This physics confounds even the greatest scientists

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Quantum physics, or more precisely quantum mechanics, is a branch of physics that completely contradicts what our eyes have been used to for centuries: tiny elementary particles can be in two places at the same time, can behave like waves, and can change their state depending on the observation. The theory is perfect, but it is almost impossible to understand - we tried to understand it with the help of Lajos Diósi, physicist and scientific advisor of the Wigner Research Center for Physics, Doctor of the Hungarian Academy of Sciences.

Let's first try to explain understandably what quantum physics is, because this is a big task in itself.

The origin and role of quantum physics is linked to atomic physics and the knowledge of the structure of the atom. Pre-science is physics, which had to be refined. At the beginning of the twentieth century, we came to the conclusion that Newtonian mechanics could not be used to explain the properties of atoms, strange things contradicted the application of Newtonian rules. Especially when we got an idea about the structure of atoms.

When did we start breaking down atoms into smaller parts?

In the second half of the 19th century, at the beginning of the 20th century, they already knew. But how the electron behaves in the atom, for example, Newton's otherwise perfect physical theory.was no longer applicable. In the case of atomic systems, something else had to be invented. This became the quantum theory. The name comes from - and we can still say it is quite apt - the fact that there is quantization in the atomic world, i.e. there are such small quantities that you cannot go below.

Something that appears to be continuous on a traditional scale, if approached with very fine measurements, turns out to be able to change in leaps and bounds, quantum by quantum.

For this reason, a special theory, the quantum theory, was developed for the atomic world, which at the time was only applied and thought to be valid there, the basic property of which was that certain events are not continuous, but can only change in stages. It turned out about this theory that its conceptual system and mathematical structure are very different from what we have known since Newton. The notions that our objects can move along certain coordinates in space, and that they can apply certain forces to each other, were dissolved in quantum theory in an incredible, almost mystical way. To this day, there is a saying that you can't really understand this, but you can apply it and get used to it.

Basically, what is difficult about it is that it is very difficult to imagine and apply it to our own experienced world. You have to rewire your brain to think in this system.

The majority of researchers and university professors still admit that our approach, accustomed to Newtonian physics for centuries, cannot adapt to this. We see that things are somewhere, their place, their presence, their path are defined. And we can describe their behavior, their dynamics, their state with some kind of traditional method.

In contrast, what happens in quantum theory?

Atoms laugh at this kind of conservative behavior. Atoms and particles smaller than atoms do not follow the traditional forms of behavior developed over centuries, the way inanimate objects in nature behave. The fact that physical science came to recognize this, made us able to articulate the properties of a world that cannot be grasped by the millennia-old scientific approach. It was a very big result, and it shows that physics, as well as other exact natural sciences, are capable of recognizing abstract behavior in nature for which we do not have visual tools. We are able to recognize structures and describe their behavior that cannot be fitted into our approach at all. Not only our everyday approach, but also the scientific approach and the people of science are in trouble,if they have to fit into this new world.

Can we describe this quantum world in a few words? Can you explain the basic assumptions in a few words?

It would be difficult, because here too there is such a variety that the abstract nature of the matter actually allows. When quantum theory was developed, Schrödinger introduced a so-called wave function scheme. Physics differs from mathematics in that we have to add stories, we always have to offer some kind of perspective alongside mathematics.

This story was that an electron - because this was the guinea pig in the physics of the particles that make up the atom - does not have an orbit and a place, but a function distributed in space, a certain density distribution must be assigned to it, and where this function is dense enough, the electron stays rather than where this function rings down. It is also a complex function. It is not even true that this spatial density would be similar to when something is really assigned with probabilities to appear here and there, because it is even wilder. But it is enough for us to imagine: there is not one orbit, one place assigned to an electron, rather something always distributed in some space. By the way, it has been a hundred years since people thought they understood quantum theory, and great scientists are still slapping themselves on the forehead saying yes, well, I didn't think of that.

Is this field of science that fast? Is there still so much to discover in it?

It is inexhaustibly different from the previous conservative physical worldview. For example, when Newton finally defined his theory, which was already considered conservative 200 years ago, in a form that is still valid today, it was possible to get used to it, neither the physicists nor the engineers were surprised. What quantum mechanics still produces after its first hundred years is quite mystical.

So should this be imagined as, with a little exaggeration, every day there is a discovery that still needs to be taken into account for theories?

