Decode Quantum with David Wineland

Welcome to the 74th episode of the Decode Quantum podcast. In our series of three episodes recorded in Lindau where dozens of physics Nobel laureates were gathered with young scientists, we had a chance to meet **David Wineland**.

This podcast was recorded on July 1st, 2024, in Lindau, Germany during the 73rd **Lindau Nobel Laureate Meeting**. You can learn about the context of that unique event in this past post, **Back from Lindau**, July 2024.

Biography

David Wineland is an American physicist currently at the University of Oregon who is specialized in atomic physics, and in particular, uses laser-cooled trapped ions to implement the elements of quantum-computing. He became a laureate of the Nobel prize in physics in 2012 along with Serge Haroche of Ecole Normale Supérieure and Collège de France, Paris. He received his PhD in physics from Harvard University in 1970 on a topic we'll see later in our discussion. He was then a post-doc at the University of Washington where he worked on electrons in ion traps. In 1975, he joined the National Institute of Standards and Technology (NIST) where he created a group working on ion storage and was also an academic at the University of Colorado, Boulder. He and his colleagues were among the first {laser cooling was demonstrated at the same time by the group of Peter Toschek in Heidelberg} to laser-cool ions in 1978 and then demonstrated other optical techniques to control ions and implement the first two-qubit logic gate in 1995. He and colleagues also worked on the creation of the most precise atomic clock using quantum logic on a single aluminum ion in 2019. The 2005 experiment was the first demonstration of quantum-logic spectroscopy. The most precise quantum logic clock using an Al^+ (aluminum) ion was demonstrated in 2019. This work later contributed to the creation of trapped ion quantum computers from the companies IonQ and Quantinuum.

The following transcript from the podcast has been edited by David Wineland and Olivier Ezratty. It is slightly different from the podcast audio recording to clarify the discussion content.

What brought you in quantum science and then quantum computing?

As a young kid, I liked mathematics, so even in college, my major for a while was mathematics, but I was taking some physics classes, and I liked it. I had always been pretty good with mechanical things, so when I got to graduate school, I started looking around for what people were doing. I was a graduate student of **Norman Ramsey** (1915-2011), who's a Nobel Laureate, and he and his colleague **Daniel Klepper**, who later went to MIT, they had invented and demonstrated the first hydrogen masers. Hydrogen masers are not the most accurate clocks, but they're good flywheels. They can hold the coherence of the oscillations for a long time. So, they're still actually used in practice. I only did the maser work as a graduate student. After graduating, I went to the University of Washington under **Hans Dehmelt** (1922-2017), also a Nobel laureate. His interest and probably his most significant work was focused on measuring the electron magnetic moment to about 12 digits. I think it is the most precise test of quantum electrodynamics theory versus experiments that's been done.

Do you remember the topic of your thesis?

It was "The Atomic Deuterium Maser", a simple title. Norman Ramsey wanted to have precise measurements of the hyperfine structure of all three hydrogen isotopes. Tritium had been done in part because tritium frequency is very close to that of hydrogen, so they could use the same apparatus. But deuterium has a substantially different wavelength. So, it was basically the same prescription, but it required some changes in size versus the hydrogen maser to make an accurate measurement.

How is the difference in the number of neutrons you have between tritium, deuterium, and hydrogen changing the spectroscopy?

It is mainly just in terms of the hyperfine structure. It changes the hyperfine frequency because of the different nuclear magnetic moments in the isotopes of hydrogen. For example, the tritium nuclear magnetic moment is very close to that of the hydrogen nucleus, but deuterium nuclear magnetic moment was quite a bit smaller, leading to a hyperfine wavelength over four times larger than that of hydrogen and tritium leading to a larger apparatus. But the experimental techniques were basically the same.

Masers were invented before the laser. They operate in the microwave regime. Why was it interesting back then to work on these wavelengths?

I'm not sure about this, but at that time electronic coherent sources of microwaves were available (e.g. Klystrons) to compare against the maser radiation, whereas coherent sources of light were not available.

Norman Ramsey's interest was just having accurate measurements of all three isotopes. It turned out that the deuterium masers had some interesting features. But the hydrogen maser is still easier to work with. I don't think anybody's ever made a second deuterium maser.

In your initial scientific career, what drove you to get interested in ions? It's a bit different than what you did initially.

