This is a transcript of Mysteries of Physics podcast episode 4 'QUANTUM MECHANICS', published on 29 March 2023.

NOTE: Transcripts may contain errors. Please check the corresponding audio before quoting in print.

Funding Statement: Great Mysteries of Physics is a series supported by FQxI, the Foundational Questions Institute - a think tank and funding agency that explores the foundations and boundaries of science. Find out more at fqxi.org.

Miriam: Welcome to Great Mysteries of Physics from The Conversation. I am Miriam Frankl, and I am your host for the series. So far we've talked about a lot of weird things from time running backwards to parallel universes. But arguably the most counterintuitive bit of physics out there is quantum mechanics. So that's the theory describing nature on the small scale of particles and atoms. Unlike something like string theory or multiverse, quantum mechanics isn't really speculative. The maths works out beautifully. In fact, it's something I vaguely remember from my short and sometimes painful stint as a PhD student in physics.

And the theory has been tested over and over in labs around the world. Technologies that we use daily, such as MRI scanners, lasers, or even smartphones, rely on quantum mechanics. So why is it still a mystery? The problem with quantum mechanics is not so much whether the theory is correct or useful, but it's more about how to interpret it. Does it really represent how nature behaves or is it some sort of weird mathematical approximation? And if it does describe physical reality, why don't we see any quantum effects on the large scale objects around us?

According to quantum theory, each system, such as a particle, can be described by a wave function, which evolves over time. And this wave function allows particles to hold multiple contradictory features or be in several different places, for example, at once. This is called a superposition, but oddly, it's only the case when they aren't being observed. So although each potential set of features in a superposition has a certain probability of appearing, the second you actually observe it, it just randomly picks one, for example, a single specific location breaking the superposition. And physicists often refer to this as the wave function collapsing.

An unmeasured quantum object therefore behaves a bit like a die thrown in the air, being in a mix of many different possible numbers. And when we finally do measure it, the object behaves a bit like a die that has landed showing a specific outcome or number. The outcome of a quantum measurement is truly random, and that's actually unlike a die throw, which appears random, but in reality isn't. It's just very difficult to predict every single speck of dust or air molecule that affects its path so we think of it as random. Uncertainty is inherent in this strange world, you cannot precisely predict things. Famously, you can't know position and momentum at the same time.

There are many other weird features too. Quantum objects can behave as particles or waves depending on how we're measuring them. And they can be entangled with each other, so they appear to somehow share information, even if they're light years apart.

Chris Timpson is a Professor of Philosophy at the University of Oxford and an expert on the foundations of quantum mechanics. I started by asking him to describe quantum mechanics and explain how it's different from non quantum physics, which is also referred to as classical physics.

Chris Timpson: It's a theory which focuses on the behaviour of the very small, primarily or large scale features, such as the initial conditions of the universe, which we in cosmology might need to treat quantum mechanically too. So it's a departure from the ordinary logic, if you will, of classical physics that we're used to, and provides us with a delightfully puzzling, richly structured framework in which to formulate the more detailed laws that we take to hold describing the behavior of things like electrons or photons or the electromagnetic field.

Miriam Frankel: And it's often sort of described as being very counterintuitive and weird. What is it about it that's so weird.

Chris Timpson: I'll begin by mentioning that any piece of physics is weird. Quantum mechanics is that, and more so and really what makes it so is the way it confounds not merely what we would normally take to be true about the world, given our common sense understanding of medium sized objects around us, but the fact that the way that the properties of things fit together doesn't respect classical logic. So famously we have the notion of quantum superposition. There is a notion of superposition within classical physics too. When one plucks a guitar string, for example, one has a superposition of the different frequencies and the different harmonics mathematically one's adding together these different states to create a new allowed state. But in quantum mechanics, something different happens because we have superposition against this background of a non-classical property structure.

Miriam Frankel: The quantum world is strange and hard to understand. Intuitive. Chris offers some help with the analogy of a pool table.

Chris Timpson: To explain what I mean there, we're used to the idea, for example, that a material thing, an object, say a billiard ball, something like that. We think it has a position at a given time and we think it has a momentum at the same time. So maybe it's sitting there completely still. It's got a position in the middle of the pool table, uh, the billiards table, uh, it's sitting there stationary, it has a zero velocity, zero momentum. So we've got two different physical properties there: position and momentum and the one object has a definite value of both at the same time. In quantum mechanics, that's not allowed. That's not allowed for position of momentum, and it's not allowed for the rich range of other properties that one needs to introduce in quantum theory to just give detailed descriptions of the physical world.