Yes, something that could be important that no one thought of. There was, for example, the surprise, which today is called quantum informatics, quantum computation, quantum cryptography. After many, many decades, it became clear that quantum behavior in information management, encryption, transmission, and storage opens up horizons that were previously unimaginable.

Where does the development of this stand now? How much is a quantum computer in its infancy currently?

In 2000 and 2001, I gave the first two interviews about what the hell a quantum computer is. In 2000, I said that within ten years there would be no real movement here.

And it wasn't.

When I gave that interview, the big tech companies started to discover how much money they have to invest in this because, who knows, what will become of it. Today, there is no tech company, especially a telecommunications company, that does not invest trillions of dollars in such research.

Compared to how much money goes into it, how is research progressing?

Compared to how difficult the task is, there is progress. But at the moment, no one is talking about the possibility of such a breakthrough that, for example, tasks that can hardly be solved with traditional computers could be solved in the foreseeable future with quantum computers, which may still be silly, but already work correctly.

Now we at that we have very imprecise toy quantum computers.

We know that these small atomic building blocks, qubits, are very sensitive to noise. They are the most delicate structures in the world, and if, for example, an equally delicate structure comes close to them, they both lose their intended function. We know that noise is a fundamental enemy and can hardly be eliminated. Nowadays, developers expect us to find a task that may not be useful, in fact, but one that we know that if we wanted to solve it with an ordinary computer, it wouldn't be completed until the end of the world. However, on these silly little imprecise quantum computer toys, we can prove that we can solve them in finite time.

Is there any idea already what kind of useful tasks could be about?

These are optimization tasks. Physicists and mathematicians with absolutely crazy, abstract talent are also working on how to provide theoretical fuel to developers. But even though I gave the first domestic interview about this twenty years ago and wrote about it in my theoretical textbook, there are already specialists in this field in Hungary. So, unfortunately, it's no longer me who has to be asked about where the quantum computer is now.

Let's go back to quantum physics specifically. When we talk about this, most people usually think of Schrödinger's cat, and perhaps the basic premise that it illustrates, which is that an atom can be in two places at the same time until we observe it. How can the average person imagine this?

For the average person, the biggest mystery in this is that atomic and smaller particles are not in a sharply defined place but there is always some uncertainty about where they are. It was possible to prove this about the photon many, many years ago, and then they thought you might as well be hung for a sheep as for a lamb, let's see if they can be in two places at the same time.

In the case of electrons, this was amply proven already in the late twenties, and then for photons as well, they also jumped further from there. For a long time, even the in series Nobel prize-winning discoverers of quantum theory themselves believed that there were two theories, one for the macro world and the other for the atomic world. Then it gradually became clear that this terribly complicated, abstract quantum theory is true not only for the parts that make up the atom, but also for a whole atom. Then for a molecule, then for larger and larger objects. It was a little difficult to follow them experimentally, because it required an increasingly sharp experimental technique to be able to show: the quantum theory is also valid for a very large molecule.

Was this still a theory or already an experimental proof?

Experimental development is very, very slow. However, on the theoretical side, we are now increasingly convinced that the starry sky is the limit. Twenty years ago, Zeilinger's experiment proved that large fullerene molecules also know the same thing that was proven about electrons already in the 20s. Today Zeilinger is the president of the Austrian Academy of Sciences, the record is still held by the University of Vienna with a giant molecule consisting of 2,000 atoms. There are no two separate theories in the world, the Newtonian one must actually be part of a much more general one, and this more general one is the quantum theory. At that point, you could begin to ponder that yes, but what would happen if the quantum theory with all its mysteries were really true for a sugar cube, or a billiard ball, or us. And actually Schrödinger had already dealt with this, but he himself said, I think, he was just kidding.

It was more of a thought experiment than a serious theory.

A thought experiment, yes, which he didn't think would move anyone.

Its popularity probably stems from the fact that it finally has a character that everyone can catch, the cat.

It has, but the significance of this was only revealed decades later. Earlier it used to be a paradox that was very interesting, but it had no relevance to how we develop and apply quantum mechanics. However, when it turned out that

> **not only is quantum mechanics the theory of the microworld, but it also very likely applies to large, even astronomical objects and dynamics,**

Schrödinger's paradox did emerge. He expressed this more dramatically: it is not known whether the cat is alive or dead. We have simplified this a bit so that even a physicist can do research, without having to call a priest to the cat or a psychologist to the physicist. The physical equivalent is to take a larger object, a billiard ball, and place it under the validity of quantum mechanics. Let's look at the case when it also has a wave function, then it no longer has a location that can be precisely determined, and horribile dictu, let's assume that there is such a thing that it is both here and there at the same time. This is a call to waltz.

