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Authors
Gill, Manraj
Nuckolls, Kevin
Patel, Saavan

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Undergraduate

Interview with Professor Siddiqi: Quantum Scale Measurements

Kevin Nuckolls, Saavan Patel, Manraj Gill

Berkeley Scientific Journal: How did you get started in your field of research?

Dr. Siddiqi: I am working now with quantum information devices, putting together quantum mechanics with electronics. Of course I didn't do that when I was an undergrad. In reality, science is motivated by fundamental questions, and the overarching theme that links all of this is how to use superconductive devices. These are devices that don't have resistance. In the early days of this science, these devices were used as amplifiers. They still are, of course, for detectors and for astronomy. This is because you get rid of resistors, which are a source of noise. This is classical noise due to thermal fluctuations. If you get rid of this noise, things get very quiet and you have very good detectors.

Later on, it was realized that if you get rid of this resistor then you can also have things that have a long life time in the quantum mechanical sense. In an amplifier, you don't make an oscillator, or a pendulum, you make something with no Q (the quality factor, or the Q factor). If you were to make an amplifier or a pendulum, without a resistor it just keeps on ringing. This isn't always the most useful device in the classical domain, but in the quantum domain it is very useful.

What this means is if you have a system with quantized energy levels, the life time is very long. For example, let's translate from the classical world to the quantum world. I take a pendulum, a mass on a spring. It oscillates by going back and forth like a sine wave. The quantum version of this is that you have a system with multiple levels and it goes back and forth between levels. This is called Rabi oscillations, the quantum analog to a pendulum. Those oscillations also die out over a period of time, depending on how much resistance you have. In the classical sense, you would have drag that slows the pendulum down, in the quantum sense, you can have noise that slows that delay down. So if you want to keep quantum systems alive, it's the same in the classical sense as having an oscillator which doesn't break down or has a high Q.

So a lot of the science that we learned in the old days of low temperature physics with superconductors and electronics has mapped onto the quantum problem. We simply quantized a lot of those techniques we knew from the classical domain. At the same time, we discovered that you can actually use these quantum devices for something, for information processing, for factoring numbers and cryptography, for simulation, for information and so on.

BSJ: We were also interested in your personal attachment to the research, and how you picked quantum information theory from the vast number of fields.

S: Science all has the same denominator, which is: it should be done with precision. You should look at those questions that have relevance to reality. Now what's interesting of course is the relevance changes from decade to decade. Problems that are interesting now become less interesting later. That's not how I think, I ask what the fundamental building blocks I need to understand something, and whether or not it's popular is not relevant to me.

For example, quantum mechanics is an interesting theory because it's one of the most debated and also one of the most successful theories we've had in modern times. For 80 years we've tried to understand very basic tenants of this theory, but at the same time can't prove it wrong. You can't do an experiment that says this is not quantum. That's a very interesting point for us. This particular idea is driving a lot of us, we all ask the question "can we see quantum mechanics in our daily lives? Can we build a circuit or a computer that obeys quantum mechanics?" We can't see any reason to say no. The only way then to do this is to try to build the computer. That's really what motivates a lot of us, what are the limits of quantum mechanics, how far can we push this. Can we clone a quantum undergraduate? Something with that level of complexity, that's always an interesting question.

BSJ: A lot of our readers are not familiar with quantum physics, how would you explain the goals of your research?

S: One of the most fundamental things we look at is the idea of quantum measurement. This is the postulate that has stirred debate for 80 years. When you look at something quantum mechanics, you have to perturb it. You have a state of an electron, which is spin up or spin down, you can write a wave function that says its half the time spin up and half the time spin down. What does it mean to be here and there at the same time? It's completely against any classical notion we have. What does it mean for the cat to be alive and dead at the same time? That's really what quantum mechanics told us.

The founders were totally right, if you make a measurement, the outcome will be a stable state, or an eigenstate. Now the question is, what does it mean to make a measurement? Does it happen instantaneously? That's really what was troubling. Is it "poof" the box opens and the cat dies immediately? What is the process, nothing is instantaneous in life. What we've been trying to do is track that evolution. Say we start with something that is half alive and half dead, spin up and spin down, now what does the measurement do to that state? As you gain more information about the state, the more you push it to a classical state. Once you have enough information to determine the state it's in a classical state.