So if instead of a billiard ball, we have an electron. If it has a definite or a fairly well localised position, it has to have an indefinite value of momentum. It's not just a matter that we are ignorant of what momentum it might have, there's simply not a fact about what momentum it might have.

Miriam Frankel: This weirdness of the quantum world led Schroedinger to develop his cat thought experiment, which has now reached meme status of fame and we've talked about it in many episodes before.

Chris Timpson: Well, the famous example that arose from discussions between Schrodinger and Einstein of the Schroedinger cat. So there, that's a macroscopic, a large scale illustration of what would happen if one amplified up the quantum superposition to the macroscopic level.

And we have the two distinct states of the cats, two incompatible properties being alive or being dead. It may be that the cat's alive. It may be that the cat's dead. But what quantum mechanics also allows is the superposition of those two things, where it's neither dead nor alive. And it's not that the cat is smeared out between standing up purring and lying down dead. It's that it's an entirely new, non-classical way of being where it's neither one state, neither the other, and neither the smeared out state. So because of this non-classical property structure, we have interesting superposition, which means that we can't apply the normal rules for understanding what the contents of the material world is like.

Miriam Frankel: Right. And so with superposition, you, you know, it's closely connected to something being measured, isn't it?

Chris Timpson: Well, indeed, we don't find cats being in a superposition, an indefinite third state between being alive and being dead. Um, so when we observe things, we seem to find that superposition doesn't exist.

This is one of the great puzzles then that quantum theory presents us with. If at the fundamental level of the physical facts underpinning everything, that we take to underpin our macroscopic experiene, if at this fundamental level, superposition is rife - and it is - typically nothing has any definite values of anything you would hope it would have definite values for. It's all spread out in the um, extremely rich superposition state. How does that scenario end up giving rise to the determinate classical physics that we know and love? We think that might have something to do with the effect of measurement itself. That measurement somehow destroys superposition.

Miriam Frankel: This is called the measurement problem, and it is one of the biggest headaches for quantum physicists. For some reason, measuring something seems to break superpositions, but why? Is it something to do with consciousness?

Chris Timpson: Or it could be that when we think about what a measurement process does, when we recognize a measurement process to be just another physical interaction amongst others, it could be that the way that superposition manifests itself in a measurement process is one in which the fact that we become part of a big superposition like the cat. If we interact with the cat in the box, we could become part of the superposition too. So there's a splitting of physical facts into the cat is dead, the observer sees the cat dead, the cat is alive, the observer sees the cat alive. So it could be, if we describe the measurement process using the standard rules of quantum theory, that the reason we don't see superposition at the macroscopic level is that it's hidden from us. Not that it's not there, but hereby lie enormous reams of controversy.

Miriam Frankel: But there isn't anything in quantum mechanics itself to say that it's required to have a consciousness or anything to be an observer. It could just be a detector and a laptop measuring an electron, then that's an observer, essentially.

Chris Timpson: That's right. I mean, there have been certain approaches to understanding quantum theory that have said, well, there needs to be something about the self-conscious observer because at least at that point we know the indeterminacy ends, if you like.

So it's alleged that superposition no longer exists once the awareness of a definite value for the state of alive or dead of the cat, or a definite value for the position of the billiard ball has entered the mind's eye. So in that sense, some people have argued that there's something about conscious experience specifically, which is different from just a recording device in the lab.

But again, from the point of view of the physics of observers, which for understandable reasons don't treat of questions of our self-conscious awareness of our experiential states from the point of view, the physics of observers, then a recording device in the lab would do just as well as me in terms of the difference it would make to the description of the microscopic systems.

Miriam Frankel: Not only does nature seem to be random and all fuzzy if we're not looking. Particles can also be mysteriously connected even if they are light years apart. And that means that if you measure the state of one, then you'll instantaneously know the state of the other. For example, let's say that we prepare two particles to be entangled in this way in the lab, and that each particle can spin in one of two different directions.

We then send one to a lab in Australia and the other to a lab in Norway. While we are not measuring the particles, they will be in a mix of both spins simultaneously, and if we measure the one in Australia, it will pick a value at random. But quantum theory says that instantaneously the one in Norway will also be set to spin in the opposite direction. It sounds weird. How does it know immediately that the one in Australia has been observed in a specific direction?

Despite this, scientists use this property in the lab constantly. It is used in quantum computing, for example, and using entangled lights in communication can also help guarantee security. Marcus Huber is a Professor of Physics at the Technical University of Vienna. He actually does research involving entangled particles of light called photons. He is, however, in a very echoey room at the time of recording, so please bear with us as the sound recording isn't the best.

