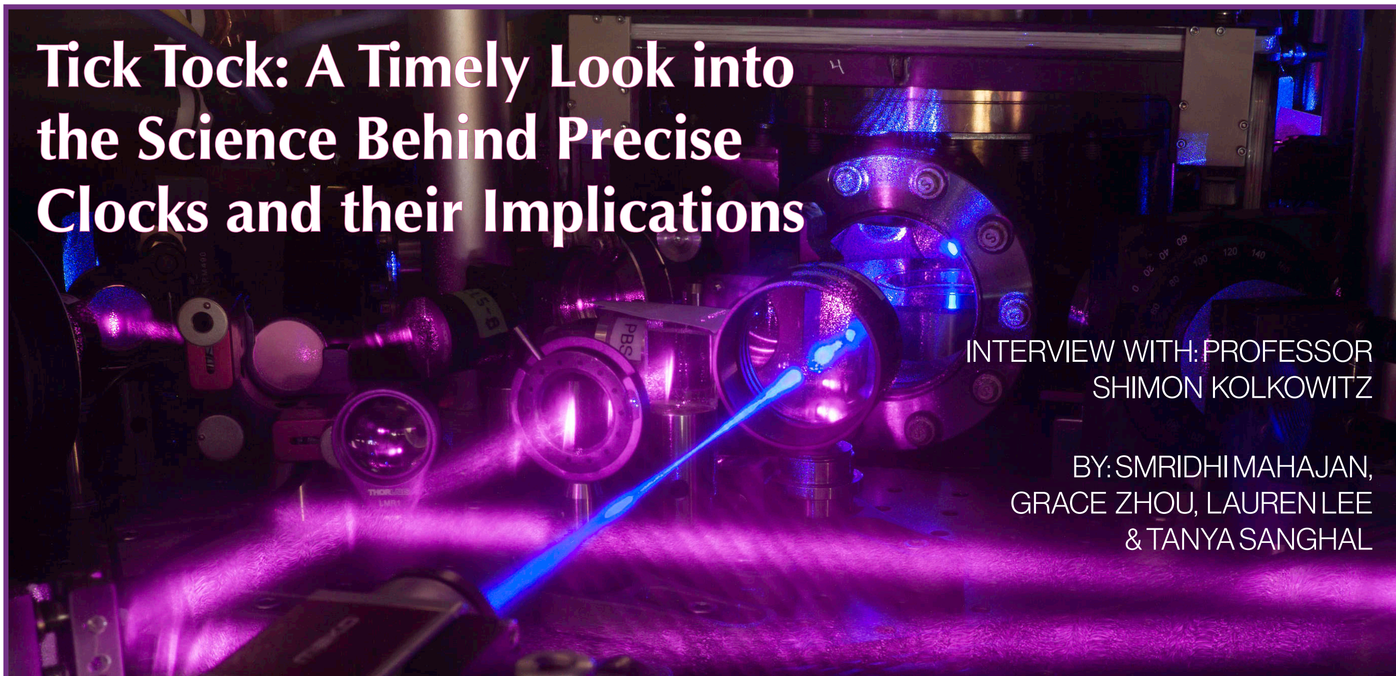
Publication Date

2024

DOI

10.5070/BS328264285

Undergraduate



Tick Tock: A Timely Look into the Science Behind Precise Clocks and their Implications

INTERVIEW WITH: PROFESSOR SHIMON KOLKOWITZ

BY: SMRIDHI MAHAJAN, GRACE ZHOU, LAUREN LEE & TANYA SANGHAL

Dr. Shimon Kolkowitz is an atomic physicist and quantum scientist. After graduating from Stanford University in 2008 with a distinction in physics, Dr. Kolkowitz earned his Ph.D. in experimental physics at Harvard in 2015, where his research focused on quantum sensing. He then joined Professor Jun Ye's research group as a National Research Council (NRC) postdoctoral fellow, working on metrology and quantum science with optical lattice atomic clocks. In 2018, Dr. Kolkowitz joined the Department of Physics at the University of Wisconsin, Madison where he created and conducted research on optical lattice atomic clocks. Dr. Kolkowitz is a 2019 Packard Science and Engineering Fellow, a 2022 Sloan Research Fellow, and a recipient of the NSF CAREER award. In July of 2023, Dr. Kolkowitz joined the UC Berkeley Physics department as an associate professor and the holder of the Herst Chair.

At UC Berkeley, Dr. Kolkowitz hopes to build a second atomic clock, conduct novel experiments to explore the interaction between relativity and quantum mechanics, and ultimately help bring atomic clocks in space.

BSJ: What got you interested in physics, specifically AMO physics and atomic clocks? What draws you to experiment-based physics as opposed to theoretical physics?

