Welcome to the Science Podcast for May 7th, 2021. I'm Sarah Crespi. Each week we feature the most interesting news and research published in Science and the sister journals. First up, Rich Stone, former international news editor, is back with us to talk about a concerning signal coming from the ruins of Chernobyl, and what scientists can do about it. Next, researcher Shlomi Kotler, talks about quantum entanglement, and how this hallmark of quantum physics can now be observed not just in ions and atoms, but in macro-scale objects, the width of a human hair.

The nuclear disaster in Chernobyl happened 35 years ago, in April 1986. And there is still so much to learn about this event and its consequences. Just last week, Science published a paper on how there were no more mutations, in average, in second generation survivors. These are children of people who were exposed. This is good news. But, meanwhile at the site itself, researchers are concerned about sustained fission reactions happening deep in the basement of the facility. Now we have our former international news editor, Rich Stone. He wrote about these concerns over conditions at the site. Hi, Rich.

So Rich, what exactly is being detected here? Why is this concerning, and how do they know that it's happening?

So inside the destroyed reactor, it's a extremely high-radiation environment. There's a lot of places that researchers can't actually physically go without endangering their lives. And so they've rigged the reactor with sensors. And sensors detect, primarily, gamma radiation and neutron flux, so the number of neutrons emanating from the nuclear materials in the basement of the damaged reactor hall. So they've been seeing an increase in neutron flux pretty steadily from three areas within the damaged reactor. And one room in particular is of big concern to them.

These increased streams of neutrons, they indicate that there is ongoing fission?

That's right. So initially, the researchers thought perhaps their sensors were malfunctioning. They wanted to rule that out. They thought perhaps these are spurious readings. The reason why they were dubious that they were actually seeing an increase in neutron flux, is why this might be happening in the first place. So you have to step back to a little bit of the history of Chernobyl. After the reaction, basically, the core melted down. There was a huge fire. The structure was severely damaged, and Soviet engineers hastily built a concrete and steel sarcophagus, called the shelter, over top of the damaged reactor. The shelter was quite leaky, so rainwater would seep in. Water moderates neutrons. By moderating the neutron, it made it more likely that a neutron would encounter a uranium nucleus and make it split, sort of, spark fission.

For a long time, there was a very anxious vigil that the Ukrainian physicists would
be watching the fuel in the bowels of the reactor. And when rainwater would come in, the rate of neutron flux would increase, indicating fission was happening and they would have to do something about it.

0:03:42.6 SC: Some of those measures involved running in real fast and spraying it down.

0:03:48.3 RS: There are amazing stories of heroism that you generally don't hear about what happened in Chernobyl after the shelter was built. Scientists would have to go inside the sarcophagus, and sometimes go to a room in the bowels of the damaged reactor where they were seeing these high neutron counts. They would race in, they would spray a solution of neutron-quenching gadolinium nitrate, that would basically sop up the extra neutrons and avert a criticality event. So this happened, most famously, on an occasion, 1990. And then several years later, the sarcophagus was fitted with a sprinkler system that could spray this neutron-quenching solution, just try to reduce the need for these people to risk their lives to try to address the problem.

0:04:45.1 SC: As you mentioned, this is spurred on by exposure to water. And not only is this sarcophagus sitting on top of this facility, but now a large shelter, called New Safe Confinement, has been placed over the wreckage of the facility. And that's also keeping rain water out. But we're still seeing this fission occurring.

0:05:05.2 RS: That's exactly how, kind of, odd and disconcerting this is, because when the New Safe Confinement was put into place in late 2016... It's impervious to water, so people assumed that neutron flux measurements within the shelter would gradually go down. And that predicted result has happened throughout many of the areas within the shelter. So many of the sensors are in fact showing a decrease, or at least a stable neutron flux. That's why when some sensors started registering an increase... And this has been a steady increase since 2016. It's not been fluctuating, it's been gradually rising. The Ukrainian physicists first wanted to make sure these were real readings. And then when they confirmed that, as far as they could tell, this is an actual increase in neutron flux, they had to explain why this is happening.

0:06:01.0 SC: There's no rainwater. What's happening now? What's the mechanism?

0:06:05.4 RS: There is a hypothesis about what's going on. It could be, as some Ukrainian scientists speculate, that some rooms in the basement of the shelter were actually too waterlogged. And as water recedes, as these rooms start to dry out, it approaches a more optimal, kind of, ratio of water to nuclear fuel. And that's why they're seeing this rise.