This quantum mechanics depends on how much information you have about the system, the more information you get about the system, the more you push it to a classical state. The quantum mechanical superposition only works perfectly if there are no observers. If you have any observers, that's what causes decoherence. Putting all of those pieces together is very elegant. Trying to understand that there is nothing instantaneous, and as soon as information starts to leak out of the system you push it into an eigenstate, is something we see in our day to day life. It's the measurement that's doing that, it's the act of measurement that's actually bringing on the classical behavior. That I think is very interesting to test, and seeing how you can actually can track the state. You can actually watch it move to decoherence.

What I did in my most recent nature paper (*Mapping the optimal route between two quantum states. Nature,* 2014), is we actually watched it real time. How can you watch it if you are decaying it? This is very interesting, if you observe a quantum system when you cause it to decay, but there has been information extracted, you can do things with that information. You now have it in your possession! That is really the difference between quantum feedback and decoherence.

Now let me say something about that. If you have a state where the spin is up or down in the classical sense, and you start to measure it and see it's way over here. If you were extracting this information, [you have] no idea what the motion of the spin is, but you do know what the spin is. So when the environment measures a quantum system, it's decoherence, because you are losing the information to decrease the freedom. However, if I am the source of decoherence, I

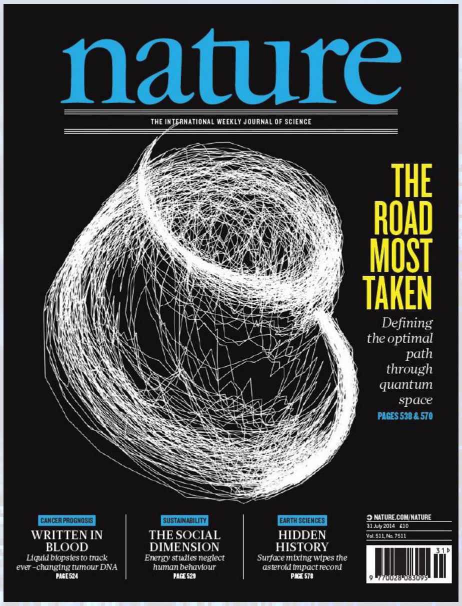

Figure 1. Cover of Nature in July, 2014: 'The Path Most Traveled' is a review of *Mapping the optimal route between two quantum states.*

actually have the information, so you can use the information to push the system back. That's the idea of quantum feedback. You measure it, but then you correct it. That's really the heart of this science of quantum feedback.

We've understood that it's okay to perturb the system, that's natural, it's built into quantum mechanics. If your measurement is efficient, and you are the only source that is taking information, then you have a chance to correct it. If you lose the information to someplace else, you can't correct it. The idea is: yes, quantum mechanics has this stochastic nature to it, but nonetheless if you are the observer you have this information and you can process it. You can compare that to classical feedback. If you were a thermostat for this room, what would you do? First you'd measure the temperature the room, then you'd adjust it to the desired value. The funny thing about quantum mechanics is that as soon as you measure the temperature of the room, it lights up into a fireball. This a problem! You have to control it back, so you measure the temperature before the fireball to correct for it. However if this information went somewhere else, you can't correct for it, it would be permanently lost. Nothing is lost in quantum mechanics, it just transfers from one system to another. No information is ever destroyed, you just don't have access to it. If you don't have access to it, it might as well have been destroyed.

BSJ: What experimental setup do you have to do these measurements? What were the problems associated with these?

S: We work with electronic circuits. So the idea is the following: you can take the particle that is truly a quantum object, like an electron, or an atom. In reality what is an atom? An atom is an anharmonic oscillator. A harmonic oscillator is a mass on a spring. What does a quantum oscillator look like? It has evenly spaced energy levels, that's not what an atom looks like, it has unevenly spaced energy levels. So you need an anharmonic oscillator to mimic the behavior of an atom. How do you make an anharmonic oscillator? You make a spring that is non-linear, or an inductor that is non-linear, like a pendulum. That is what a Josephson junction is, a non-linear inductor.

