AstronomyCast Episode 252 for Monday, February 13, 2012: Heisenberg's Uncertainty Principle

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Fraser: Welcome to AstronomyCast, our weekly facts-based journey through the Cosmos, where we help you understand not only what we know, but how we know what we know. My name is Fraser Cain; I'm the publisher of Universe Today, and with me is Dr. Pamela Gay, a professor at Southern Illinois University – Edwardsville. Hi, Pamela. How are you doing?

Pamela: I'm doing well. How are you doing, Fraser?

Fraser: I'm doing really well…working back into our schedule trying to catch up. We're actually recording this a little bit early than the actual Monday, so I think we're getting back on track. Again, if you don't know, for those of you who only listen to the podcast, we record these now as live Google plus hang-outs every Monday at noon Pacific, 3:00 Eastern, and 8:00 London time, so if you want, you can join us live; you can sort of jump in to the podcast at the end, and ask us questions. We'll hang out for about a half an hour after we record with the audience -- really cool, really fun, really neat way to connect with us. You guys get to pick Pamela's brains to ask her any questions to see just how super-smart she is.

Pamela: Any *astronomy* question…

Fraser: Any question you like, whatever, you know – the more math, the better.

Pamela: No.

Fraser: Alright, well let's get on with today's show. Quantum Theory is plenty strange, but one of the strangest discoveries is the realization that there's a limit to how much you can measure at any one time. This was famously described by Werner Heisenberg with his Uncertainty Principle how you can never know both the position and the motion of a particle at the same time.

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Fraser: Alright, Pamela I guess we need to reflect back to our Uncertainty principle, or I guess, our Quantum Mechanics conversations. So what is the sequence of discoveries in Quantum Theory that led up to Heisenberg making this very famous principle?

Pamela: So this is actually based on the realization that things, particles in fact, aren't simply little discrete bundles of matter that fly around like little tiny ping pong balls, but they're actually made up of waves, and so when I'm talking about a photon of light, I'm talking about something that has a wavelength that gets refracted and interacts with the material around it in much the same way that ocean waves will interact with seawalls as they pass through them, and waves will interact with one another in water creating dead places and places with particularly high waves. This realization that particles are also waves at the exact same time meant that suddenly in trying to describe what does it mean for something to have a location, the world kind of fell apart mathematically and we had to rethink everything. It was no longer a particle that has an edge here, and an edge here, and this radius going off from the center in both directions. Suddenly, it became we're going to combine wavelengths of various sizes to build up a particle, and that's a much different thing to try and deal with.

Fraser: So is that kind of like asking what is the position of a wave? I mean, you can imagine a wave crashing on the beach, or imagine a tsunami, right? That causes this huge ocean wave that ripples across the whole ocean, and you know, five hours later, you can ask yourself, "Where is the wave?" Well, how much wave? At which places? I mean there's going to be some wave. What's the height of the wave? What's the power of the wave? You know, it's almost the entire ocean at that point.

Pamela: Right, and you do have this problem of just, definitionally, what do you use? And you can…with particles you can start to say, well, an electron is made up of this vast combination of wavelengths that all interfere to localize the particle in one place. Now, the only problem with that is once you've combined all of these different frequencies to say "the particle is right here," well, now you've started to lose all of the momentum information. It actually turns out that when you have one beautiful, nice wave function, you can very beautifully define what its velocity is. We know how to do that, but when you start combining all of these different wavelengths that all have different velocities, or different frequencies, depending on how you choose to add them up, or what mediums you're dealing with, when you start adding all this stuff together suddenly you realize, "I no longer know exactly what the momentum of this object is because there's simply limits on, not my equipment, not my technique, but limits on what I'm able to come up with for the momentum based on all of these wavelengths combining together to tell me where the particle is."

Fraser: And I think this is a pretty common misunderstanding of this whole Uncertainty Principle is it's not about the, you know, you getting in and changing the position of the particle as you attempt to measure it, it's not about a sensitivity of the instruments, there's actually a…it's impossible to do both at the same time.