That's right. Near the end of my graduate school, I was reading what other people were doing, and I saw what Hans Dehmelt was working on. He had done some measurements on the magnetic moment of helium ions and their hyperfine structure. That was interesting to me so I applied to work with him, but when I got there, his focus was on the electrons. So, I worked on just electrons.

And so, your early work, the first experiments you did on ions, they led you to make advances in many fields. I mean, it's amazing, because you have atomic clocks, spectroscopy, and, of course, quantum computing.

In the case of ions, we were thinking about precise frequency standards and so on, but the kind of techniques we were using would also later apply to implementing logic gates.

What's funny is back then, even the term "qubit" didn't exist yet. So, you were toying with quantum objects. There was no quantum computing.

Shor's algorithm was a stimulus for a lot of people to jump into quantum computing.

There's, there's some synchronicity between what you did and this creation of Peter Shor's algorithms.

Key initial experiments on trapped ions were in the mid-90s as well. Yes, I think we were well poised to make quantum logic gates. We had to make a few changes in what we were doing, but basically, we were able to use the basic techniques we had developed to implement the logic gates.

Can you describe how you use ions to create atomic clocks?

It's not just ions, but atoms in general. The idea is that you first must find some transition that you can measure precisely. What that means is you should be able to account for of all the systematic environmental perturbations to the clock transition frequency, like stray magnetic fields. The cesium clock has been the standard for the second, in part because the systematic perturbations are easier to understand than in some other atoms. The time taken to count 9,192,631,770 oscillations of its hyperfine oscillation defines the internationally agreed on definition of the unit of the time – the second. The idea of using ions to make clocks is the same. We just want to find transitions in ions where we can precisely understand and correct for the environmental systematic shifts in the transition frequency.

Was it a way to improve the accuracy? Because there have been a lot of improvements with several orders of magnitude since then.

It's a continual process of getting better and better.

How many orders of magnitude did we gain in atomic precision?

In the mid to late 90s, the uncertainty in the Cesium hyperfine frequency was about 1 part in 10^{13}. With trapped ions and neutral atoms, the uncertainty is now about 1 part in 10^{18}.

In the mid-nineties, it looks like trapped ions were probably the first to be positioned to create qubits.

NMR was just a little bit later, then superconductivity came much later. So, was it the first qubit that we ever created?

Some of the basic ideas of quantum computing with one qubit, such as rotations of a qubit were demonstrated with NMR, but NMR is very difficult scale. That is, it's hard to see how macroscopic samples could interact to make gates at the quantum level. So, although NMR experiments were able to demonstrate some of the basic ideas, it wasn't clear it couldn't be scaled, and interest came to focus on atoms, ions, and superconducting qubits.

Could you explain the main differences between cold atoms and ions as qubits, because we hear a lot about both?

Fundamentally, for qubits, you don't care whether they're neutral or charged. You just want to be able to control their properties and the actions you impose to make the logic gates. So, I don't think there's any fundamental difference and there's no clear winner. There's atoms and ions, but there's also a large fraction of the work on quantum computing that is done with superconducting devices.

But there's still a big difference. The difference is with the control, how you position the ions versus the atoms. You have more control capabilities with ions. Is it the main difference, or are these all different?

At this stage, I don't think that ions are necessarily more controllable than neutral atoms, but time will tell.

I was not meaning to create opposition, but maybe explain the difference from a scientific standpoint, even the experimental standpoint. An experiment to drive ions is way different from the ones you use with cold atoms.

One difference there is that with ions, we can talk about their motion in simple terms. For example, a single trapped ion is a harmonic oscillator. We use this motion as a transfer mechanism to transfer quantum properties of the internal states, the quantum information, from one ion to the other.

One big difference is you use a circuit for an ion trap to control the ions, you don't have a circuit to control the atoms, it's a vacuum. Is it a big difference?

Yes, we use electric fields to trap and move ions. However, neutral atoms can be trapped with the electromagnetic fields associated with focused laser beams, so-called "optical tweezers" and two atoms can be brought together to make logic gates by moving the laser beams appropriately. The mechanism for logic gates is different than ions, but I would say there's no obvious winner yet on using ion qubits versus neutral atom qubits.

When you mean the motion, you mean you're making a reference to phonons?

It's the harmonic motion of the ions, so yes, we can call them phonons.

Okay, and then you have ions shuttling which is different.

Yes, we can move ions with electric fields that act directly on the charge of ions, but neutral atoms can be moved with optical tweezers. The systematic effects that come into play are different so at this point, I think the choice between ions and neutral atoms is not clear.