SK: I got into physics because I have always loved learning about science, especially how the universe works. I would like to understand it better – it has always excited me to learn about why something is the way it is and how it works. Especially as a kid, I loved looking into space and reading science fiction novels. My mom was a geophysicist and her father was a physicist, so there is some history of that in my family. Both of my parents really encouraged my interest in science. I was generally interested in biology and physics, and then I had a really great high school physics teacher who got me excited so when I went to undergrad, I decided to try it out and see how I liked it. I have stuck with it ever since.

In terms of atomic physics, I took a pretty winding path to get here. As an undergrad, I did not really know what kind of physics I wanted to do. I went to a seminar by a neutrino physics professor (Giorgio Gratta) who was studying neutrino oscillations and working on an experiment to look for neutrinoless double beta decay, which is a special kind of radioactive decay that certain elements might exhibit. To detect these rare events for neutrino physics, he was actually utilizing AMO physics. When I got involved in this experiment, I started working on lasers to help with that spectroscopy. One of the graduate students then told me how these same kinds of experiments are also being used to make quantum computers; I did not know what a quantum computer was, but it sounded really cool. I got into that and then decided that this is what I wanted to do for my Ph.D. I worked on quantum computing and related stuff for my Ph.D. but became a little bit skeptical that we will be able to build a quantum computer anytime soon– it is a really big challenge and still very far away. So, during my Ph.D., I got much more into using quantum systems to measure things such as sensors and clocks and other applications of quantum systems, aside from quantum computing, to learn about the universe and the world around us. Then, for my postdoc, I worked on these optical clocks, and that is how I wound up doing this. That is what is fun about science – everything is connected to everything else. You never know how the research you are doing will have an impact, and sometimes it ends up being useful in ways that you never expected. That is one of the things I really like about it.

In terms of experiment, I really prefer building things with my hands and having a physical intuition for things. My favorite part of my job is when we see new data for the first time. Nobody has ever done that exact experiment before; there is always something different about it due to imperfections. Understanding that data to learn about that physical system and then the universe is something that I really love and is a big part of why I am an experimentalist. However, there is always some theory; you need to understand the experiments that you are doing and there needs to be some motivation for it. One thing I like about atomic physics is that the theory of atoms, compared to most other things in nature, is pretty straightforward. Another thing you can do is collaborate with people– I collaborate with very good theorists who help with the harder concepts and can explain things to me. You do get some amount of control over how much theory versus experiment you do as an experimentalist, but you always need to understand what is going on. To make the connection between theory and experiment, you need a physical intuition and an understanding of how to connect the calculations to the actual thing, and you also have to remember that things are not the idealized version of what you have written down on paper. Often, what you see has nothing to do with the theory that you wrote down and you need to be able to diagnose and troubleshoot that.

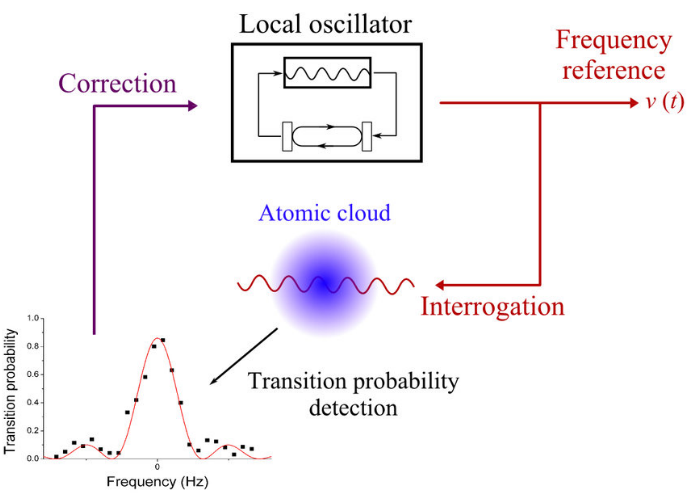


Figure 1: Schematic overview of the principles of atomic clock operation.

BSJ: How has the move been from the University of Wisconsin? Has your research, in terms of your scope and role, changed between institutions?

SK: I am still in the process of moving, I started the job here back in July of 2023, but some of my research group is still back in Wisconsin. The atomic clocks are still in Wisconsin because we have pretty stringent requirements on the environment that we do these experiments in. These very complex atomic experiments require a lot of lasers and optics and if the temperature in the room changes, the optics drift around, and the alignment of the lasers changes, and so does the frequency of the laser light. So we want to do these experiments in an isolated and well-controlled environment. Lab space is currently being renovated to enable me to continue my research at Berkeley but we still have some space back in Wisconsin for the clocks. One of my graduate students who is now a UC Berkeley graduate student is still living in Madison and running experiments along with a research scientist in my group. They will move as soon as the experiment can move out here. I am spending a lot of time on Zoom and Slack, but down the road, my move to Berkeley will allow me to expand and build a second atomic clock that we can do comparisons between and with a whole new set of capabilities that will enable new kinds of experiments, but only once the new lab space is ready.