Marcus Huber: Nowaday, we've mastered creating entanglement. We shoot a strong laser at a non-linear medium, and what happens is one of the strong laser photons is getting absorbed and two new lower energy photons, particles of light are created. And because of conservation laws and because of some other quantum facts. Those two created photons now share very strong correlations and in fact, they are indeed entangled. And what we're doing right now is we're sending them across the night sky, or even daylight sky in Vienna, um, to a receiver station in a neighbouring state.

And there we actually managed to find these single photons, pick them out from the air and do measurements on both of them and compare our results and actually find those pristine correlations that make up quantum entanglement.

Miriam Frankel: So you are trying to discover more about how these particles are correlated. For example, with light, we often talk about polarization, it's polarized a certain way, so if one is polarized one way, the other will be the opposite way. Is that right?

Marcus Huber: You can tune it. It depends on how you create them. You can also make them correlated. So like if one of them is H polarized, the other one is also H polarized. Or you can flip them and make them anti-correlated so it’s really about the design of the source. And what my group, what we are working on actually is exploiting far more properties of photons. For instance, talking about the wave function. Also, a single photon, despite being a quantisation of light, it propagates as light. It propagates as a wave. And so they can also be correlated in their positions, or you can entangle them in colour, like if one photo is red and the other is blue, and vice versa.

Miriam Frankel: And what are you trying to learn from sending them across the night sky?

Marcus Huber: Oh, this is actually already a bit of a mature quantum technology. This is more to the effect of using disentanglement as a means to secure in communication.

Miriam Frankel: Okay. Right. So you want to be able, for example, to get this entanglement to last and not be disturbed for a long distance.

Marcus Huber: Exactly. Like recently we sent like over 10 kilometers of urban sky and just the fact that we can still find these single photons, that we can prove their correlations, we can prove their entanglement.

Miriam Frankel: How do you find them?

Marcus Huber: We use a strong guiding laser and try to align it with the single photon beam in order to know where to look and then a complicated lens array. And we know very well the exact frequency of the photon we're trying to detect. So we use very strong filters to try to filter out all the other light. Cause you can imagine there's lots of light. And then we have extremely well synchronized clocks between these two places that we keep having to synchronize such that we define like a window of a couple of nanoseconds.

And if both detectors click within this very short time, in this very narrow frequency band, we hope those are the right two photos we've just identified. And the truth is sometimes they're not. And this is the challenge to proving entanglement because if we just measure some random photons, they will not show any of these quantum correlations.

But by virtue of actually proving these quantum correlations, we proved that in enough instances, the twos we found were actually the ones that were produced by the source.

Miriam Frankel: So entanglement works well, but how? How does one particle know which state its partner is in? When we measure them, do the two somehow communicate? Because if they did, this would have to happen faster than the speed of light, which is forbidden by Einstein's theory of special relativity. So this feature of the quantum world in which a particle isn't just influenced by its immediate surroundings, is called non locality. Einstein didn't like this, and he called it spooky action at a distance.

He didn't believe that quantum mechanics could be the full story. So instead he thought that there must be some sort of underlying hidden variables, like a secret instruction set, which told the particles how to behave. That would make everything less confusing, just like a die throw can in principle be predicted perfectly, meaning it isn't truly random, even if it appears that way.

Perhaps the quantum world isn't truly random either, but in theoretical work, the physicist John Bell showed that there can be no hidden variables. He showed that if quantum mechanics describes the real world with particles being there, even if we don't observe them, then it must also be non-local. That said, he made a few assumptions such as that cause and effect must flow forward in time, that measurements have only one outcome, and that everything in nature hasn't been predetermined since the dawn of time. If we were open to any of these options, we could actually get rid of non locality. But most physicists prefer not to. And evidence for entanglement has stacked up. It's been backed by experimental research using Bell's tests, so it's pretty hard to explain away weirdness in quantum mechanics. You get rid of one weird thing and you are stuck with another. But many physicists aren't too worried about the results. Marcus, for example, takes the following view of quantum randomness.

Marcus Huber: I am actually not bothered by it at all. I mean, we actually encounter a lot of randomness in our daily lives, although if you wanna come back to it from first principles, a lot of that classical randomness could be explained away by a fundamentally deterministic theory where we just lack specific detailed knowledge that gives rise to the seemingly random events at the macro scale. Um, but that's why I think I'm intuitively not bothered by randomness. And if you wanna look at it from a fundamental perspective, if you want to exercise randomness from quantum mechanics, it gets really weird in the sense that you would still have to explain how these so-called Bell inequalities can be violated, which kind of confirm that there is no local realist description of quantum mechanics. And if you want to get rid of the randomness therein, if you want to explain everything we can observe in our experiments without randomness, you have to go through some really weird and longwinded explanations that I'm much more uncomfortable with.