And so more than 20 years ago, you created the blueprint for QCCD, the ion trap circuit, where you use ion shuttling where you control them. That design is quite old now, and it looks to be adopted by most of the players now. So, what happened in 20 years of progress in that space?

I think people just got better at controlling the systems, particularly the traps, where the trapping electric fields can be generated with all electrodes lying in a single plane using microfabrication techniques. When I was at NIST in Boulder, in relatively close proximity to us was the company Quantinuum. Some of our former students are working there, and they've used the idea of shuttling to advantage. It's still in its infancy, but it looks like it is a scalable way to make a large system.

There were arguments on Paul traps and Penning traps, there are different ways to trap the ions, so there was a lot of learning, a lot of experimental and theoretical learning along those last 20 years, so that's what I wanted to get from you. What did we learn through these two decades in controlling the ions and then controlling the gates as well?

Controlling individual gates involved control of some basic atomic physics. But to scale up, it now looks like you must somehow have a means to transfer information between groups of ions. And one way to transfer the information is to move ions from one place to another. Those are some of the basic ideas and people are getting better and better at doing it.

When you want to build a scalable quantum computer, is it an engineering challenge, is it a technology development challenge, is it a scientific challenge, is it a mix of all of that? How do you view those different challenges?

In the case of ions, I don't think there's been any real fundamental new ideas recently in terms of basic operations, but the scaling is a real engineering challenge. The basic idea has been to have separated groups of ions and devise ways to connect the groups. We have talked about moving ions. Another way is to teleport information but that requires first establishing entanglement between ions in the different locations. The basics of teleporting have been demonstrated but doing it on a large scale will be challenging, so my guess is that physically moving the ions will be important in realizing a large-scale device.

What's interesting in that space is when you look at the various qubit modalities, they all have advantages and inconveniences. And so, when you look at trapped ions, it's very typical, you have very high fidelities. As far as I know, these are the best in town. Recently we had three nines of qubit utilities for two-qubit gates, which is really good. I mean, even at the scale of 20 qubits, even 56 with Quantinuum, and with 99.87%. But still, it's difficult to scale and the gates are slow.

The large scale 2D architecture has not been proven yet, so it's interesting to ask how we can maintain high gate fidelities while scaling. I'm sure people will come up with some new basic ideas, but I think the challenge right now, at least for the companies that are interested in this, is that it is an engineering challenge.

There's still a lot of fundamental research happening, right? Can you explain what is being done on the fundamental side right now?

I can give one example being explored at the University of Oregon. The basic idea was thought up by my younger colleague there, David Allcock. His idea is to effectively use different species of ions by using multiple levels in a single species of ion to accomplish different tasks, some to be qubits and also to transfer information by shuttling and some to provide state measurements. The other thing to keep in mind is we need to work at relatively low ion temperature, so we need to do laser cooling to reach those temperatures. David's idea was just that we could do the laser cooling on one transition and not interfere with the qubits that are based on another transition. And I think people are starting to also think about this as well.

Quantinuum is using two species as well, ytterbium and barium. One for cooling and one for computing.

Yes, that's one way to go and we had implemented this scenario previously with other ions. I think the difference with David Allcock's idea was that you could use the exact same ions for cooling and computing, but using different transitions for qubits and for cooling.

When you talk about spins, we refer to silicon spin qubits, like you have with companies like Intel and others, in Oregon, by the way, but spins are everywhere. Can you explain how you see spins as well when you control ions in quantum computing with trapped ions

We have often been careless using the term "spin." This comes from the idea that any two-level system can be represented by a spin-1/2 electron in a magnetic field. The term "spin" is just easier than saying "two-level system" each time.

It's been a problem when you try to explain in a simplistic manner how you segment the qubit types because the most simplistic way is to say with atoms, so called atoms or ions, then you have electron spin, whatever. You can put NV centers, silicon spin, whatever. Then you have photons. And then you have a sidetrack for superconducting qubits, which are artificial atoms. But it can be criticized by some physicists to say, oh, but superconducting qubits, in some cases, they are using photons. Spins are everywhere. You see, it's difficult to explain that in a simplistic manner. To be exact, scientifically.

With atoms and ions, you're thinking of spins and with superconductors, the physics is different, but you're still talking about qubits. One thing with atoms or ions is we do have to consider their movement. We use it for logic gates, but we also need it for transporting information throughout the processor. In addition, the ions to generally be cold, because their movement perturbs their the spectrum.

