Understanding Quantum Physics
An Interview with Anton Zeilinger

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The essence of quantum physics for a general audience

Books & Ideas: Many popular science resources (journals, TV channels, websites, *etc*) regularly endeavour to reveal to their readers the essence of quantum theory and to explain its most prominent paradoxes. How would you explain to the general public what quantum physics is? What are its basic, specific rules that can help anyone understand, with no maths, most (or even all!) apparent paradoxes of the quantum world?

Anton Zeilinger: It is actually quite an interesting phenomenon that the general public is so much excited about quantum physics. This comes, I think, from the fact that quantum physics tells us that some of our everyday ways in which we look at the world are wrong. What is wrong is the assumption that, for example, every object has to be at a definite place at any time. This is not true anymore. Some people say that a particle can be at two places at the same time, which again is not good language. The good language is that there are situations where it is completely undefined where the particle is, and it is not even us who do not know, but the particle itself also does not know, so to speak. So this is an objective non-existence of a feature of reality. And that is new in quantum physics. That did not exist in what we call classical physics before quantum physics. It is also not true in relativity theory, by the way. There also we have a well-defined space, well-defined time, well-defined locations, and this kind of objects. This is one thing.

The second point is that we, in our everyday view of the world, with classical thinking, we always believe that for whatever happens there is a cause. There is an individual cause for individual events. Like when a stone hits me on the head, I know somebody has thrown it at me or something like that. Now, in quantum physics, we have learned that these causal structures, as we call it, exist on the level of large ensembles, but not always in the case of individual events. Like for in a radioactive atom, it is defined how many atoms will decay within, say, the next minutes. But it is absolutely undefined and there is no causal explanation why this specific atom decays *now*. So this is another interesting message from quantum mechanics, namely the limit of causality in very specific situations. But I should say that many public presentations or discussions make the mistake that they abandon this idea in general. This is not true. One has to be very cautious, when this happens.

The third point, which I would like to convey, is that we can have a situation, where two systems separated by a large distance are connected in a very new way. This is called entanglement, "intrication" in French. It simply means that if I have two particles which collide and interact with each other, and they fly apart, if we just imagine like billiard balls, two billiard balls fly the opposite, two quantum billiard balls would also fly opposite, but it would be undefined in which direction they fly. They fly in all these different directions at the same time. When I make one measurement, I observe one particle, for example, here. Then the other one in that moment changes its state from being possibly everywhere to only being at this place. And it is wrong to assume that I have just revealed where they were before, and that I did not just know it. The particle themselves also did not know. There was no well-defined feature. So to me, these are the general properties of quantum mechanics. In a more technical language, this is related to superposition. To the fact that superposition means various possibilities are superposed in a new kind of description, which we call the quantum state. Superposition of the quantum state is the general feature in that situation. And I should also mention that in my personal conviction, these phenomena are not limited to small systems. So far they are, but this, in my eyes, is a technical issue, and I hope that future bright young people will have the possibility to observe such phenomena also for very big objects.

On teaching quantum mechanics at school

Books & Ideas: Science, being a way to unveil Nature, is an intrinsic part of human society. What do you think about properly teaching the basics of quantum mechanics at school on a regular basis? Opponents to this idea refer to the complexity of that subject. But the same argument can be put forward, for instance, about an electron with its size and charge, which is nevertheless presented to schoolchildren.

Anton Zeilinger: When we talk about what can be taught at schools, I always tell my colleagues who work in schools, because I teach for them also, that the most important message, which everybody should take home, also those who will not become scientists, is an understanding of how good the description of nature already is, how precisely we can calculate things. It is not just a way of talking about nature. Like when you step into an airplane, you trust on the Bernoulli law within less than one per cent of validity. It is really fantastic how precise all of this is. When you turn on your Iphone, you use a lot of technologies, but to an unbelievable precision. Some of the devices work only because a certain atom has this kind of features and another atom has another kind of features, particularly, for example, rare earth atoms. They have been used in some modern technologies. So this is the most important message. That science provides a mathematical understanding of the world. And in that sense, I believe that quantum physics should also be taught. Quantum physics, certainly, cannot be taught using all the formalism, all the equations. But it can be taught at school on the phenomenological level. You just tell them. Here are radioactive atoms. They could decay or not. All these kinds of things. I have been giving lectures to children even. You know, six, seven years old. And they understand the concepts. If you tell them the right way. It was quite fascinating and the questions are really challenging. They have very good ideas. I think, this is important, because, it could very well be... Actually, I personally find it unlikely that there would not be a deeper theory as the next step. History has always progressed in steps. And if there is a deeper theory as a next step, then we probably have to change some of our fundamental ways of looking at things. And that should start early. So children should learn very early what the fact is.

Remaining challenges in quantum theory

Books & Ideas: I would like to address now a more scientific question. Are physicists satisfied with their present understanding of quantum mechanics, whose mathematical basis was developed many years ago? What is the main white spot in quantum theory that we face nowadays, if any?

Anton Zeilinger: Quantum mechanics provides a fantastically precise description of many phenomena. Like, for example, laser is described by quantum mechanics. All of chemistry is described by the Schrödinger equation, which is an equation of quantum mechanics, and so on. It is fantastically precise. The issue is the interpretation. The issue is, what does it mean for our view of the world? And we see a very interesting phenomenon, namely that there are different schools of interpretation, where everyone is convinced that his or her interpretation is the correct one. That he or she thinks that the other ones are completely wrong and there are even sometimes emotional fights.