BSJ: What are the mechanical foundations of atomic clocks, and how do atoms serve as a frequency reference in these clocks?

SK: Interestingly, atoms in atomic clocks typically are not really the things keeping time. The way a clock works is you need something that exhibits some kind of periodic phenomenon or oscillation that you can count; a classic example is a grandfather clock that counts the swings of a pendulum. Then there is something called an escapement, which is a little mechanical device that converts the swinging motion of the pendulum into the ticking and movement of the hands on the face of the clock. The actual clock itself is the pendulum and the escapement is the thing that counts the oscillations. The hands on the clock, the counters, tell you how many oscillations happened. That is essentially how all man-made clocks work, the ones in your phone recording this interview, in our computers, and even the clocks on microwave ovens. These clocks mostly are little quartz tuning forks that are vibrating at a very specific frequency. Because quartz is piezoelectric, your phone can count those vibrations electrically instead of mechanically. The problem with a grandfather clock, or one of these little tuning forks, is every one you make will be slightly different. If the temperature changes, then because the material has a coefficient of thermal expansion, the size of the tuning fork or the length of the pendulum will change, resulting in changes in the frequency of the clock. So the problem is that no two clocks are identical, and over time, no clock will be consistent with itself because of fluctuations in the surrounding environment. If we all want to agree on what time it is, we need something called a frequency reference. For most of history, the frequency reference was an astronomical phenomenon, such as seeing where the sun is in the sky. Is it over my head or did it just set? Or where is a certain star? One could look at those things and say, "Okay, I can use this to correct for the fact that my clocks are imperfect, and we can all look up at the sky and agree on what time it is." However, that is not the best way to do things, both because it happens on slower timescales, and as it turns out, even those things are not perfectly reliable and periodic. The Earth's rotation about its axis and the Earth's orbit around the sun are both impacted by external factors like the presence of the moon and other bodies in the solar system. So, even those frequencies change; the day is not exactly always the same length of time and the year is not exactly the same length from year to year. In addition, for physics experiments, and especially when we are measuring things extremely precisely, we want something that we can all agree on that does not require going outside and having clear skies, etc.. And that is what an atomic clock is. Instead of using astronomical phenomena like the periodic motion of the planets, we can use the transitions between states inside of an atom as our frequency reference. From quantum mechanics, we know that the energy levels of an atom are quantized, the electron orbiting the nucleus of an atom can only be in certain states and those states have different energies associated with them. Those energies are inversely related to the frequency of light by a fundamental constant called Planck's constant. I can relate the difference in energy between two different internal states of an atom to a frequency of light, which could be a color of light in the visible part of the spectrum. If it is outside of the visible spectrum, like in the microwave part of the spectrum, then it isn't visible to our eyes anymore, but it still has a frequency. What I can do with an atomic clock is take my imperfect man-made local oscillator and multiply it by a constant, and then compare that frequency to the internal transition of an atom and see if it is on resonance or not. If the frequency is on resonance with the transition, then my clock is ticking at the right rate, but if the frequency starts to drift away from resonance, then I can use my atoms as a frequency reference to correct for that drift or that imperfection in my particular man-made oscillator. For example, the standard way we define a 'second' is with a certain transition in an atom of cesium, which is the element that we have chosen. If I make a clock and you make a clock, we can both agree that our clocks will be consistent as long as we have both compared to this frequency, the cesium "hyperfine" transition, under the same conditions. This allows us to make clocks that can be very precise, accurate, and that can agree with each other. In principle, atomic clocks work anywhere in the universe, you do not even need to be in the solar system to agree on the definition of the second and make a very accurate and precise clock.

BSJ: Where does clock instability arise from, and how do you measure it?