One key advantage of ions is the many-to-many connectivity, so you can implement CNOT gates between whatever ions you have, at least at mid-scale.

Well yes, one idea that you mentioned already is being able to move ions around, so nowadays, even commercial companies are separating ions, different qubits, bringing them together to make gates. So that's the basic idea there, and it continues to be pursued.

But again, there's a trade-off. You can move them, you can have many-to-many connectivity, but the gates, at least now, are quite slow. So, are there ways that are being looked at to speed up the gates some way?

In many cases the gates with trapped ions are relatively slow but this needn't be the case. For example, in 2021, the trapped-ion group at GTRI (Georgia Tech Research Institute) implemented an entangling gate on qubits whose levels are separated by an optical frequency. In this experiment, they generated Bell states in 35 microseconds, significantly faster than other ion logic gates up to that time.

What's the limit? Can you explain the limit? Where is it coming from?

The main limit, at least with ions, is that the ion motion is crucial to transfer information. You're coupling mechanical oscillators together and use the difference in the coupling strength for different modes of motion that yield internal-state dependent phases for the different modes of motion. Increasing laser beam intensity can make the gates faster but at some point, other unwanted modes or internal states are coupled in which gives errors.

When meeting with a couple of companies, mostly in Europe or in the UK, there was a lot of discussions on the way you control ion gates, because you usually have either microwave RF signals or lasers. It seems that many companies want to get rid of lasers, for whatever reason that you could explain. What are the trade-offs between driving the ions with lasers and microwaves and RF signals? How do you

engineer all of that?

For current multi-qubit trapped-ion logic gates, you need to cool the ions down, and that means lasers. In general, it looks like it's easier to perform logic gates with laser beams. In principle you can implement logic gates with RF or microwaves, but it looks much more efficient if we do it with lasers. Perhaps some of the bright people out there are figuring out ways to get around this limitation.

I saw you mentioning the role of engineering. What is your understanding and view, particularly when you worked at NIST, about the engineering cycle? Because each of the groups, every qubit modality has a different cycle. When they create a physical chip, it takes a while to design the circuit, then it takes a while to manufacture it, then tape out {tape out?}, then characterize, then test. This cycle has a length that's different across the different qubit modalities. So, do you think trapped ions are in mid-range length cycle, and how can we speed that up to increase the speed at which we improve the technology?

I would say, at least for ions, I think it's a fair statement, to say that nobody has come up with any dramatically different ideas than what's being pursued right now. There are always bright young students coming up, and maybe they will figure it out, but the basic ideas have remained the same for quite a while.

There were no recent improvements in the way you just manufactured the circuits themselves.

At least from my view, I would say there haven't been any dramatic changes.

I think IonQ was manufacturing its initial circuits at Sandia Labs, I think, in New Mexico. Other companies use either GlobalFoundries or Infineon in Europe. They try to use larger fabs to get higher quality. It looks like there's a key figure of merit in the quality of the circuit as it scales. Are there some changes happening in that space?

Fabrication techniques must be improved. Certainly, the companies and even some of the experimentalists working on trapped ions are relying heavily on that.

Do you think we could create a quantum processor with trapped ions, which would be monolithic with how many qubits? A monolithic system before you interconnect those systems.

That's where I think we are headed, but maybe I don't know what you mean by monolithic. As systems are scaled up, they are becoming monolithic. But the basic ideas, I think, haven't really changed significantly.

One company sticks circuits next to the other to scale it in a 2D surface. That would be semi-monolithic, I would say, it's got a big, large surface, but then you would have to interconnect maybe larger systems with photonic interconnect. It seems that many, many researchers and companies want to interconnect QPUs with those photonic links. Have you seen the progress in that space?

With trapped ions, you can teleport a qubit without moving the ions although it first requires entanglement distributed between the two sites. I would be surprised if people deviate from the idea of being able to move ions around, say locally, maybe in a small processor or something like that. I'm thinking that idea will probably prevail. But then you must worry about when you scale up, somehow you must transfer information.

It's always related to the way you create logical qubits and what's the overhead. And so, if with these very high qubit fidelities you can scale quickly, like creating a good logical qubit with a good fidelity with a minimum number of ions, then you may be in a position to create a viable system with let's say 100 logical qubits on a single system. That's maybe the goal.

