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Quantizing Gravity: Unlocking the Mysteries of the Universe's Most Well Known Force

INTERVIEW WITH: PROFESSOR HOLGER MÜLLER

BY: JAMIE ELLA SCHWARZ, SOHINI OZA, SANIA CHOUDHARY

__Holger Müller__ successfully applied for his first patent when he was 14 years old and later received his undergraduate and graduate degrees in Germany before joining the Steven Chu lab at Stanford as a Postdoc. After joining the physics faculty at UC Berkeley in 2008, he began leading research in advancing technology to advance and apply atomic, molecular, and optical physics. His lab, the Müller Group, specifically does work involving electron microscopy, laser cooling, optical readings of neuronal action potentials, and atom interferometry. Atom interferometry, the focus of this interview, is the technique of using atoms' wave-like properties to make highly specific observations about them. Müller's atom interferometer is revolutionary in that it can hold an atom stable in free fall for up to seventy seconds, allowing researchers to measure the possible quantum effects of gravity on matter.

BSJ: What inspired you to begin your research on atom interferometry and observing gravity?

HM: There was no moment when I thought, "Yes, I will do atom interferometry and observe gravity." It was a journey. The journey started when I was a graduate student in a group in Germany where we tried to make extremely frequency-stable lasers like clocks, and for a short time, these were actually the most stable anywhere. By now, that record has been broken many times.

My PhD advisor graduated from the Steven Chu lab at Stanford, so when I graduated, my advisor said I should talk to Steven Chu about postdocs. I was not really that interested in Steve Chu's work, but I went there so as to not disappoint my advisor. To my surprise, 30 seconds after Professor Chu started talking, I was hooked. That was how I started working in interferometry. It was just a very convincing postdoc advisor.

When I started my work here at Berkeley, I had experience in these two fields—atom interferometry and very stable lasers in optical cavities as a pair of mirrors—where you send a laser beam back and forth, and it has nice properties. The most natural thing to do was put the two together and make an even better interferometer, and that is what we did over the past couple of years. Now, it is so good that it is actually the best method to test these aspects of gravity.

BSJ: What was the invention process of the optical lattice interferometer like? How do its structure and function relate to what you have observed so far?

HM: The optical cavity is more or less like a resonator for laser light, so it has two features: It makes the light wave stronger by resonance, and the wave has a certain optimal shape. Like how the shape of a violin gives the violin its sound, the shape of an optical resonator determines what the laser beam between the mirrors looks like, and it will always remain the same shape. That stability removes some errors from the atom interferometer, which turned out to have very beneficial effects. We could now use the light to hold the atoms so that they would not fall. The classical method of atom interferometry is to let atoms fall, but then after at most two seconds, they are gone. In this machine, we can hold them for a minute and still work with them.

A longer answer to what moved us in this direction includes a scientific controversy: Steven Chu and I had an idea many years ago to view what the atoms do inside the interferometer through a lens of relativity theory. If things move very fast, you are forced to use relativity, but if they do not, you can still use it. I think that viewing physics through a lens of relativity is very elegant, even in cases where it is not necessary to do so. Since the atom interferometer works so well, you can measure the properties of the atoms with extremely high accuracy, and we found that the properties agree exactly with the theory.

If you are in a gravitational field, it affects the speed of a clock, a famous relativistic effect known as the gravitational redshift. While people send clocks into space to measure this, we claimed that the atom interferometer confirms the gravitational influence on the flow of time in a lab. We thought that it was a harmless, almost boring insight, but we published it anyway. To our surprise, people pushed back against it super strongly, and they argued that the analogy was either wrong or at least badly misleading. One of their arguments was that the atoms in the atom interferometer are always moving because they are in free fall, which complicates the interpretation, they argued, and makes it less of or not at all a confirmation of gravitational redshift. We said, "But in the lattice interferometer, we can hold the atoms so they do not move," resolving this counterargument. That is why we got so excited about doing it.