SK: What allows an atomic clock to work is comparing the frequency of the local oscillator to the internal frequency of an atom. This is ultimately limited by a few things like how many atoms you have available, how identically you can prepare the status of the atoms and the environment of the atoms, how well you can compare the frequencies, and how stable or reliable the local oscillator is on its own, because that determines how often I have to compare to my atoms and how fast I have to correct for these drifts. So, the quality of my atomic clock is limited by the quality of my local oscillator. If I have to constantly check, I cannot do as good of a check. I have to be much coarser and faster in my corrections and then I cannot make a precise measurement of exactly what the frequency is. It turns out that one of the primary things that limits these clocks is how good the local oscillator is. Another thing that limits it is how many atoms you have. To measure if the local oscillator is on resonance or not, I prepare all my atoms in the ground state (the lower of the two quantum states making up the clock transition), and then I shine my light which is hopefully on resonance with my atoms, and see how many of them ended up in the excited state by counting them. It turns out in quantum mechanics, there is this weird thing where an atom can be in a "superposition" of these two states, meaning it is in both states at the same time. Another interesting thing is that when you make a measurement, you actually destroy that superposition, impacting the system. When I measure my atoms, I only ever measure them in one state or the other state. And so if I only have one atom, I am only ever going to measure it either in G (the ground state) or in E (the excited state). And if I have two atoms that I can measure, two in G or two in E or one in G and one in E are the only outcomes I can get. There is only so much information about whether I was on resonance or not that I can learn from a given number of atoms. The ideal situation is to be on the edge of the resonance so that if the local oscillator frequency drifts one way, I will measure fewer atoms in E, and if it drifts the other way I will measure more atoms in E. That is actually the ideal situation where I want to operate, where my local oscillator is parked half on resonance, and when I measure the atoms I get half in E and half in G. In this case, every measurement of every atom is a coin flip. And I am trying to check if my coin is weighted or

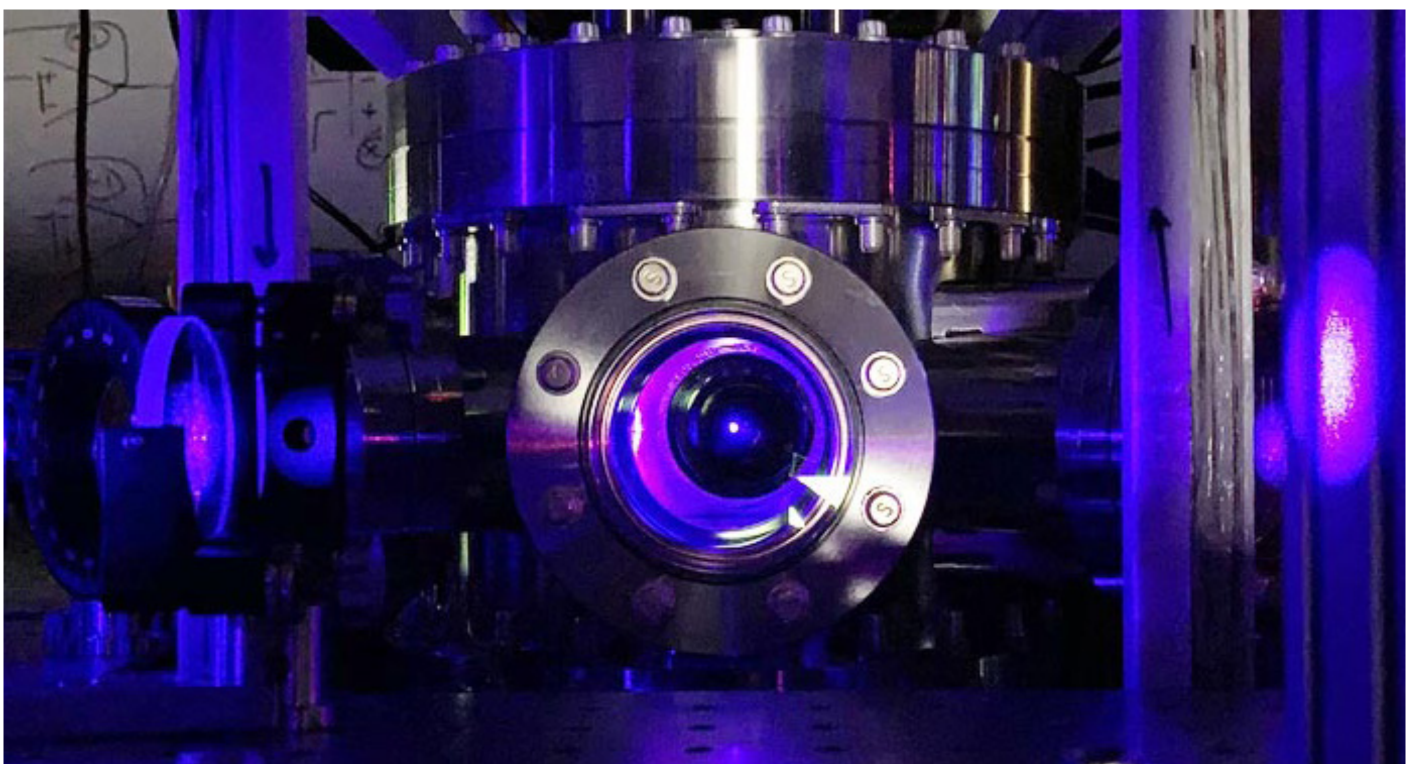


Figure 2: Strontium atoms cooled to near absolute zero are placed in a vacuum chamber to create an optical lattice atomic clock.

not, is it a perfectly fair coin that is exactly 50-50, or is it slightly more likely to end up in E than G. My ability to determine whether a coin is fair or not is determined by how many flips I do, or in other words, how many atoms I have. And so, the number of atoms, how good the local oscillator is, and if the environment of the atoms is fluctuating, will all limit the performance of these clocks and result in some level of instability.