So, I make a circuit with a Josephson junction instead of an inductor and I shunt it with a capacitor: I have an anharmonic oscillator. So, basically, I have particles in a well, which is not a parabolic well. In quantum mechanics, if it's a parabolic well, they're all evenly spaced. "Particle-in-a-box" is unequally spaced. I don't know how to make the "particle-in-a-box," but I know how to make "particle-in-a-cosine-potential." That's what you get with a Josephson junction.

So you make a circuit that is this oscillatory type

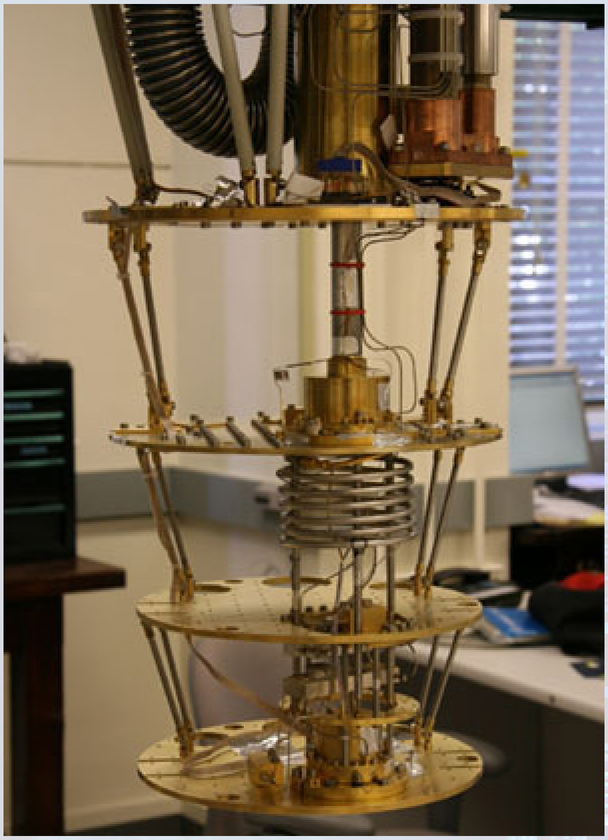

Figure 2. Cryogen-free dilution refrigerator used to cool the system to temperatures as low as 10 milliKelvin.

of circuit. Then, you have to get rid of the decoherence, the resistance. Cool it down to very low temperatures, 10 milli-Kelvin (mK), and get rid of all the stray light. You close up all the boxes, paint them black, shut them tight so no photons get in. One photon of visible light is death. It will completely destroy your circuit. So you have to cool it down to low temperatures, keep the light out, go ahead and make it low loss. Make sure the materials on your chip are low loss. Any oxides, so on and so forth, fingerprints, oils, junk, and whatever. This stuff is the source of decoherence; it's a source of resistance. So you can imagine your thumbprint oil is measuring the qubit (quantum bit) because it's resistance, right? It's taking information out. So you want to get rid of all of those sources that are extracting information. Stray light is taking information out. It means somebody in the universe can observe your system. They've shown light through your box and gotten rid of it.

So, you have to get rid of all these sources and work in the microwave domain, because frequency is related to temperature. The frequency you work at will set the temperature you work at to see quantum effects. So we work in the microwave, 1GHz, 5GHz, 10GHz. This sets the temperature at about a Kelvin. So we've cooled down to 10mK, then you see quantum mechanics. Those are the challenges that you need. You need to make it small, also the size scale. So, it should be of order of a micron or less. So, nanometer size scale. Nanometers at milli-kelvin at gigahertz,

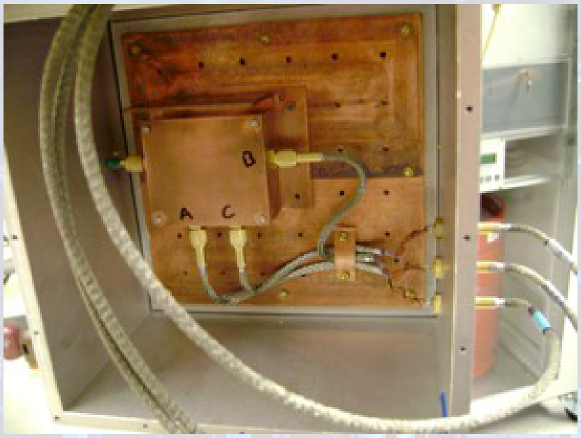

Figure 3. Shielded aluminum and copped boxes used to make measurements to minimize "Sources that are extracting information from the system."

this is what you need to do to see quantum mechanics.