Miriam Frankel: So you're referring here, for example, to retrocausality. So that's the idea that causes can go backwards in time. So something in the future can cause something in the past or for example, super determinism, which is this idea that everything is determined from the beginning. So it just looks random to us. But actually there is some sort of hidden master plan behind it. Is that right?

Marcus Huber: Yes. These are perfect examples of things that make me even more uncomfortable. Because I mean, this is really a conspiratrial universe where you say, ah, well technically actually quantum mechanics isn't really true. Things aren't really random. But whenever we look into nature, coincidentally, it has been predetermined that all the outcomes of all of our experiments look exactly as if they were random. That seems very contrived.

Miriam Frankel: Chiara Marletto, a research fellow in quantum physics at the University of Oxford isn't too worried about the strange world of quantum mechanics either.

Chiara Marletto: It doesn't trouble me. It's more like it intrigues me. And, um, with each of these scientific revolutions that we've had, more counterintuitive elements have been brought about by the new theory. So, for example, even with general relativity. Um, so up to then we thought that time, let's say, was an absolute concept and then suddenly we learned with relativity that it's not, and things like distances and durations are not absolute concepts. So they depend on the observers. And so in that sense, I think I see quantum theory similarly to relativity in the sense it's, um, a radical departure from what classical intuition tells us.

Miriam Frankel: Nobody can deny the astonishing success of quantum mechanics and describing the micro world. But does it really describe how nature itself behaves? It is, after all, not exactly what we observe around us.

And it turns out that the physicists have rather different ideas about whether quantum mechanics really describes an objective reality in its entirety.

So I asked Chris about the different interpretations, starting with the Copenhagen interpretation, sometimes also known as the 'shut up and calculate school', which goes back to the 1920s and a Danish physicist called Neils Bohr

Chris Timpson: There are so many, and that's part of what makes it fun. I mean, my official position on all these is agnosticism. So you'll find many people who will articulate and argue for one particular view. Several of these, we've already touched on. The Copenhagen interpretations what they share is at least a partial step back from the full-blown descriptive aim of physics. So core components of the quantum mechanical theoretical apparetus won't be taken to be descriptive of microscopic things in this kind of view. So the quantum state, this thing which describes these lovely superpositions, um, that's just a tool for making predictions about the behavior of macroscopic measurement scenarios. It's not a statement of how an individual microscopic particle is. So that leaves us with a view of the world, which gives up the aims of description below a certain level of the theory.

Miriam Frankel: Now I was just gonna ask about QBism. So is that like an extreme version of sort of Copenhagen then, in that it kind of takes quantum mechanics to be a tool for an observer, or as they call it an agent who's trying to make actions in the world and it's… the sort of quantum measurements that we do are sort of, they're all about updating your information as an agent, as an observer, rather than describing exactly what's going on. So there might be a, a real physical world out there, but quantum mechanics is about how you interact with it as an observer, us an agent.

Chris Timpson: Yes, that's right. So taking the view, QBism due to Carl Caves, Chris Fuch, Ruediger Schack as a, a delightfully extreme version of Copenhagen is a useful way of thinking about it. Um, and it is important for them. I mean, one of the reasons it's extreme is that people like Bohr would think that even though there's no facts typically about microscopic goings on what electrons are getting up to in between measurement processes, he and others in the Copenhagen tradition would at least say, but there are objective facts about what the probabilities for measurement results are. The QBists say, well, even that's not the case. A correct way of understanding probability is not in terms of objective facts in the world that makes certain probabilistic judgments true, rather probabilities or expressions of an individual agent's degrees of belief that such and such things will happen and different agents can disagree on what the probabilities are without actually disagreeing about anything objective, and this helps us resolve some of the questions about non-locality and so on. So QBism has advantages in that it resolves the non-locality problematic. The disadvantages are that it's really stepped a long way back from the descriptive endeavor of physics.

Miriam Frankel: If you want to believe that quantum mechanics is an objective description of the physical world, then you are what philosophers call a realist. But it's not an easy position to hold. If there are things such as superpositions, which can be described by wave functions, and these are randomly collapsed by observation, then what happens to all the possibilities that we didn't measure? Here's Chiara on what happens when a superposition breaks down.