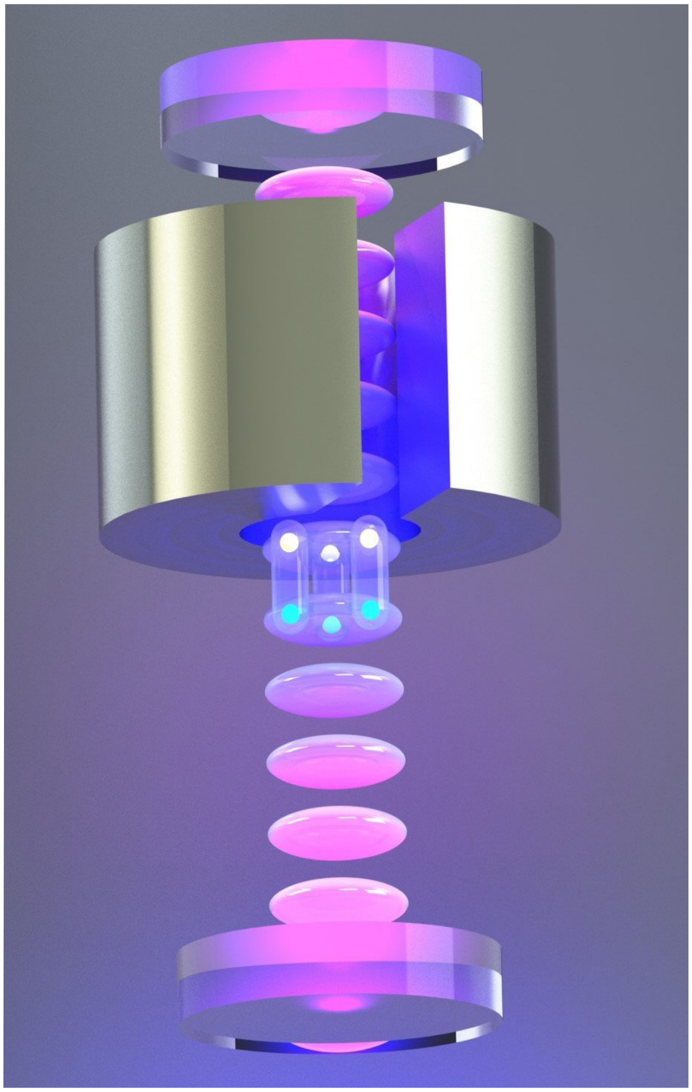

Figure 1: Lattice atom interferometer probes source mass gravity

BSJ: In setting up this experiment, you had to isolate the atoms from vibrations and from Earth's gravity. What were some of the challenges that you faced in creating this ideal environment, and how would the experiment change if you were to do it in a zero-gravity environment like space?

HM: These are two big questions. Let's tackle them one by one. If I want to hold something so that it does not fall, what I have to do is apply a force upward that balances the downward force of gravity. For the atoms, the laser inside the cavity provides that force. What do we want to do with the atoms? We have a tungsten mass close by that will attract the atoms a tiny bit, but since the tungsten mass is much smaller than the Earth, the gravitational attraction of the tungsten mass is about a billionfold weaker than the force of gravity from the Earth. Therefore, it is a billionfold weaker than the force provided by the laser. The gravity from the Earth does not change much, but the force of the laser is made by us in the lab, by human-made imperfect devices, and so it changes all the time. It changes because the laser strength varies with time and because the laser beam shakes a bit when somebody is walking in the lab and causes slight vibrations in the floor. Also, it can change because the laser beam is brightest in the middle and darker as you move away from the middle. This force varies a lot, and it is a billionfold stronger than the force we want to measure, so we have a huge varying force that we are not interested in and a tiny force on top that we want to measure.

So, how do we measure the tiny force without measuring the huge force? The trick was introduced by my postdoc, Cris Panda, who worked on an experiment measuring electron-electric dipole moments, something extremely small in the standard model but measurable in some theories of physics. The idea is that if you can modulate the signal you are interested in without changing the other, you can separate them. So, we moved the atoms from underneath the tungsten mass to be on top of it, reversing the sign of the force we wanted to measure while not changing the force of gravity of the Earth. Likewise, we moved the mass in and out, and that switched the force on and off without switching the Earth's force. With these two switches, we could sufficiently suppress the systematic noise and signals.

What would be different in space? When we prepare the atoms, we cool them down to nearly absolute zero, so they do not move a lot from their thermal energy, but we do not get them to absolute zero, so they still move a bit. So, in space, the time limit for atom interferometry is no longer given by the atoms falling down; it is given by the atoms moving out of the experiment by thermal velocity. Because the laser beam no longer needs to balance gravity, it can be a lot weaker. It just needs to balance thermal velocity, which means you could turn it down tenfold, maybe even 100-fold. That is great because everything gets ten times easier if you can turn down the laser ten times. That is what you could do in space.