BSJ: What is quadrature Ramsey spectroscopy? What equipment and techniques does it require, and how has your lab leveraged this technology to reduce clock instability?

SK: Let us say that I know that the frequency of my local oscillator is only going to change by some maximum amount in the time it takes me to do multiple comparisons with the atoms. That allows me to do a measurement with my atoms that can target that level of deviation. A new technique we developed, which we named quadrature Ramsey spectroscopy, lets you do the same sensitivity of measurement while handling a larger range of possible deviations of the local oscillator. The issue is that each atom measured is only ever up or down, so we have ways of converting that into some information about how far off from resonance my local oscillator actually was. The more stable my local oscillator is, the more tightly I can target my measurement to learn about that frequency to the next decimal point. So for some given local oscillator, I need to make sure that I can handle the maximum frequency deviation each time I do this comparison, which limits the precision of the measurement.

sophisticated algorithms, resulting in a better absolute clock. What we showed is that if you split that same number of atoms into two clouds, you can learn more information than if you did the same thing to all of them. We even went one step further in that paper and split them up into four clouds of atoms and showed you could determine even more information by doing that. It does get harder as you have to get more sophisticated with the degree of control that you have over the atoms. The main message is that we showed that what people typically do in these clocks is not optimal; even if it is easier. It is easier to understand and engineer if you do the same thing with all of the atoms in the clock, but if you can split them up, you can more efficiently allocate and take advantage of the resources that you have.

BSJ: What are the physical limitations for splitting up the atoms, and why does it get harder to continue dividing them?

SK: The quadrature ramsey technique is actually very easy to implement; I think that a lot of people will start doing it. What we did was split our atoms into two clouds and then slightly shifted the frequencies of those two clouds to learn slightly different amounts of information. In this case, we applied a magnetic field gradient. Since the atoms have some sensitivity to the local magnetic field, their energy level shifts so that each cloud has slightly different resonance frequencies. This lets us implement quadrature Ramsey: two clouds of atoms experiencing slightly different magnetic fields. Once you go beyond two, it turns out that you need to do different measurements to each cloud instead of doing the same measurement. That is much

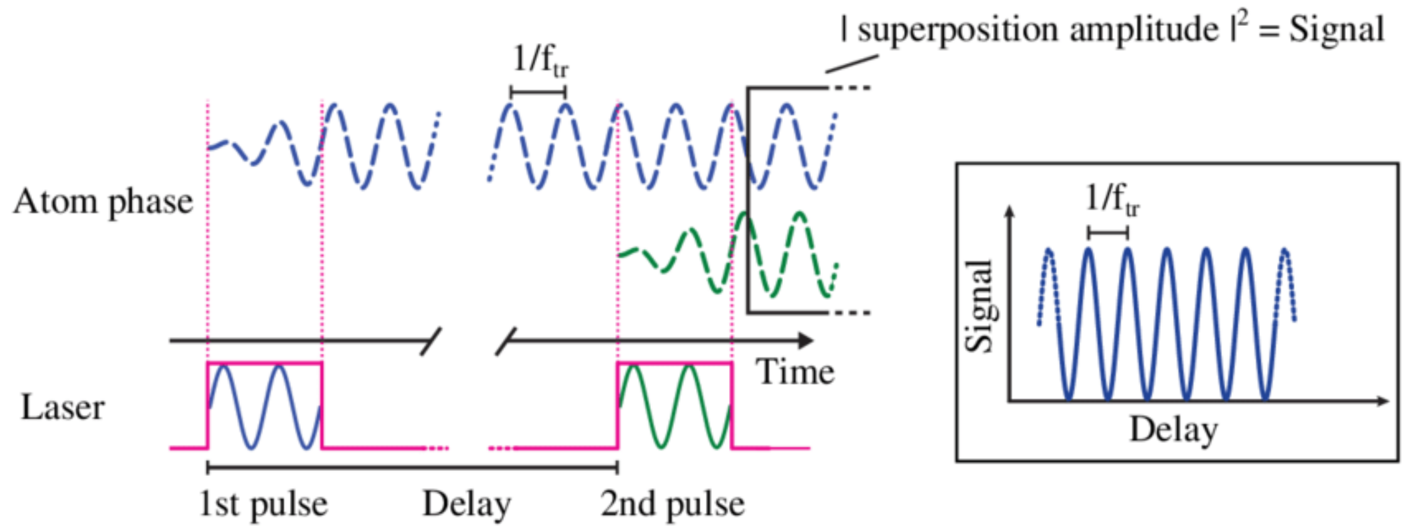


Figure 3: An illustration of a Standard Ramsey Spectroscopy. This demonstrates the principle of applying two short pulses of electromagnetic radiation to a sample of atoms or molecules. The delay in between the two allows the atomic states to evolve according to their natural frequencies. The second pulse interacts with the atoms and allows for determining the transition frequency between energy levels. The quadrature part of this technique refers to taking the measurement of the atoms from a ninety degree angle. Analyzing in-phase and quadrature response of the atoms allows for more information to be extracted from the experiment and provide a more complete overview of how the system is behaving.