Pamela: Right, and there is a certain amount of you're interfering with this process as you get involved, so there's two different ways that this gets looked at. One of the ways that it gets looked at is as a relationship between the energy of an object, and the time at which you're looking at the energy, and so since …when you measure the energy, well, you're interfering with the system and you're probably changing the energy of the system. You're either able to say very precisely what the energy is, but in the process of making the measurement, you lose the time due to all the general relativistic effects that have to take place -- and time and GR are not friendly together, or you run into problems with you can measure the time that you're making the measurement very, very accurately, but in getting the time just so, you lose track of the energy. It's pick one, and there's a "greater than" sign in this, so the way the Uncertainty Principle is written is the accuracy with which you don't know the energy, the uncertainty, the "indeterminacy" if you're speaking in German, of the energy multiplied by the uncertainty in the time of the measurement, or the "indeterminacy" in the time of the measurement multiplied together is always going to be greater than an amount that's set by Quantum Mechanics. Now, you can have more error than that. It's perfectly reasonable to say, "My equipment doesn't work that well. My knowledge of the system isn't that great."

Fraser: "My big, fumble fingers keep knocking the particles around."

Pamela: Right! Exactly! Yeah -- "My hadron collider…" but once you put all those pieces together, you can't get better than a constant set by Quantum Mechanics. It's easy to understand this when you start looking at position and momentum, so we use momentum because you have issues with "as your velocity changes, so does your mass," but mass and velocity play together in momentum. That's a variable that takes into account both of those properties, so here you can actually start to imagine how you're affecting the system. If I want to know how fast something is going, the best way that I can do it, in some ways, is to actually measure how the impact of that object transfers its energy to another object. Well, I have now just completely changed where that particle's going to be because I've impacted it on something. Now, at the same time, I can very precisely know where a particle is by bouncing things from all directions off of it and looking to see… it's sort of like how a scanning electron microscope works. You just [missing audio] bouncing particles off of something, you know exactly where it is, but in the process of bouncing all these particles off of it, I have clearly changed its velocity. So in both of these types of measurements, by trying to get at one of the two variables -- either the position or the momentum, I've affected my ability to know the other one. So since you need two different ways of measuring position and momentum, you can't get at both simultaneously with accuracy.

Fraser: And so what impact does this actually have on the actual particle itself? As you say, if you are colliding it into something, I guess you're ceasing its momentum.

Pamela: Yeah…yes, that's one way to look at it.

Fraser: And discovering its location…but I mean are you actually bonking the particle around with your measurements? But I guess you've got this wave-particle duality, you've got this situation where things like photons and stuff can act a bit like particles, and a bit like waves, and in many cases, it's the act of measuring that forces the particle into one state or another. Is there some of that at play here? Is that what the Quantum…sort of, the Quantum part of this is about?

Pamela: And this is where…actually, when people first heard this they got rather annoyed because it just seemed like it shouldn't make any sense, and Einstein, who really didn't like Quantum Mechanics at all, was one of the people that tried to say, "No. This doesn't work. Here's a thought experiment. Go look at this; I think this says it doesn't work." So one of his thought experiments was to actually say, "Let's consider a particle that's passing through that narrow slit, and by passing through the narrow slit, you're taking a wave function and causing it to bend and distribute itself in a different way. We've all seen this with seawalls, or at least with pictures of seawalls, where you have this beautiful linear wave approaching the seawall, and then the part of the wave that passes through the hole in the seawall ends up rippling out as a curve. Well, he said that by considering a wave passing through a slit, you end up with uncertainty in the momentum that can be proportioned to the size of the slit, but you can determine the momentum that's introduced in this very accurately by looking at "Well, how does the wall recoil?" So his idea was you get some of the information by looking at what passes through the slit, we know how to do that, and you get the rest of the information by looking at the wall's response to the parts that hit the wall, and Heisenberg, in thinking about this, pointed out that we don't actually know the wall's position in momentum with sufficient accuracy that we can just throw that out to get the wave perfectly. So once you start putting into consideration the uncertainty in our knowledge of the wall, that's where our uncertainty comes back into the problem, and no you can't use that cheat, but Einstein was not deterred by this and he kept coming up with new thought experiments.

Fraser: What was his famous quote: "God does not play dice."

Pamela: Yeah, and it turns out God may not, but the Universe certainly does.

Fraser: He did not like this…yeah. OK, well, I guess we should step back a bit and really understand how Heisenberg sort of formulated his original principle. And what exactly does his principle state?