If someone says that quantum mechanics is also valid for such large bodies, then a wealth of new questions opens up, which can be and, in my opinion, are worth answering. And this is actually something that I myself started to deal with very, very early, and then throughout my career. Fortunately, not only with this, because then I wouldn't be sitting here, since it was considered so extreme that in my time it would have been impossible to get a job, write a thesis, or obtain research status with it. Despite the fact that I did not only deal with this, everything had something to do with it, but no one needed to know this: all my theoretical research, which can be called successful, can be attached to this.

Your most recent research topic is related to gravity. Gravity is such a step part of quantum physics, particle physics and the standard model itself. What's wrong with it?

The fact that it cannot be fitted anywhere. This is also the case here. Quantum mechanics is logically a perfect construct. Perfectly applicable. Not a single experiment has ever contradicted it, and where we could measure accurately enough, everything proved it.

You could say that there is nothing to see here.

But there is because of two things. One is that if we want to create a logically closed theory, we need to put a strange but harmless capstone on quantum mechanics. Our greatest mathematician until now, John von Neumann, made this at the end of the twenties: he was forced to place the capstone in such a way that the human had to play a role in it with his own perception and observation. This is one of the mysteries of the well-known history of quantum mechanics: that the electron is here and there, or that the cat lives and dies, as long as someone is not looking at it. And indeed, in the case of Neumann's rigorous demands, something like this must be placed as a capstone. The truth is that this does not affect the provability of quantum mechanics at all. But it makes that physicists, philosophers, theologians, and metaphysicians have been vexed for almost a century.

You mean the human factor itself?

Yes, the fact that even a John von Neumann was unable to formulate a fundamentally objective physical theory without having to refer to the subject. To the subject observing the electron, the cat or the billiard ball. I say, this is a logically necessary assumption, which can hardly be replaced by any other, non-subject-evoking assumption. Neumann saw this as the most obvious, but it in no way affects the objective applicability. It would just be logically very difficult to complete the theory if I took this off the top. Kepler still, I think, referred to aesthetic and theological explanations for his laws, but this gradually faded from modern science. The subject has no role in how the theory describing the behavior of the physical world should be formulated.

If I understand correctly, this was only necessary just to connect quantum mechanics with what we see and perceive?

Yes, to have experimentally verifiable predictions of quantum mechanics. We live in a macroscopic, experimental world, we really need to be able to assign recognizable times to physical phenomena with arbitrary precision, so that things have a trajectory, to be sure that yes, this pointer has now moved from zero to five. According to Neumann, the connection between the microworld's own laws and our macroworld can be established when someone looks at it and measures it.

We can only imagine the tangible in the Newtonian sense, whether it is here or there, alive or dead, cold or hot.

This is one of the open questions, and I may be in the minority among scientists, but I don't think it has any relevance for the applicability of quantum mechanics. That lets me sleep well.

There is another thing that makes no one sleep peacefully, and that is that gravity is also incompatible with quantum theory. This led to the idea that quantum theory might have to be changed because of gravity, and vice versa. This is a fantastic, promising thing, which would mean that a new discovery would come out of this conflict that gravity is incompatible with quantum theory. The idea is that von Neumann's subjective part of the theory can be replaced by some traditional objective mechanism, so we can kill both birds with one bullet, the incompatibility of gravity and quantum theory can be solved immediately. I started in this direction.

Where is the research related to the theory now?

I created a provisional theory of this concept over thirty years ago. It is a very, very temporary thing, you can tell that there is a lot of bullshits in it that cannot remain in a definitive theory. But science works like this: if you start in the right direction, if you succeed in formulating and examining an imperfect concept, that means progress. I described a model formulated in equations that would try to solve the combination of gravity and quantumness at the same time, but above all it could eliminate this von Neumann's mystical reference to the subject and replace it with a physical process. This theory was also formulated a few years later than mine by Roger Penrose, who was already world-famous at the time by the way, for what he received the Nobel Prize fifty years later, and what has nothing to do with this.

Yes, he won the Nobel Prize for black holes.