What we developed to enable quadrature Ramsey is rather than just taking one cloud of atoms and measuring them all the same, which is what is done in almost every atom clock; we instead split the atoms up into different ensembles of atoms that we can independently measure. Then in principle, we can do some degree of different measurements and operations to each cloud. Having that extra control allows us to get more information and do more more demanding, but we developed ways to do that. One way would be by shining different lasers on the different clouds, but that is not ideal since we want all of them to be as similar as possible. If you start shining different lasers at different times on different clouds, that is not great from a clock perspective and it makes your experiment more complicated. You could also apply a very large magnetic field gradient so that each one is totally distinct, so that when you shine the clock laser light on the atoms, it only addresses one cloud at a time, but that is also not great for clocks. We worked very hard to come up with a way where, even though we only slightly shifted the frequency of each cloud from the others, we can still characterize and control it very well, and run a sequence where because of those slight differences, we prepare them in different states. Once they are in different states, we can apply the same exact laser pulses to all of them and still do different sequences to each of them to learn more about exactly what the local oscillator is doing. We are not the only group that is going in this direction, but it is a very exciting direction right now. There is a whole different kind of atomic clock that has only recently been developed, made up of individual single atoms, where each atom is trapped on its own and you have independent control over each of them. The performance of those clocks is not so great yet, because they typically only have a few hundred atoms whereas we have thousands of atoms. We are coming at things from the top down and they are coming at things from the bottom up. Both approaches are really cool and exciting and I'm sure in the end we'll meet in the middle. It really looks like we can still keep making better and better clocks – there is a lot of room for improvement.

BSJ: To what extent can the atomic entanglement be incorporated beyond the standard quantum limit, and to what overall cost on the precision of measurement?

SK: All experiments I have mentioned so far and have done in my group do not involve entanglement, but that is a direction that my group and the field are going in. No one has yet used entanglement to make a better clock, because it is challenging for a number of reasons. These entangled states are generally fragile and very sensitive to noise so they do not last very long. Another problem is the problem of dynamic range, meaning you need to know that your little oscillator didn't deviate by more than some amount and that determines what measurement you can do. When you are using entanglement, you are trying to learn very precisely about what the local oscillator did, but if you do not already know exactly how much it might have changed by, it is very hard to take advantage of the added precision of the entanglement.

I am confident that to really utilize entanglement, you are going to have to break up the atoms into a bunch of different sub-ensembles and then use each one to learn a little bit more about what you are doing. So our experiments with quadrature Ramsey and so on are actually steps in the direction of making entanglement useful to push beyond the "standard quantum limit."

Regarding limitations on the performance of the clock, first of all, there is the time that you spend actually entangling them when you are not comparing them to the local oscillator. That is one kind of penalty you pay, but then also depending on how you engineer that interaction, it can also then result in shifts of the frequencies of the atomic transition. Fundamentally, when you make these clocks, you want your atoms to be isolated from the environment as much as possible, but in order to get them to interact with each other, you need them to strongly interact with their environment, meaning the other atoms. And so you have to be very careful about how you do that so that it does not end up introducing additional shifts of your clock frequency, and potentially also broaden your clock transition. There are a lot of other people working on this, but it is really hard and so far, people have not managed to actually make a clock that works better with entanglement than it would without entanglement.

But it is one of the big goals of this whole field of quantum sensing and quantum information science.

Looking at quantum computers and these other related applications, it turns out to be quite challenging to balance somewhat contradictory and conflicting requirements. For example, one reason these clocks work so well is the atoms in them are very well isolated from their environment, but that also means that it is very hard to entangle them with each other.

Managing that conflict and tension between them, is one of the big challenges of building a quantum computer, where you are trying to do computations where your individual quantum bits only interact with each other and not the environment.

So, the environment is essential to performing the experiments. In quantum mechanics, everything is about interactions. It is especially important whether or not your system interacts with the surrounding environment. And a quantum system, if it interacts with the environment, loses the information–the state, the entanglement, and the superposition all get washed out once it has interacted with the environment.

BSJ: How do you design experiments to check the principles of relativity? How does height difference and the use of a miniature clock network play into this?