Chiara Marletto: The idea of a collapse suggests this sudden jump to one value or the other. And I think it's interesting that you can actually describe the process all within quantum theory. And so you can look at the observer that's looking at this particle as also as a quantum system. And so when you do that, what happens is that the observation is no longer this singular event that causes a collapse, but in fact, the observer joins the super position as well. So before the measurement, there is this particle that's superposed and there is an observer that's about to look at the particle. And then after the measurement, if you describe the observer according to quantum theory, what happens is that the observer becomes part of this wave function too. And so there is one branch of the wave function where the observer sees the particle here. There is another branch where the observer sees the particle there and these two branches can't communicate with each other. That's important because otherwise there will be some inconsistency. They're always like two separate channels in a sense, but they both exist. And what happens is that the observer becomes entangled with, uh, the particle. And you can continue like this further and further so you can think, well what about if another observer comes along and asks the first observer? Where did you see the particle? Well, uh, this is something that was considered by this thesis is called Eugene Paul Wigner. And Wigner invented this thought experiment called the Wigner's Friend, where a friend comes along and asks exactly where did you see the particle? I mean, in one branch the first observer says, I've seen it here, and in the other branch, he says, I've seen it there.

Miriam Frankel: So before Wigner knocks on the door of his friend's lab and asks what outcome they saw. To Wigner, his friend is in a superposition of both branches. One where they see the particle here and one where they see the particle there. So while the friend inside the lab may argue that they have a definite answer as to where the particle is, to Wigner outside the lab, the position isn't determined.

So now these two people, Wigner and his friend will say that the state of reality of the world is different. And this idea that different observers of the same event can have different facts about what happened, such as where a particle is, is mind boggling. It suggests that there is no such thing as objective facts. But it has been demonstrated to be the case in the lab.

For example, recently in an experiment by a team at Heriot Watt University in the UK, albeit using simple photons as observers. So how do you make sense of that?

Chiara Marletto: And in this sense, the new observer just joins in the super position, and it could go on like this ad infinitum in a sense, and it's all consistent. The beauty of quantum theory is that the way it describes this process without sudden jumps is that all of these branches are not communicating with each other. So in a sense. This process is completely describable within quantum theory, and it's a consistent picture. So in a way, you can think of quantum theory as being kind of democratic because it reads the observer and the observed on an equal footing in a sense.

Miriam Frankel: So what you're describing is what they're called, uh, many worlds interpretation, is that right?

Chiara Marletto: That's right. Yeah. Yes.

Miriam Frankel: So does that mean that each of these branches, some take it to mean that each branch exists in a different universe, basically?

Chiara Marletto: Yes, that's right. So one way to dramatize this fact that is described by the theory is that, uh, these branches are different universes, which are not in communication with each other.

Miriam Frankel: There are other interpretations and alternatives to standard quantum theory. One set, for example, of rival models are called collapse theories, and these offer a physical mechanism for how the wave function might collapse. So for instance, when a system reaches a certain size or mass, this might trigger its weight function to collapse.

And this explains why we don't see large objects like people in a superposition of being here and there at the same time. But it also means there's nothing special really about the act of measurement. But which school of thought is the best? Some interpretations are more popular than others - at a conference on the foundations of quantum mechanics in 2011, for example, a survey of a small sample of 33 physicists revealed that the most popular approach was the Copenhagen Interpretation with 42% preferring it. But that was a decade ago. So which approach is gathering the most support now? I put this question to Chris.

Chris Timpson: I think slightly paradoxically, all of the available options are gathering more support. That is, more people are understanding what's available, uh, they're understanding what the kinds of problems are and understanding the really interesting and important work people have been doing to tease out the differences and the implications of these various approaches. So I think that they're all flourishing, um, both theoretically and experimentally. One of the very interesting things is, concrete experiments can be devised, which would lead to empirical differences for different interpretations of quantum theories. There are lots of good experiments, which are testing things like these dynamical collapse theories that I mentioned, um, or that are looking for other signatures of strange behavior that we wouldn't expect to see in one interpretation versus another.

Miriam Frankel: But maybe it doesn't have to be this complicated. Some physicists, including Marcus, have started realizing that maybe part of the measurement problem in particular can actually be solved with a bit of information theory and thermodynamics, which is the science of heat and work. Physicists didn't use to think that thermodynamics or information was that relevant to quantum mechanics, but it's becoming increasingly clear that once we measure a system with a measurement apparatus, we don't just extract information from the system, we also disturb it by transferring energy to it.

One idea is that measurements lead to a system picking a state while entropy rises, entropy being a measure of disorder of a system. So that's something we covered in the first episode, the second law of thermodynamics says that entropy always increases in a closed system. That's why we see events which increase in entropy, such as an egg breaking and splattering, but we never see the reverse, such as an egg spontaneously reassembling back into its shell.