Pamela: So his principle states that…when he first wrote this, there was no detailing of constants, but what his principle states is: "The uncertainty…" -- and he actually used the word "indeterminacy" in his paper, except in the final footnote, but when the paper, which was written in German, was translated into English, whoever did the translation took the word from the footnote and used it for the entire paper, so while the original paper mostly talks about the "indeterminacy" of the position and momentum, we've translated this in English into the "uncertainty of the position and momentum." It's semantics. So what he discussed was the accuracy with which we know a particle's position multiplied by the…I guess it's lack of accuracy is a better way to put it. The lack of accuracy with which we know its momentum, when you multiply these two things together, those two indeterminacies, those two uncertainties are always going to be greater than some set amount that is defined by the nature of the Universe. He looked at the Planck constant; since then we've started using the Planck constant divided by two pie divided by two because we like to divide things up, but some form of the Planck constant is that limiting factor, and this all boils down to looking at the wavelength nature of things, and part of the inspiration for looking at this was the realization by Prince De Broglie -- and I love the fact that you're getting royalty involved in the defining Quantum Mechanics…

Fraser: Not the musician, but an actual prince.

Pamela: Right, yes. He looked at the wave nature of things and realized it's not just light that has a wave nature, it's actually baseballs, and human beings, and everything that exists has a wave-particle duality, and we've actually experimentally been able to prove this. You can take Buckyball particles, little carbon molecules that…I believe they're as many as 60 atoms involved in one of these crazy little molecules -- you can take one of these carbon Buckyballs, and put it through a slit, and then put a stream of them through a slit, and they form the interference pattern that you would get from sending light through. We can do this with electrons. There's a whole variety of experiments that have been done showing that matter does behave, does self-interact in the same way that waves of light do. So De Broglie, in thinking about the wave nature of things, was able to describe the wavelength of an article as of a particle, rather, as being equal to the Planck constant "h" divided by the momentum of an object.

Fraser: Yeah, you just "mathed out" on us there.

Pamela: Yeah, so for a human being, our De Broglie wavelength is something like 10 to the -37 of a meter, so we're talking at like subatomic scales here for human beings' wavelengths -- so we're not going to interact with one another going through doorways in Quantum Mechanic natures, but the De Broglie wavelength starts to take on more and more importance as you start looking at fast-moving, very small particles, and it was while Heisenberg was thinking about the wavelength nature of particles, while he was thinking about how particles interact with one another, how you measure different interactions that he started to realize that it's this wavelength nature and our inability to say, "This is in the center of a wave" that means that we can never accurately know the position of a wave, but if we do somehow look at the full wave packet, the combination of all those different wavelengths to see the particle nature of an electron, of a Buckyball, in doing that we've removed the momentum information that we get from the wavelength. So it was just in looking at how do we measure these two different things, what aspects of the objects do we rely on…then we realized, "Crud! We can't get perfect accuracy."

Fraser: And so what are the implications, then, of the Uncertainty Principle in sort of just modern engineering, modern physics? This is one of those principles that actually does have an implication in electronics and stuff, right?

Pamela: It does, and it runs into annoying things where we actually can't completely localize particles with CCD detectors and such, where when we have…or the timing – pick one. So if you're doing extremely high-speed photon counting, you can either know exactly where the photon hit your detector or exactly when the photon hit your detector. You can't know both.

Fraser: Wow!

Pamela: So I mean, think about how this then affects things like well, those faster-than-light, pesky neutrinos that were, or were not (and I'm on the were-not-detected side of things)…so you can either know the exactly when or the exactly where, but there's always this uncertainty involved, and you have to start taking into account on, well, you can't know exactly where the detector was – exactly. You can't know exactly where the neutrino was – exactly. You don't know the times and energies – exactly. There's always this fuzz to everything.

Fraser: Right, and so you've got a situation where you've got these particles, or I guess you're dealing with the speed of light, and so the distances they're traveling is relatively short. I mean, we're looking at from one part of Switzerland to France, right? So you don't have a big, long distance, and you can know the distance, you can know where these particles are hitting, which I guess this is key for those neutrinos, but it's that timing that tells you whether they're traveling faster than the speed of light that is really hard to get a handle on, so you see it rearing its ugly head with the faster-than-light neutrinos. That's really cool.