0:06:30.3 SC: So they were through it before, for this increase in neutrons, but now they're kind of approaching something that's a better condition. Okay.

0:06:37.3 RS: Yeah. I mean, it sounds counter-intuitive, right?

0:06:39.2 SC: Right.

0:06:40.0 RS: But that is the leading explanation right now. And outside experts agree that the data
looks solid. It's just a matter of, what does this mean? Like, what can be done about it now?

0:06:49.6 SC: And when we talk about criticality, how big of an event would that be?

0:06:56.3 RS: I would say, don't think about this as a nuclear bomb. It's not an explosion anywhere near that magnitude, it would be a scheme-driven kind of explosion that...

0:07:06.8 SC: Like a boiler blowing up.

0:07:08.1 RS: Yeah, exactly. Just like that scale of explosion, which could be kind of like a little puff that wouldn't lead to anything and then you blow off the steam and then the fission would subside. Fortunately, it would be nothing like the original Chernobyl accident. That spewed a radioactive cloud over a lot of Europe. You're not gonna see a release like that, especially with the New Safe Confinement in place. It's possible that that could bring down the shelter.

0:07:40.3 SC: The inner sarcophagus?

0:07:41.8 RS: Yeah, the sarcophagus. You could see that destabilizing and that would be a huge headache for having to dismantle the shelter, and you'd have a lot of radioactive contamination within the New Safe Confinement itself.

0:07:57.3 SC: What are some of the options here to prevent the criticality from happening?

0:08:02.3 RS: Well, one good thing is that it's not an immediate threat. Ukranian scientists think there's a few years to figure out a strategy for how to deal with this before the neutron flux gets so high that it could trigger kind of an uncontrolled event. So one problem is one room where they're seeing this, it's pretty inaccessible, extremely high radiation. There's talk about developing a robotic system that can withstand the extreme radiation, go in and drill into the fuel-containing masses. They'd have to drill through debris that's covering the masses, insert a boron cylinder similar to a control rod in a nuclear reactor that would sop up neutrons and quench the fission. So that is one idea that's being explored now.

0:08:50.7 SC: What I've read is that robots were not gonna help back in the 90s with this clean-up. They weren't able to withstand radiation, the electronics and the machines. Is that something that has improved? That technology is improved?

0:09:02.3 RS: Robotics has come a long way, especially with the robotics designed to decommission nuclear facilities. So there is optimism that robotics can be developed that can access this room, and there is hope that this neutron flux will subside on its own, that given time as water drains away, it may recede from that optimal ratio of water to nuclear fuel, and then you'll see the flux decrease and they won't have to do anything about it.

0:09:34.9 SC: Right, and this is where natural nuclear reactors come in. I had never heard of this before, but this can actually be an example, fission fizzling out on its own without human intervention.
0:09:45.9 RS: Oh, this is bizarre Sarah. In Gabon there is uranium deposits that two billion years ago became a natural nuclear reactor. Fission was occurring, and what governed that process was rainwater. So over the course of a couple hundred thousand years, you have these cycles of fission in the ground at this one site that eventually did peter out, but it could be a very similar process within the bowels of the Chernobyl reactor.

0:10:15.3 SC: Figuring this out how to approach this problem with a robot or some other means could help us work at the site of the Fukushima disaster in Japan. How are these sites similar?

0:10:27.7 RS: They're similar in a lot of ways, and in that you have molten nuclear materials at Fukushima as well, that magnitude, the hazard, the radioactivity problem that people have to deal with in Japan is quite similar to what you see in Ukraine. So for example, the robotics that might be developed to address the fuel-containing masses in Chernobyl might be applicable to what Japan can use as their hopes to move swiftly to clean up the Fukushima site.

0:10:58.1 SC: What is the timeline for taking Chernobyl apart?

0:11:01.1 RS: That's all being worked out now. The first priority of course, was put in a New Safe Confinement in place, and so that was a huge €1.5 billion project. Ukraine, its preference is to work as expeditiously as possible to take apart the shell to remove the fuel-containing masses and put them into geological repository, but there is a compelling argument as well for waiting because as time goes by the radiation subsides, so you already have a significant decrease in radiation 30 years after the accident, 30 years later, you would have a lot less and maybe robotics will be even better able to handle the task at hand.

0:11:42.3 SC: Rich, you've lived in Russia and Kazakhstan in some of the '90s. Have you visited Chernobyl?