There is a quantum industry trying to build quantum computers and quantum information processors. One of these companies wants to get NASA interested in flying such a thing in space. As you can imagine, once you put things in space, they take much longer to build and get much more expensive, so you really need to show that there is a meaningful advantage. In our case, the advantage is very clear: You do not need such a strong laser anymore.

BSJ: What role did you play in NASA's Cold Atom Lab experiment on the International Space Station?

HM: The Cold Atom Lab, or CAL, started roughly ten years ago in a meeting at the University of Maryland. We were all put into a room and nobody told us what we were supposed to do except that there was some idea to put CAL onto the space station. It was our job to figure out what to do. At first, we were all very confused and everybody was looking at the other people, hoping that they would know what we were supposed to do. Some of them were very accomplishedaccomplished academics, and everybody thought that they were going to tell us, but they were just as confused. Slowly, people started talking, and they had some ideas. The ideas were put into a paper, and from there, a mission concept developed. I loved it because it went relatively fast, unlike these huge space missions like the James Webb Telescope that are decades in the making and billions of dollars over budget. CAL is the opposite. It is much cheaper, smaller in scope, and faster, and that is what I love about it.

I think it is very good that CAL exists because it demonstrates that you can run atomic-physics experiments in space that really work. Our community is very bad at making things that just work. Our experiments always look like there are hundreds of thousands of knobs only graduate students know how to work, and if you do not run them daily, they start falling apart, and a week later, they do not work anymore. So it is a great achievement that this does work.

What it is not is a science mission. It was sold as a science mission, and it did achieve some science, but I wish they were a little bit more clear that the first mission's main value is showing that the technology can work. The science coming from the second mission is much more important.

BSJ: This experiment also deals with the potential of the screen fifth forces, the chameleon, and the symmetron fields. Can you elaborate on the significance of these mystery forces and how the experiment addressed them?

HM: Chameleons and symmetrons are a theorist's brainchild and an experimentalist's dream. In what sense? Cosmology describes the expansion of the universe, and this expansion is not only ongoing but also accelerating. The reason for the acceleration is called dark energy, but the word "dark" in the name is supposed to signify that we do not know what it is, and that is largely still true. Some theorists early on thought that dark energy must be caused by some sort of new particle, and if it is indeed a new particle, which is still unclear, then you can immediately deduce that it has to be an extremely light particle because that would naturally make it fill the whole universe evenly. If it is a light particle, then it should also generate a force between regular objects. In the same way that photons are the particles of light and are responsible for the electrical force, any new particle that exists should generate forces.

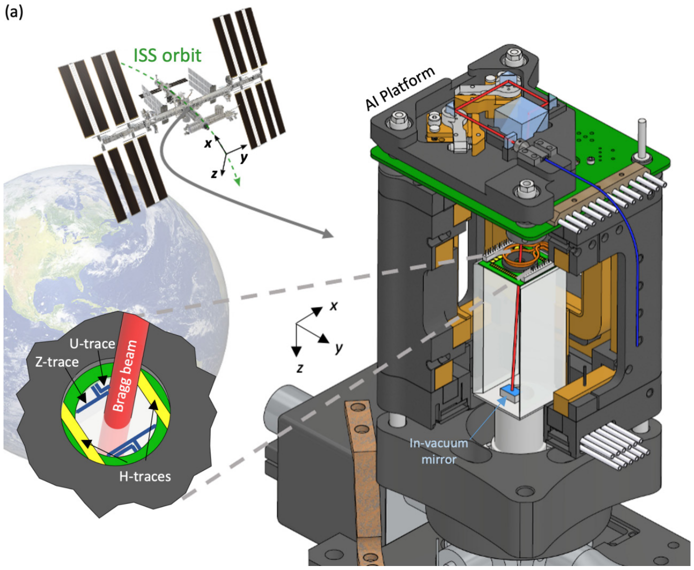

Figure 2: Atom interferometer setup onboard the ISS.

Then, you immediately run into contradictions with experiments that have never found any force other than the well-known ones. Paul Steinhardt, Justin Khoury (Steinhardt's graduate student), our collaborator, and Amanda Weltman came up with this chameleon theory, and they said, "What if the particle has a mass that is a function of the local density of other masses, so that in the lab, close to other massive objects, it would become extremely short ranged and therefore hard to measure, and that way, this particle could still help explain dark energy by filling the universe, and yet it would not be measurable in laboratory experiments?" It was a kind of conspiracy theory built to evade experimental constraints.