Now, what does that mean? It means probably that we have not found *the* final way to look at it yet. It probably means that some key of viewing at the world is missing. So, therefore, my personal opinion is that we should look at this discussion of different interpretations as a fruitful discussion, which at some level might lead to something new. But it will lead to something new, if it leaves the philosophical level and leads to consequences, which then can be either seen in experiment or if they lead to a deeper new view, which opens up new directions for science.

What is the role of experimental quantum physicists?

Books & Ideas: Can we see modern quantum physicists as *quantum engineers* trying to apply known laws and rules to build increasingly sophisticated quantum systems and structures (like, for instance, applying thermodynamics to invent and improve a steam engine, or applying solid-state statics to build the Eiffel tower)? Or is there something more fundamental behind their inventions?

Anton Zeilinger: We have seen a very interesting phenomenon in the last twenty years. And that is, there were people who started experiments on fundamental phenomena in quantum physics at the time when these experiments where only motivated by curiosity, even philosophical considerations, because the predictions of quantum mechanics are counterintuitive. They are mathematically precise, but counterintuitive. So these experiments were started, and they confirmed quantum mechanics.

So, you could say why did we do these experiments? Well, there were interesting consequences because they suddenly opened up the mind of people to the question: “What could we do with it?”. And there is a big difference between knowing something from the book or having it realised in the laboratory in real experiments. I saw that myself when we did the experiments on two slit diffractions of neutrons thirty years ago. It was clear what came out, but after talks even famous physicists came and said: “It really works that way?” Isn’t that interesting? And that opens up the mind of people for the next step, and for the next step after the next step, and so on.

We are at the level now, where we have come out of these fundamental experiments, where we have development of many new techniques which, I am really convinced, will lead to a new technology, quantum information technology, new computers. I am convinced that we will have this because there is no fundamental reason, which tells that this is not possible. It is a bit of a challenge, but that's a different story. It will be done.

On the other hand, it also has sharpened our intuition of what is really interesting in quantum mechanics, and what are really the foundations. And there is a new school now. Young people, in theory, work on what is called the reconstruction of quantum mechanics. What are the basic principles from which we can derive this modern theory? And there is a little progress. There is really hope that we can put quantum physics now on a more solid conceptual level, which, I am convinced, will open us again up for going further.

What are the main questions now for modern physics?

Books & Ideas: By the end of the 19th century, there were only several "minor" questions left to be answered by physicists. The rest of our understanding of Nature seemed to be complete and solid. But it was exactly these several issues that gave birth to the age of quantum mechanics. In your opinion, what is the most pressing issue nowadays, the main topical question to be answered by modern physics, which might lead to the next revolution in our understanding of Nature? (I know that it is hard to make predictions, especially about the future, but we never give up…)

Anton Zeilinger: If we look at this status of science today, it is one of the most successful things which mankind ever did. It's fantastic. It's completely changed our lives in an immediate way. Many of us would not be alive anymore without the progress of science, and medicine, and so on. So, this is quite clear. The question is, where do we stand? And I personally believe that most of the future is ahead of us. If we just consider history, modern science starts with Galileo or with Newton, people like that. So, it is not more than 300 to 400 years old, which is nothing on the scale of the history of humanity. So, I find it very unlikely, that we have found most of it. So, if somebody, for example, believes that we are close to the theory of everything, then my reaction is: "Probably, we should have more fantasy for many possibilities".

And if you ask about open questions, there are many open questions. The famous example is the unification of the two best theories which we have in terms of the conceptually deep. And that is general relativity theory and quantum mechanics. These still stand separately. Why is this an issue? Because, there are actually some conflicts between the two theories. In relativity theory we have space and time well defined, but in quantum mechanics we learn that the sources of space – masses – can be in a superposition of being in different places, which means that space cannot be well defined at some level. And the fact that some of the brightest minds in physics have been working on this issue for eighty years now, at least, and have not found a solution, means that the solution will be extremely deep. It will be extremely significant if somebody finds it, and it will probably be in a direction where nobody expects it to be. That has happened before in science. So this is one of the interesting challenges. And I think that it is basically like Einstein. Einstein was not known when he did his things. Any young physicist can make a contribution. I am really convinced of this, if he or she adapts the right background while training.

This is one case. The other one are these questions of dark energy and dark matter. I would not be surprised, if we do not find them in the usual way. You know, the dark matter and the reason for dark energy, or whatsoever. They have the potential, they smell a little bit like the ether in the old electrodynamics theory. I might be wrong, but it could be the case. Again, if that is true, we need a new way to look at the world and not just small modifications of gravity theory. It must be something deeper.

In quantum mechanics, we have this challenge of what some people call the measurement paradox: affected upon observation, the quantum state, which has all these possibilities, changes and we have one specific measurement result. I belong to those people, who think that this is outside of physics. It cannot be described in physics because physics is a theory, which has a unitary time evolution. But I feel the chances that this tells us something about the role of observation in the world and the role of information. Maybe there are situations, where we have to reconsider the Cartesian cut, the Cartesian cut between *res cogitans* and *res extensa*, between the observer and the observed. Maybe, there is something which we do not understand yet. I would like to add a point, which is very important for me. When one talks about these things, people very often get associations with strange esoteric ideas and so on. You know, everything is the wholeness of everything, and so on. I do not believe in that. What I am talking about is specific scientific questions, which can be answered, I hope, by scientific investigation, by future generations. And I hope, that I am still alive and somebody has a really good new insight.

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