BSJ: Now that you've eliminated these noise producers, how do you measure how well you did?

S: So, the longer the lifetime, the better you're doing. That's a good question! You'll never get rid of them completely, of course. So, this is the notion of an open quantum system or a closed quantum system. So the idea of a closed quantum system, this is rather ideal. Maybe you only do it on the blackboard. You write some quantum object that nobody talks to. At some point, something in the universe, maybe gravity, right, the graviton talks to it. We haven't reached those levels yet. So that's a fundamental question: What is the longest lifetime you can get in a quantum system? We don't know. Is there some fundamental source of decoherence, information extraction that is there? Maybe it is gravity…non-uniformity in the gravitational field. We don't know.

So, you do better and better and the lifetimes have changed a lot. When this field started in '99, lifetimes were on the order of a nanosecond. That's pretty short for those oscillations to die out. Now, they're on the order of almost a millisecond. That's pretty long. In the electrical domain, a lot of stuff happens in a millisecond. Your computers work in many gigahertz. You get a lot of data operations done in a millisecond. And that's really why there's a lot of excitement in this field, because if you can get, let's say 10 operations in the computer science sense, bit flips, then you can do error correction. Once you can do error correction, you don't need to make the coherence time any longer any more. You just correct for the errors as they happen. And that's really where the field is at right now. We're just on the threshold of implementing error correction.

BSJ: You spoke about using this quantum feedback system to take information and use that information to stabilize. We understand that your experiments are performed in a very small period of time, and so, we were wondering how you make sure that the feedback that you're getting is still relevant to the state of the system. You mentioned that if take a thermostat and you

take the temperature as it blows up in a fire. How do we know that that fire is the same as it was?

S: So, it is real time feedback. So, for example, I have the following problem, I want to stabilize this arrow at this position. I can continuously measure deviations from this point and correct for them. So what are the relevant time scales? The relevant time scale is to close the loop. The feedback has to be faster than the characteristic time of fluctuations. So this happens fast, but the fluctuations are slow. So the lifetime, let's say is of order of microseconds, so if I feedback at 100 nanoseconds, that's faster than the lifetime. So the faster you can feedback, the more accurate your correction is.

And it's adaptive, so it's real time. So I can keep sampling it, right? And keep pushing it back. The graininess, the granularity will come in with how fast you sample. So, for example, if I want to see how smoothly I hold it here, maybe it's jerkier. So that sort of a question of time scales. So the point is that you should extract information faster than the decoherence time. That's the only thing you have to fulfill. It makes a lot of sense because the decoherence time is the time for information to flow out to the environment. So you should pull information out faster than the environment. So that sets the fundamental time scale for doing that.

BSJ: So, at this stage, you're able to make sure the particle doesn't decohere for a certain amount of time using the feedback system. Forever. So are you able to, say, have it decohere to one state and then bring it back into coherence afterwards?

S: Yes, well, we can let it go to a particular state and then bring it back and revive it. The difficulty is the following: the efficiency of the measurement is not 100% yet. And that's not because of the amplifier. It's because of the actual losses in getting information from the quantum system to the amplifier. So, for example, here's my quantum object. There's information flowing out. Some of that is lost because you have a resistive channel along the way, you have a wire. [It comes before] your amplifier and the part that I lose tells me how efficiently I can stabilize the state. And that is hovering somewhere between 50-60% for us at the moment. So for every two photons that come out, we see one, one gets lost.

So that limits how well you can stabilize a state, stabilize a process, so on and so forth. As that gets better, the ability and the fidelity by which you can produce a state will get better. But yes, once you can track a state, you see that there is no concept of decoherence. Decoherence means you have lost information, but I know where it is. It might not be where you want it to be, it might not be where you think it is, but you can always correct for it later.