With the ideas we have now with trapped ions, I think it's scalable, but the actual implementation of the scaling is becoming an engineering problem. Of course, people will undoubtedly come up with new ideas that we haven't considered, perhaps better ways to transfer information and so on. Even with what we know now about the basic operations in principle, it seems it's just a problem of scaling, which is a problem of engineering. I think that the ideas we have now are scalable, but it would be nice if there were more efficient ways to think about scaling than we have now.

When you hear about Serge Haroche talking about these issues, not especially on trapped ions, he says there's a lot of science efforts still to be undertaken to solve many of these problems, not just engineering. But there's a lot of science still. But there's still a debate among the physicists between these two, I would say, two challenges, science on one hand and even including theory, and on the other hand all the engineering. So, there are different opinions on that. I'm just trying to argue about what makes sense or not.

The scaling is certainly very hard, but it doesn't seem intractable, it's just that we have to get much better with the basic operations. So, in that sense I agree with Serge. I think improving basic operations will also require scientific innovation.

Let's talk about the young scientists that you met also in Lindau. How do you feel to be here and to exchange with them?

It's always a lot of fun for me. They're the future, not me.

Yesterday young students were advised to talk with the Nobel Prize laureates and not be shy. Do you help them? Are you shy to talk with these young people too? How can you help them to have this exchange with you?

I don't feel I have had too much of a problem interacting with the students and I'm not shy about speaking with them. I mean, it doesn't take people long to figure out I'm a pretty normal person. I'm not really that special and I certainly don't feel I'm any kind of genius.

And do you like to learn from them? Do you discover topics that you would like to study now if you have time?

Certainly, in our research group, we let people explore. They don't have to think about quantum computers all of the time. I think there's a lot of more fundamental, interesting experiments that we can think about. So, we try to encourage our students to do that, because for physicists anyway, I'd say discovering new physical effects is the real reward, not making a quantum computer. In any case, all members of the group can learn from someone in the group who is thinking about more fundamental physical effects.

And how can we attract more young people in quantum science?

Yes, we always need more bright young people. I think one of the attractions of our work is that we've been able to make demonstrations of fundamental physical effects like teleportation and making Schrodinger's cats. I think that's probably the main interest of most students and certainly the main interest for myself; that, is to be able to demonstrate some of the basic physics principles.

This is not your first time in Lindau? You've already come a few times?

I've been here two or three times before. Of course, COVID interrupted coming here more often, so it's been nice to return.

And before you became be a Nobel laureate?

No, not as a student. Unfortunately for students in the United States, they generally don't know about this program. I try to tell our students, that there's this opportunity, but it's not well known in the US. It's a great opportunity for the students.

Let's discuss the questions we have about the reality of this world.

There is the "measurement problem," and it's interesting to think about that. I don't have any grand ideas. I think that one of the nice aspects of our work is to be able to demonstrate and verify some of these things that people take for truths.

Even though we may not understand what's happening on a large scale?

Even if we think we do understand. A good example is teleportation. Just to be able to do it is kind of interesting, and I think the students find that sort of thing interesting as well.

What's weird, it's even beyond teleportation, because once you have created a connectivity between the two distant qubits, you manage a global state of the whole system that's mysterious to some extent, because it's a global state, non-local. So, when the experiments were done in the 80s, with Aspect, Zeilinger, etc. It was only a couple of photons, and then you look at the probabilities, but when it's a huge system with a lot of quantum objects, and it's still a large quantum system that you control on a global basis, it becomes even more mysterious, I would say, to some extent. The scale makes it more mysterious.

I agree with you. When it's done on a large scale, it's natural to think there's some sort of super-luminal connection between Alice and Bob.

Sometimes you discover new problems, maybe not with trapped ions, but let's say superconducting qubits. They discover new sorts of noise, correlated noise, cosmic rays, whatever. As you scale, you discover new problems.

It's probably an overstatement to say this, but for the last few decades, I think we know what the basic problems are in making a quantum computer, and I would say to scale up is just an engineering problem. And so, I feel we haven't made any fundamental discoveries with, trying to scale up. But I think what's interesting is just to be able to demonstrate some of these basic ideas and effects, and I think the students enjoy this too. And of course, as you say, we might make some fundamental discoveries along the way that modify our current thinking and that would be a great reward!

Thank you, David, for this discussion!

Thank you as well! It was a pleasure to discuss these things with you.

In the next episode of our Lindau recordings, we host **Bill Phillips**, laureate of the Nobel prize in physics in 1997 and we will shift gear toward cold atoms.

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