Yes. So, Penrose was thinking about something like this, and he came up with a very similar concept, he based it a little differently, but his equation was the same as my equation. Not many people paid attention to me, let's say not even to him, because it was impossible to check the whole thing experimentally, it was such a small effect. For thirty years or so it was impossible to do anything with it. Then these thirty years passed, and on the one hand, the elegance of the theory compared to other competing theories, and on the other hand, the interestingness of the concept drew more and more people's attention to it. And Penrose himself traveled the world with this theory quite persistently. And when the techniques of experimental physicists became sophisticated enough, a mutual motivation arose. I can safely say that our theory has become one of the motivating factors for highly advanced quantum technologies, which, after putting my name before Penrose, is called the Diósi-Penrose theory because of the time order. I didn't start naming it after the two of us, I waited for others in literature to do so, but now I call it that too. So the theory came close to being experimentally verifiable.

What technology are we talking about in the experiments? Can you explain in a simplified way how we can measure something like this?

If it is true for electrons that they can be both here and there, then we should see if this is also true for macroscopic bodies. Our theory is that the larger a body is, the less stable its superposition here and there is. Our common theory with Penrose shows that the more massive something is, the more it defies Schrödinger's cat situation, and yet it prefers to decide that it is either here or there.

That would explain what we see.

Exactly. In the macro world, quantum mechanics is gradually modified so that these strange states, if they do appear, disappear immediately.

Any idea when this particular shift is?

The particular equation shared with Penrose tells exactly this: at what mass, at what speed should this state disappear. Whether this disappearance really happens should be verified experimentally, let's say, with a grain that is no longer atomic in size, but very small. Experimental technologies are used to try to examine such particles in a completely noise-free environment.

Does this completely noiseless environment mean a vacuum?

Not only vacuum, but also ultra-cold temperatures. For a certain type of experiment, we know that the environment should be cooled down to nanokelvin. But there are other experiments where such a low temperature is not needed. You have to imagine that if a stray gas molecule, even a single one, goes there, the experiment is no longer authentic. Or a single infrared photon, which is not visible light, goes there. Or the examined particle loses a single molecule or atom in its agony, because it was not properly bonded on its surface. By noise we must understand such quantum-sized effects, we must get rid of them or somehow exclude them.

What has been researched about gravity?

My theory connects gravity and the fact that these mystical Schrödinger's cat states are thrown out by nature itself. The larger the mass, the less it allows such a state to exist, which state is certain to exist for an electron and a macromolecule. We worked this into the theory by inviting gravity, but it should be known that this is not yet a solution to be able to combine quantum mechanics and gravity. It could only mark a path where to go.

Our experiment that we recently published is very indirect. Because the best theory, which may just be ours, definitely predicts a side effect: very, very weak photon radiation. And this weak radiation can be calculated how much it is, if the concept as we think is valid. That

due to gravity, these Schrödinger's cat-type states decay as mass increases.

The cat decides whether it lives or dies, and from there we arrived at our conservative world. We calculated this weak electromagnetic radiation - it depends on the theory having a free parameter, which can be as large as the size of an atomic nucleus, can be as large as an atom, or can be in between. This is a parameter. And that gives you room to play. The measurement we performed limits this parameter range from one side. It is impossible for the size of the atomic nucleus to be the parameter, it can stay slightly below the atomic size, but it cannot go much below it. We excluded this because we detected very few photons.

These few photons do not show that something is wrong with the theory, rather they mean a clarification.

This means that a parameter range of the theory has narrowed. It is possible that a subsequent experiment will narrow it down so that the theory can be thrown out in this form, but for now we believe that it will survive in this parameterized form. It is worth adding that regarding the technology of its kind, this is a top experiment, because again it was done noiselessly - this time the experiment had to be performed noiselessly not for quantum reasons, but because the number of the predicted photon number of electromagnetic radiation is so low that the cosmic background radiation had to be completely excluded. We have the methods for this, some go to a gold mine in South Africa, while the Italian science policy decided more than thirty years ago to build three giant halls for particle physicists half way through the road tunnel under the Gran Sasso, here the background radiation is low, our experiment also took place here. Penrose's version predicted seventy thousand photons in two months, we, however, only found 576.

And what's the next step then? Now what comes to try to prove the theory?

The next step I would expect to take is the direct experiments that try to force each of these tiny particles into a superposed here-and-there position in a lab with such a noiseless, low-temperature, or otherwise extremely low electromagnetic noise background. Then we will see if it stays in that state, if it tolerates it, or if the effect that we calculate by including gravity starts to kill this superposed state.