SK: The main effect that we can see and what we measured recently is the gravitational redshift, which is gravity changing the passage of time; this is a prediction of Einstein's theory of general relativity. What the redshift refers to is this– say you have one clock placed on the ground and another clock identical in every way raised some height off the surface of the earth. Since the higher clock has a greater gravitational potential energy, it will tick faster than the clock on the ground. This is an effect of relativity and is featured quite prominently in the movie Interstellar, where time passed more slowly for people closer to the black hole than the person that was further away from it. It is a much weaker, but still real, effect on Earth. For example, if you are a meter higher, time passes at 10-16 seconds faster than a meter lower, so over the course of your life, your head will be about three hundred nanoseconds older than your feet by the time you die at the age of one hundred. That is a very small effect, but our clocks are so precise that we can measure it. In our experiment, we measured this difference over a millimeter scale. We created multiple ensembles of clocks that we can independently measure, so we made a string of five clouds of atoms that were separated in height from each other by just a couple of millimeters between each neighboring cloud; the total distance between the highest and lowest one was one centimeter.

We have gotten good at measuring very small differences in frequency between these strings of clocks. That is perfect for the gravitational redshift because as they are being held in this vertical string, time for the highest cloud of atoms is supposedly ticking faster than the one below. We did this measurement and we were able to see the difference in the rate of passage of time for clocks that are separated by just one millimeter in height with respect to another one; that confirms that relativity is correct. Now, people are also really interested in turning this around and using this to measure Earth's gravity and relative heights of different places on Earth. It turns out that we do not exactly know, with respect to Earth's gravitational potential, how high different locations on Earth are with respect to other locations. So, we can use these clocks to measure that quantity better than any other existing technique, and we are doing so using the theory of relativity, which I think is pretty cool. People are interested in using this for things like geophysics, seeing that one region is rising or masses are moving around deep underground, which is an emerging field called relativistic geodesy. Our measurement shows that you can use this to measure millimeter scale height differences; but we did it in the most controlled possible environment where all these clouds are in the same vacuum chamber, experiencing the same environment. It is much harder if you take these clocks to different places and put one on a volcano and one somewhere else. That is much harder but the kind of thing that people ultimately want to do.

BSJ: What experimental results are telling of the existence of dark matter? What information would be needed for unifying the theories of quantum mechanics and gravity?

SK: In my group we are working towards doing searches for certain kinds of dark matter with our clocks. When you do those kinds of experiments, there are two possibilities: the more likely one is that you see nothing, which is what everybody has seen so far. However, we have reasons to believe that dark matter should couple to luminous matter, or normal matter, at least very weakly. So when we do these searches, we are looking at certain regions of parameter space where one axis is mass and the other axis is the strength of the dark matter coupling to luminous matter. Seeing nothing means the dark matter couples less strongly than you could detect, or it does not have the mass that was being searched for, or it is not that specific kind of dark matter that interacts with normal matter in the particular way your experiment is sensitive to. If instead you do see a signal, then other people have to go out and replicate it. Most likely, if you did see something, it was actually something else that you just interpreted as dark matter. For example sometimes there is a fluke of statistics, or there was some known physics that you had not thought about. That is all part of research; it is healthy and natural. Presumably, someone at some point will actually detect dark matter and we will learn what it is, but before that there will be a lot of null results and also false positives.

In terms of quantum mechanics and relativity, we do not know how to unify quantum mechanics and gravity. We do have some ideas about how to do experiments where relativity and quantum mechanics interact with each other a little bit. That is different from having a quantum theory of gravity – this is not saying we can write down how gravity works using the language of quantum mechanics, rather exploring how classical gravity or relativity manifest themselves in quantum systems or how quantum systems experience gravity. Those are different but somewhat related questions, and we do not actually know the answer. As I already explained, time passes differently at different heights with respect to Earth's gravity due to relativity, and in quantum mechanics an atom can be in a superposition of being in two places at the same time, but what does it mean for an atom to be in a superposition of experiencing two different times? We can write down a reasonable guess about what should happen, but nobody has been able to experimentally verify it yet. What you do with that information is honestly a little bit beyond me, too, in the sense that if we do the experiments and see what the theorists tell us to expect, we do not learn very much new physics. But since we do not really know how to reconcile these two very important theories of physics (gravity and quantum mechanics), there is the chance that we might really see something quite different from what we expect. That would be really significant and might help guide us in the direction of really unifying these things and writing down new kinds of theory that can capture both at the same time. The most likely outcome though is that we see what you would most naively expect to see – we will have learned something new, but it has not really told us how to unify these theories.