So thermodynamics may therefore explain why some events can't be reversed. And some physicists believe that quantum measurements are like that. They cause a superposition to collapse into a fixed state while entropy rises in the measurement equipment. And that's exactly what we see in real experiments. So the joint system of the measurement apparatus and the quantum objects results in an overall increase in entropy, even though the entropy of the quantum system slightly goes down.

So Marcus argues, that's why we always measure a superposition collapsing into a fixed state rather than the other way around, a superposition suddenly appearing. Measurements seem to be irreversible in this way he says, because entropy is ultimately increasing.

Marcus Huber: You could say that somehow the measurement problem is the second law for Neurodynamics in disguise.

Miriam Frankel: And is that proven? I mean, do we need to do any experiments to show that this is really what's happening? Or do people just accept this and have we now solved the measurement problem?

Marcus Huber: If I were to claim I've solved the measurement problem, then I think a lot of people would strongly disagree. But it's also because of which variants. I mean, all this says is actually all I'm saying is that this part of the measurement problem isn't actually a problem. Other parts of it may still be, like what happens to the other parts of the wave function? How do we pick which universe we are in? How is our identity defined? These are all things I have no answers to

Miriam Frankel: But so do you think everybody is convinced of this idea that it's the second law of thermodynamics that makes a particle, for example, suddenly pick a location and not go back to being in a mix?

Marcus Huber: I think there is a sizable proportion of quantum physicists that are very convinced of this. But by far not all.

Miriam Frankel: Marcus explained to me that while the entropy of a measurement experiment always increases, the entropy of the system that is being measured goes down. So that's essentially what happens in your fridge when it's connected to power. You know, the entropy of the cool part of the fridge is going down while the overall entropy of the entire fridge system, including the electronics goes up, so to reduce entropy in a certain spot is hard. We have to do work on the system, increasing the entropy overall, but instead of power, a simple measurement such as an observation could actually do that to a quantum system, an idea that Marcus is using to create a miniature quantum fridge.

Marcus Huber: So we here at the Technical University, we're using an atomic gas cloud to manipulate it with some strong laser fields and strong potentials and move it around and essentially use it as a thermal machine, as you would use a classical refrigerator with the same kind of primitives where you expand the atomic gas, you compress the gas, you connect the gas, you move it around. And in this way, this cloud of atoms can become its own refrigerator, so you can use part of the cloud to cool down another part even colder. And there are other proposals, I've recently seen, for instance in levitated nanoparticles. You can cool the emotional ground state even colder by keep monitoring their position and then compensating all the time for how they're moving. So there's lots of ways and different creative ideas how measurement can help you to cool down quantum systems.

Miriam Frankel: While thermodynamics might be able to help us understand measurements, it doesn't seem to tell us exactly why and when quantum mechanics stops applying. Why don't we see cats in positions? What happens at the mysterious border between the microscopic quantum world and the microscopic normal? Here's Chiara.

Chiara Marletto: There's a difference between what happens naturally. Like if we look around, it's very unlikely to see things like rockets that fly to the moon and in fact, up to a point it looked like those objects couldn't exist because they were not around right? We didn't have rockets up to the time when we decided to actually build one. And before, at some point there was a moment where we couldn't even imagine doing something like that right? So there is this difference between what we see existing at present, and as you say, quantum effects are difficult to observe at our scale. So what you might say, well, they're actually not there. Um, but actually that's not a right conclusion because there is another thing that is not what exists, but what's allowed to exist, what is possible, and now to understand what is possible in a really fundamental way, you should really have to look at the laws of physics that you have because they're a bit like a user's manual for the universe.

And if you look at the laws of physics that we know, quantum theory specifically, there's nothing in those laws that says it's impossible to do, to have quantum effects at the scale of, um, I don't know, a human being. It's difficult. It's just a bit like saying, well, we don't see rockets routinely. Up to the point when they were brought about, they could have been thought as being impossible, but we knew that they were not because it was not in the laws of physics saying we can't build them. Likewise, in the case of quantum effects at at the macroscopic scale. There is nothing in the laws of physics at present that says that they are impossible. So either we discover a new principle that says that they really are impossible. That would be interesting. Or in the absence of that is more like a question of we do need to try harder to make the right conditions in the laboratory to bring these effects about. So we don't see them naturally. They're not the most likely state in which objects can exist at our scale but we can construct these states.

Miriam Frankel: Why is it so rare in the macroscopic world?