So, for example, I give you the problem of parking your car on that spot. Maybe your car is there, or there, or there. It's not lost. It's just not in that spot. See, that's a very different problem. But if you lost your car in the parking lot, you cannot find it anymore. You don't know where it is. I know where it is. It's just not where I want it to be because I keep measuring it. It keeps moving around. But if I really want to put it there, then I can put a control pulse and say "Go here," and I can drive the system to that point. So that's really the feedback aspect. As long as you know where it is, you can do lots of things. Maybe I want it to go around in a circle. That's fine. As long as I know where it is, I can tell it "Every time it is deviating from the circle, go back to the circle." That's how you stabilize Rabi oscillations. If you want to stabilize a state, that means you just park in one spot in the parking lot, in your Hilbert space. I just want to be 0+1. Every time I deviate, I push it back to 0+1. So the key aspect of it is just tracking it. Once you track it, you know where it is, then you can do whatever you want.

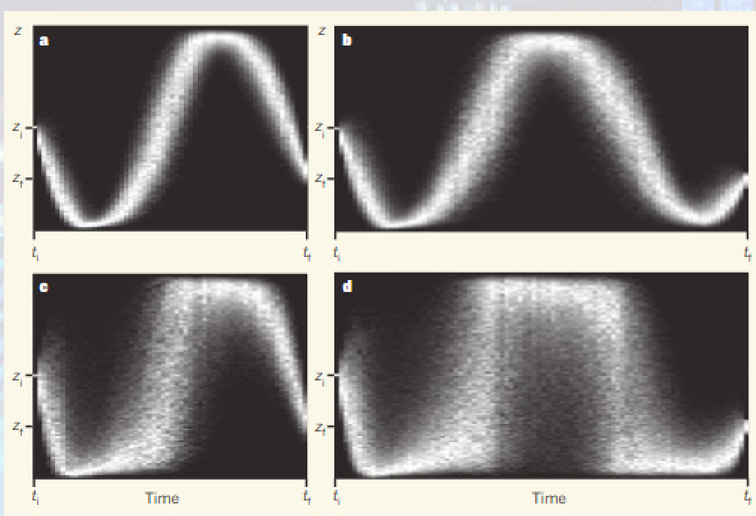

Figure 4. Representation of the quantum state where the paths define its trajectory. An increased strength of measurement leads to a more random change of state.

By the way, for quantum error correction, it is very simple because you have an error. It's either up or down. The error is: It's not up, it's down! So you continue to measure. When it starts to go down, you push it up!

BSJ: So, what kind of amplifier is it that you were talking about?

S: Yeah, so, we make our own circuitry to measure these systems. And it's also made with superconductors, so on and so forth. The funny thing is it's the same circuit as the qubit, it's just the classical circuit. It actually is a real pendulum. Yeah, so you have a "particle-in-a-cosine-potential." If you quantize the potential, that gives you the qubit. If you have a lot of levels and you don't feel the level quantization, you basically have a non-linear pendulum, and that's a parametric amplifier, just like you have in optics.

BSJ: So it's just a larger scale of this well?

S: Yes, exactly, which means bigger junction. Larger scale means physically bigger junction. So micron scale, not hundred nanometer scale. By the way, how any of these amplifiers work is actually quite straight forward. If you have a linear system, you cannot transfer energy between modes. For example, I have a transmission line, a cable, or the air, and there are two frequencies that I'm speaking at. The amplitude will not transfer between one frequency and the next, they both propagate without interfering. This is why all of your fiber optic lines work. They send lots of signals. They don't interfere with each other.

And, in fact, they work hard not to have non-linearity, because when you have non-linearity in the line, then you have distortion. That's when energy transfers from one frequency to the other. The amplifier problem is totally the opposite. I put in a signal. I want it to grow, so I want to put energy into that frequency. I have a little wave. I want this wave to grow. It means I have to propagate through some non-linear medium. And I'm in a non-linear medium, I drive it strongly with another signal and that energy goes into the thing I want to measure.