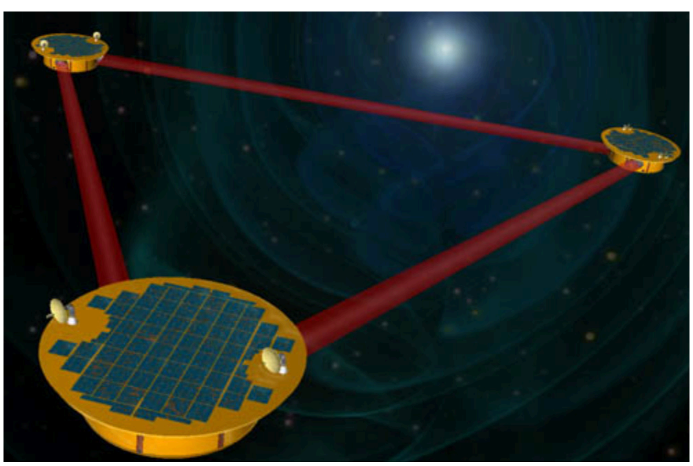


Figure 4: The Laser Interferometer Space Antenna (LISA), a gravitational wave detector, detects strains in space-time induced by gravitational waves.

BSJ: What are other applications of atomic clocks in physics that either your lab or other researchers in the fields are exploring?

SK: There are a lot, in addition to the experiments testing relativity and quantum mechanics and searching for dark matter that I told you about earlier, it turns out clocks have a lot of real world applications, including ones that you may not think about all the time but that affect your life every day. For instance, clocks are very fundamental to navigation as they are used in the GPS network. There are a bunch of atomic clocks in satellites in space, and that is what forms the GPS network which tells you where you are, and they are all drifting apart from each other because the clocks have the same limitations that we were talking about before. And so to keep GPS running, the US military has to constantly correct every clock in every satellite every hour or so, and if they ever stopped, then the GPS network would stop working in a matter of hours. It would be a problem if something disrupts their ability to communicate with these satellites and correct the clocks. All of GPS, all of global navigation, could fail very quickly. But if you instead had the clocks that we have in my lab in those satellites, they would work for about a month before they would have to be corrected, instead of for an hour. That sounds great, but the clocks in our lab are room scale experiments that need to be constantly tweaked and fixed to maintain them, it does not really work on its own for very long. We can run our experiments for a few hours before something stops working and we have to flip a switch or turn a knob. For GPS, the clocks need to be able to work for ten years without anyone ever touching it because it is in space. And in addition, it is very challenging to put our clocks in a small package, something that does not require very much power, and that can handle the radiation of space. So in my group we are trying to figure out ways to simplify these clocks and still get the same level of performance. If we can do that, then it will make it easier to put this next generation of clocks in space and to make GPS more reliable.

It also turns out that clocks are useful in other aspects of navigation. Suppose you do not have access to GPS for one reason or another, then the way that you navigate typically requires you to make very good measurements of the passage of time, so you want a very good clock for that. Those are real-world applications of these clocks.

There are also the fundamental physics application of clocks, which is seen in how we can measure time better than we can measure anything else. We actually define all of the units, like the volt, kilogram, and meter,with respect to the 'second', which is defined with respect to atomic clocks.

So making better clocks means we can measure everything more accurately. Our ability to measure anything with units accurately is limited by our ability to make good clocks.

You can also make a next generation of gravitational wave detectors. Right now, LIGO detects gravitational waves on Earth, which is really cool, but pretty soon there is going to be a new kind of gravitational wave project called LISA, which will be a version of LIGO in space.

You could give that detector a new set of capabilities that it otherwise would not have by putting our clocks on-board, and it would be a little bit like building a new kind of telescope that could look at gravitational waves in a different way and in a different part of the spectrum. But again, first we need to make these clocks simpler and find a way to package them up for space.

What I mentioned earlier about measuring the gravity of Earth and how one part of the Earth might be lifting or lowering the respect to another is another emerging application of these clocks.

Those are probably most of the big ones. But, I would say that there are always new ideas.
I am always trying to think of and work with other people to come up with new ways that our research can be useful. For example, there are new ideas about how you can use these measurements to search for a fifth force that we do not know about yet. You can also check if the laws of physics are changing over time. It is possible that the fundamental constants that determine the structure of atoms and the frequency of the clockrock transitions are varying in time or space, and we just do not know it is happening. We can test that too.

BSJ: What is a major goal you hope to accomplish in your lab and what direction do you see your research heading?

SK: The two things that I am most excited about are using these clocks to do new tests of relativity and this direction of exploring how relativity and quantum mechanics interact with each other. I really want to push in that direction. Even if the answer turns out to be what we expect, I would like to do these new kinds of experiments that have never been done. The other direction is to come up with ways to make our clocks more simple and reliable so that we can put them in space to make GPS better, but also test relativity more precisely, and search for gravitational waves with clocks in space.

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