Chiara Marletto: That's true with the way in which quantum effects play out in a sense that they tend to be washed out whenever there are interactions with other systems. So if you want the quantum effects on an object like a cat, you want to have full control on its dynamical evolution, on its trajectory if you like, law of motion and the more particles there are in in your object in the cat, for example, the more difficult this is because you've got to control to each one of these particles. Obviously with one electron is easier. It's still hard, but it can be easier compared to a cat.

Miriam Frankel: So Chiara doesn't believe that there is a strict cutoff at which quantum mechanics stops applying. And scientists have actually managed to show that fairly large objects can be in superpositions, including huge molecules and viruses and stuff.

But the larger the objects, the more difficult it is to observe quantum effects. Humans, for example, are fundamentally a collection of atoms who are constantly walking around being dead and alive at the same time. But the particles that make us up are also constantly being monitored in our messy world of humans and by other particles and objects. So it's because we are constantly being monitored by all the particles around us that we're not really experiencing being dead and alive at the same time, and we simply can't turn that measurement off in the macroscopic world. But how do you prove that there is no hard edge between the micro world and the larger world?

To better understand the differences between these two worlds, Chiara has co-developed a brand new framework. A meta theory: constructor theory, as it's called, aims to encompass all of physics and observers in it. It basically explains the world by stating only which transformations are possible, which are not, and why. So entities that have the ability to carry out transformation accurately and repeatedly are called constructors. And so a kettle connected to power, for example, is a constructor that can carry out the task of heating water given a sufficient amount of energy. Constructor theory takes information to be fundamentally physical and real. So rather than a mathematical concept. And Chiara and her colleague David Deutsch have shown that it can be used to describe information processing in a way that unifies the classical world of macroscopic objects, including general relativity and the quantum cosmos. This is Chiara explaining what it is.

Chiara Marletto: The name constructor theory comes from the idea of a constructor, which is something that polymath John von Neumann invented. So a constructor is a generalized computer. It's, uh, a machine that can be programmed to realize not just computations like computers do, but also other kinds of tasks. So it's really like, um, programmable entity that can, uh, realize transformations that are physically allowed. And von Neumann envisaged this, uh, object called the universal constructor, which is the ultimate generalization of the universal computer, which you can think of as a universal 3D printer, if you like, that can be programmed to construct any object that's physically permitted.

And now the theory of constructors is a theory that within physics puts fundamental limitations on this universal constructor. So it says, what are the transformations that it really cannot perform and what are the transformations that it can perform. And so it's made of, uh, this set of principles which generalize a current theory of, you know, quantum information if you like, to cover these more general machines. And so, in a sense, you can think of it as a unification of something like thermodynamics, quantum information theory and also the physics of life altogether. So these principles are really rules that ultimately limit what a universal constructor can do.

Miriam Frankel: Constructor theory is hard to understand, and quantum mechanics already works pretty well. So do we really need it?

Chiara Marletto: Quantum theory is good so far, but as always in physics, somehow there are indications that it will have to undergo some changes in the future. And the strongest indication is that there is another theory that is also excellent and corroborated, uh, experimentally in its own domain, which is general relativity, that that also claims to be universal.

So it's got the aspiration as a theory to apply to the whole of the universe. But unfortunately it's classical, so it doesn't have any of these superposition effects or anything like that. And this is one of the deepest and most interesting problems in physics nowadays. How to actually put together these two pictures.

So in that sense, physicists expect that both theories will have to be modified in one way or another. And when we, uh, look at situations of this kind in the past where we had theories that we didn't know how to modify or how to bring forward to describe maybe future experiments or unknown phenomena, one thing that has always been very useful is this particular kind of laws of physics that we call principles.

So the principles in physics are not dynamical laws. So they're not laws of motion. They're not expressed as equations with the trajectory and initial conditions, but they are expressed usually as things that say what things are impossible or possible. So, an obvious example is the conservation of energy that, you know, is part of thermodynamics that says that it's impossible to change the energy of a system unless you also modify the energy of another system, because the energy overall has to be conserved. And then we have the second law of thermodynamics, which is also about impossibility, says that perpetual motion machines are impossible. Now, these kind of principles are very general. They apply to all laws of motion that are allowed. And so when you don't know what to do to modify your theories and think of a better theory, they're really useful because they provide guidelines to guess future theories.

Miriam Frankel: So basically if quantum theories said you could have a perpetual, uh, motion machine, that would be a strong indication that quantum mechanics was wrong.

Chiara Marletto: That's right. So you can use these principles as a kind of sieve that allows you to rule out theories immediately if they happen to violate what the principle says. So they're really draconian rules of sorts. So constructor theory takes the view that you can actually have more of these principles, but they all have this idea of saying what transformations are possible and what transformations are impossible and why. And constructor theory is basically made of these principles. And so it's supposed to be a kind of more general theory than each specific law of motion. And it could be really useful now in this particular time in physics because it can allow us to have a sort of guideline to guess future theories that could improve on both quantum theory and general activity.