Clare Burrage, a theorist from the University of Nottingham, wrote a paper saying that an atom interferometer could be sensitive to this chameleon particle, and she described a setup exactly like what we were building anyway. That was such a lucky coincidence. In half a year, we ran the experiment; however, we failed to find any "chameleons."

> *"Chameleons and symmetrons are a theorist's brainchild and an experimentalist's dream."*

BSJ: Looking into the future of your research, how is the precision of this technology changing, and what are your future goals with interferometry?

HM: There are many things you can do with this technology, and we have picked one goal. You would love to be able to run atom interferometers on board a ship, for example, because if you can measure gravity on your ship, you can use "gravity-assisted navigation." Essentially, you take gravity measurements of where you are navigating, and you compare that to a map of gravity and that gives you hints about your location. But for that, your interferometer needs to be able to move even when the ship is in heavy seas. A standard interferometer cannot do this because it has to sit exactly upright, or the atoms will fall to the side.

That is one application you could use. What I also want to do is characterize gravity much more precisely, and there is a thought experiment to go with this. In the 1950s, Feynman came up with an idea. Matter can be in a superposition, where you will either find it in one place or another with 50% probability. Well, we know that this is true. We have done it in the lab many times. The atom interferometer does it all the time. So this is not just theory. But then, if the object is heavy, it should attract things to it. Yet if the object is in one place and another, or in a superposition of being one place and another, which way does gravity point? It could pull you one way, but with equal justification, it would pull you the other. The gravitational field is in a superposition, and the theorists are not really sure what that means because the theory of general relativity—which is used to describe gravity—cannot be reconciled easily with quantum mechanics. If we could observe that a gravitational field can be in a superposition where it will pull one way with 50% probability and another way with 50% probability, that would be huge because it would be the first time that anyone has ever seen that gravity is a quantum force, just like the other forces. Are we close to doing that? No, absolutely not. But we have worked out how our experiment can, in principle, do that.

BSJ: If you are unsure you can do it before your students retire, why do you think we should start?

HM: We should start because the ability to tell goes up with time, with the duration that we can run this atom interferometer, to the second power or even to the fourth power, depending on the configuration. Since we can do 60 seconds instead of two, that means we are already 30 squared, or even 30 to the power of four times closer than before this experiment. That's why we want to start. I say that because I think it's an important point about what makes science go forward. It's excellent that people support science, like the Heising Simons Foundation. They know exactly what we want. They know that this first iteration has zero chance of actually seeing the effect, and we have been completely open about how long a shot this is, and yet they say, "Okay, you want to make the first step, go for it." I do not call it high-risk research because the risk of success is nearly zero, but you have to start somewhere; otherwise, it is exactly zero.

> *“I do not call it high-risk research because the risk of success is nearly zero, but you have to start somewhere; otherwise, it is exactly zero.”*

BSJ: As your research is developing, and you are observing more and more accurate results, how do you think our global understanding of physics, gravity, and dark matter could change as a whole?

HM: That is so hard to predict with dark matter and gravity—these are really the hardest nuts to crack in all of physics. The first iteration of our experiment is going to make a very tiny step forward in that question by ruling out strawman theories of gravity. You could ask yourself, “Well, how could gravity not be a quantum force?” Because we know the rest of the universe is quantum, and gravity has to interact with that quantum world. So how could it possibly not be quantum? Nobody knows the answers to these questions, but people are theorizing about them. One very simple theory is that gravity keeps measuring your quantum systems continuously or periodically, and then, depending on the random outcome of that measurement, it generates a gravitational field, and the next time it measures it again finds a slightly different configuration of matter and generates a new gravitational field, and so on. Nobody believes that this model is right; that is why we call it a strawman theory. But the fascinating thing is, no other experiment can rule it out. Our experiment could, because what you would find is that gravity would have to be noisy, given that with each new measurement outcome, the gravitational field would change a little bit. That is not going to change anyone’s worldview about this, but it makes a tiny step forward. From there to ultimate success—where we could show a signature of quantum gravity—is a very long road, and it is very possible that before we arrive there, somebody else arrives at a similar goal with completely different methods, but we still must try.

“From there to ultimate success—where we could show a signature of quantum gravity—is a very long road, and it is very possible that before we arrive there, somebody else arrives at a similar goal with completely different methods, but we still must try.”

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