Pamela: And, honestly, I think a lot of the problems are in timing, I mean, one of the issues that comes out of General Relativity is "How do you link clocks?" And this was actually one of the thought experiments that Einstein came up with -- sort of kind of. One of the things that he said referring to the Uncertainty Principle in his other "no, this can't work" argument was consider you have a box with a clock, and you very precisely time the opening and closing of a door on the box, and you let a certain amount of energy out of the box, and you have the ability to measure the amount of energy that came out, and then you can weigh the box, so you know the amount of energy inside, and it's through this combination of measuring the amount of energy that leaves, and measuring the weight of the box after, and knowing the moment that the energy moved, well, that's a delta E from knowing how much energy came out, that's a delta T from the clock, you should be able to get all of this perfectly accurately just by weighing the box. And it was pointed out that the clock and the box are gravitationally tied together, and that this is a gravitational field that will thus affect the ticking of the clock, and so it's all tangled together, and so now the uncertainty in the time is also coming from Relativity playing a role, and it's all part of a whole, and at the end of the day it means that even if we do know where every particle in the Universe is, we don't know where they're going, and we can't predict the future.

Fraser: I think that's a fantastic example because Einstein coming up with a thought experiment, and then someone says, "Oh, but don't forget this little theory called General Relativity." Right? That's going to impact the experiment as well, and I'm sure, again, I'll bet he was really pleased with that example, and had to go back to the drawing board, but he clearly was puzzled and bothered by the implications of this theory, because as you said, he went on record a bunch of times, and spent a lot of his final years attempting to come up with a Theory of Everything, and trying to, I know, think through the implications of Quantum Mechanics, gravity, and all that together. For every thought experiment that he delivered, the Uncertainty Principle had a perfectly fine way to explain how that still was under the constraints of the Uncertainty Principle. It's quite interesting that essentially the most brilliant scientist of modern times kept bashing his head against this principle, and it kept defeating him.

Pamela: And it really does say that the Scientific Method does work, that it's not always a cult of personality. That does happen occasionally, you do occasionally just need to wait for somebody to die to get a theory accepted, but to have someone of the notoriety of Einstein going, "No, really, let's think this through," and everyone going, "No Einstein, this is right," it's just a brilliant way that the entire community together can be smarter than any one individual when it comes to figuring out what's true and what's not.

Fraser: That is really great. So then, you know, does the Uncertainly Principle have any impact on, for example, the search for the Higgs Boson, some of these big particle colliders? Because I'm sure they're attempting to measure particles very carefully.

Pamela: So here, luckily, we're mostly interested in the energies of the particles, so we're looking for the tracks, the light being emitted, the basically, what is the energy of each of these little things that gets created, and so while decay times are kind of awesome to know, it's knowing what is the energy of the objects that are decaying that is of the most import to us. So while it's annoying we can't know everything, just being able to get at "the energy is 125 giga-electron volts per c squared" – that is the information that's mostly important to us here.

Fraser: Right, but you can imagine, you've got these cascades of particles that have half-lives of certain periods, and so knowing that this particle collapsed into those particles, and released this energy at these time periods, that is starting to fall under that whole Uncertainty Principle.

Pamela: It's not…luckily, it's not the dominant problem. The dominant problem is just getting all the energy in one place at one time, and letting all of those decays happen.

Fraser: All right, well I think we're all done this week, so thanks a lot, Pamela. I really appreciate it.

Pamela: My pleasure, and I will hopefully see you soon, and don't forget if you're interested in figuring out a Christmas vacation next year, we're going to be on "the world is not ending cruise," and I'm just going to keep plugging that periodically so that we can all, all of you out there listening, hopefully meet in person and explore Mayan ruins together.

Fraser: We'll plug it until it fills up, and then we won't plug it anymore.

Pamela: That's true.

Fraser: Yeah, and that's going to be over the December 21 holiday – end of the world.

Pamela: Go to “astrosphere;” it’s on the homepage – astrosphere.org

Yeah…astroshpere.org. All right, well, thanks again, Pamela, and we’ll see you next week.

Pamela: Sounds good. Talk to you later.