Miriam Frankel: So as we've already mentioned in the episode about time, Chiara has actually come up with a pretty interesting idea for an experiment. Not only may it allow physicists to create superpositions of space times, but it may also tell us something about how to unify quantum mechanics with gravity.

Chiara Marletto: We have been working on a number of experimental schemes if you like, so they are theoretical at this stage, but they are within reach of current technology or technology that can be developed in the near future. And I think one really promising one is this one where you have two objects with a mass, which you want to use in order to probe whether gravity has some quantum features. And it's really nice to think about how it works because it's based on some of these information theoretic principles I mentioned earlier.

And particularly it's based on a kind of general fact or a theorem, if you like, that says that if you have an object in this case, gravity, that is capable of creating entanglement between two other quantum objects, then this object must have also some quantum features. So this theorem sort of says that quantum theory is a bit infectious in the sense that if you have this element that you don't know whether it's quantum or classical, but you can use it to generate entanglement between two objects that you know are quantum, then this object itself has to be quantum as well. And you can use this general principle in the case of gravity and set up an experiment where you are attempting to create entanglement between two masses by gravitational means only. So using gravity as a mediator of this entanglement. And the interesting thing is that this particular experiment can be realized at relatively low energies and also with relatively low masses.

Miriam Frankel: Yeah. So how do you know that only gravity is entangling them? How do you know it's not something else?

Chiara Marletto: So that's where the experimentalists have to actually work really hard. So we theoreticians are always very happy to say, well, you know, *assuming* that there are no other interactions. So one of the challenging parts of this experiment, which I think is what makes the experiment fun and interesting, is that you will have to make sure that this effect between the two masses, the gravitational effect is somehow distinguishable from other interactions. So either you can rule out the, for example, electromagnetic interaction at that particular scale, or you can say that they have a really radically different behaviour so you can discriminate the signals that come from gravity and those that come from other forces. Of course, other forces are always there, and I think it's a challenge that the experimentalists must meet, but I think it's quite promising that the experimental scheme actually exists in the first place because it probes its sort of sweet spot where general relativity is not really relevant, but gravity is. But you can see already some quantum effects in gravity, if there are any. So it's, it's a bit like providing the first test of quantum gravity. So it's a really interesting way of going and probe some experimental system because it's testing this set of theories, which currently we have, but we don't know how to test, which goes under the general label of quantum gravity.

Miriam Frankel: So you're saying it would suggest if gravity could untangle particles? That quantum mechanics is the more correct version of reality. And general relativity can be used, but it's not as fundamental as quantum mechanics.

Chiara Marletto: That's a brilliant way of putting it. I think that's exactly how it is. And so if we could confirm entanglement as gravitationally generated. It would be also on one hand a way of confirming quantum gravity as a kind of general idea, but at the same time, it would also refute some aspects of general relativity, and it would say that, general relativity as it is, as a classical theory is inadequate. So it has to be modified along one of the lines that are being proposed in the quantum gravity programs.

Miriam Frankel: Okay. Will it disprove or prove any of the various interpretations of quantum mechanics?

Chiara Marletto: Well it would rule out, uh, things like the variance of quantum mechanics, so it would, uh, some of the collapse theories because, for example, Penrose’s take on the collapse and also other forms of the clubs theories. They would already say that entanglements shouldn't be observed at this scale of which experiment is supposed to work. So if we do observe it, tanglement, those proposals are ruled out

Miriam Frankel: While physicists are still battling over the correct way to interpret quantum mechanics, experiments and technology are pushing forward constantly, and it does seem that some of them could help us rule out some interpretations. And of course, if we had a more complete theory of nature combining quantum mechanics and general relativity, we might be a bit less confused about what's really going on.

Until then, it can be no doubt that quantum mechanics works. It is one of the most successful theories of all time. That said, there are things that quantum mechanics in particular, and physics in general can't really explain. One such thing is life. What is the difference between a dead lump of matter and a living one? What allows things such as consciousness agency and free will to arise from a bunch of atoms? That's a question physics can't yet answer, and we'll talk about it more next time.

This podcast was created and presented by me, Miriam Frankel and produced by Hannah Fisher. The executive producers are Jo Adetunji and Gemma Ware, and the advisory editor is Zeeya Merali. The sound design is by Eloise Stevens, and music is by Neeta Sarl. Great Mysteries of Physics is a podcast from The Conversation UK with funding from FQxI.