That's how the parametric amplifier works. So, I need the non-linear medium, the non-linear oscillator. It gives you a source of non-linearity without dissipation. Because if you had your resistance because that would just kill the information. So, it's just a question of transferring energy from one frequency to the other and that's what the amplifier does.

BSJ: Can you explain the significance and the applications of being able to both monitor and drive qubit into different states?

S: For quantum informational science, there's error correction. Because you now have real time information about a state and you can correct for it. You can error correct in terms of computing and executing high fidelity computations but just in general, it means that you can beat decoherence. In a quantum system, you don't have to watch decay. If you can continuously measure and correct, you can have quantum mechanics preserve forever. You can preserve any quantum state forever. So, it's a resource and you can use quantum mechanics as a resource.

BSJ: What do you see as the future of this research in the next five to ten years?

S: What we are interested in at the moment and for the next five years is to look at what happens to many-body dynamics in quantum systems. I have one quantum system, I have another one, and another one towards increasingly more complexity. We have this five qubit system… can you measure all five of them at the same time? And what do the correlations tell you? You see, it's a big information problem. You can encode information at a very dense level in quantum systems. Each bit is now a huge Hilbert space. So, you have an exponentially increasing information space. But you can only read out, so far, one at a time. That's the problem! It is a well-known problem in quantum information science that tomography does not scale in terms of resources.

For example, if I encode in five qubits a tremendous amount of information, but if I only read out one at a time, then I need a lot of resources to read out each one. So, we're asking if you can simultaneously read out all of them. Because after all, our measurement is continuous and not projective. It's not that you measure one and you collapse the state. You don't have to collapse the state in measuring quantum systems. Can you use that to measure a many-body system? And can you use that to reconstruct a many-body state is really the fundamental question.

BSJ: So, are you looking at bettering your electronics to measure more systems? Or are you looking at bettering your understanding of how the many systems interact?

S: Both! We have to improve the loss of information. And we're doing that by putting the amplifiers on chips which gets rid of the wires. But that's hard to do. In principle, putting them on a chip gets rid of the wires and you just put a whole bunch of them together. So, both things. But you see now it's interesting… this is a new realm of quantum mechanics because it's not measuring one spin but five or ten spins. And you want to measure all of them coupled together and see how they evolve together. The question is that if I know what the system has done in time, can I reconstruct what it did at a previous time? All together in one shot. If I could, that's very useful as I can study quantum objects, not piecemeal, but in its entirety.

BSJ: Do you see this research kind of going towards quantum computing and calculations?

S: We develop the fundamental science that underpins quantum measurement. Whether one wishes to use it for measurement or communication, that's [up to them]. Perhaps there are other folks in the field who use our techniques to do quantum computing. We are more interested in the fundamental physics.

BSJ: Are there other people working on measuring quantum systems in a different manner?

S: There are people who are more oriented towards quantum computing. They would like to have some version of our science and simply adapt.

BSJ: So, essentially translating and applying…

S: Yeah! They just need it for a particular application. And we look at it in the more general sense.

BSJ: Do you see any other directions, besides computing, where applications are originating?

S: So, there's sensors for meteorology, hardware simulators for new materials, for cosmology and then there's quantum annealing, which is dealing with problems in machine learning. Quantum enhanced sensors, you can use quantum mechanics to enhance sensitivity to electric fields and photons. So, there's a lot of things that you can use quantum mechanics for. Can you build a quantum machine that obeys quantum mechanics and not classical mechanics? Non-classical electrodynamics but quantum electrodynamics? So, for us the applications will be broader that simply information science.

BSJ: And away from applications, just in terms of understanding the environment?

S: Oh, absolutely! This is fundamental quantum physics! What is the role of the environment? What is the role of decoherence? How do you manage that and how do you manage that in a many-body sense? So, absolutely, it's all fundamental quantum theory.

Image Sources

http://research.physics.berkeley.edu/siddiqi/people.html

http://physics.berkeley.edu/people/faculty/irfan-siddiqi

http://qcamp.ee.ucr.edu/

http://www.nature.com/nature/journal/v511/n7511/full/511538a.html

http://research.physics.berkeley.edu/siddiqi/photo.html

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