0:11:50.6 RS: I have. To date myself, I covered the 10th anniversary of the Chernobyl accident back in 1996. [chuckle] I was back 10 years later for National Geographic Magazine, and by the time I returned many of the physicists who I had met in '96 had already passed away. It's a high-stress job. I mean if you can imagine how high the stakes were, and these scientists would sometimes have to be on their own, pulling a graveyard shift inside the shelter, knowing that in a mild earthquake the whole thing could come tumbling down, and I'm sure it has left a deep gash on the Ukrainian psyche. They would love to close that chapter. The New Safe Confinement from the international perspective, it is like closing the chapter, it's no longer an international threat, but to the Ukranians it's still there, and it's something that they really want to come to grips with and want to, as they say in Ukraine "liquidate" as soon as they can.

0:12:53.4 SC: Alright, well, thank you so much Rich.

0:12:55.4 RS: Thanks Sarah. Good to be with you today.

0:12:57.5 SC: Rich Stone is our former international news editor and now Senior Science Editor at
Quantum entanglement was first hypothesized as a way to dispute quantum physics. Look at this crazy result, you can't be serious, but the prediction has held true for photons, ions, atoms and now, macro-scale objects. Researcher Shlomi Kotler joins me next to discuss the implications.

[Music]

0:13:36.3 SC: Entanglement is a hallmark of quantum physics. It's one of the key differences between classical physics and quantum physics. We'd expect quantum physics to work at all levels from subatomic, to macroscopic. But like many of quantum physics most exotic predictions, they're not something we usually encounter in everyday life. Observations of quantum entanglement have been limited mostly to tiny things like atoms, and photons. But in this week's issue of Science, Shlomi Kotler and colleagues report on entangling two macroscopic objects. Hi, Shlomi.

0:14:13.2 Shlomi Kotler: Hi.

0:14:13.9 SC: I didn't do this in my intro, because there's a ton of ground to cover here. But can you define quantum entanglement for us?

0:14:21.9 SK: So suppose we have two objects and you want them to be really correlated. For example, suppose you're driving your car, let's just focus on the two front wheels of the car, you want those two front wheels to rotate together, if one of those over-rotates with respect to the other then the car will move to the left, to the right, or it might skid. And so correlation is something we use on a daily basis, but as it turns out, classical physics or classical states, there's a bound to how much can you correlate two classical entities like the two wheels of the car. And that bound is set by quantum mechanics. What that means is just going back to the car analogy, when you're driving, the two wheels are driving synchronously together, but they're not perfectly synchronous. There's a little bit of jitter between them that you never notice. It is so tiny that it doesn't matter, but it's nevertheless there. And entanglement or mechanical entanglement is when I correlate those two entities to a point where I can no longer describe them as separate entities, they are now so synced, moving in such unison that now the only way I can explain that state of that system is with entanglement, with an entangled state.

0:15:49.9 SC: The objects you entangled for this study are macro-scale, they're definitely bigger than a few photons, a handful of atoms. But still they're not something you'd really encounter in everyday life. Can you talk about these objects that you entangled for this study?

0:16:04.3 SK: Those objects were developed about a decade ago, and those are drum heads. Each one looks like a trampoline, if you wish, but it has a diameter that is comparable to the diameter of a human hair. Each one of those drums is composed of 10 to the 12 atoms and weighs about 70 pico grams. So much larger than an atom, but fairly small in everyday life. But then again, all of us... Well, most of us have hair and we all...
0:16:37.7 SC: Yeah, we do experience hair in everyday life. [chuckle]

0:16:40.1 SK: We do experience and if you can feel a hair and say, "Oh, that's roughly the diameter of it." So imagine that you made a slice of a hair and said, "Well, that would be my drum." And we entangled two of those.

0:16:54.7 SC: How is entangling these macro-scale objects different than entangling atoms or photons? How is the process for doing that the same or different?

0:17:03.9 SK: The first two objects that anyone has ever entangled were two trapped ions. It was done in 2009, and they took two atomic ions and they entangled the motion, and how did they do it? They had something to mediate the interaction between them, in that case, it was a laser beam. They shined laser pulses, and the laser pulses influenced the motion of those two ions and steered the motion of those two ions into an entangled state. Basically, we did something very similar. We had two of these drums, and we wanted to use some form of radiation that would steer their motion into an entangled state, so we embedded those two drum heads into a microwave circuit and we shined microwave pulses towards those two drum heads. And as we did that, we steered them into an entangled state.

0:18:03.1 SC: So this moves them to be hit with microwaves?

0:18:06.2 SK: Yes, if you hit some object with radiation, it turns out that you're slightly pushing that object. That's called radiation pressure. So if you go about your day and you get hit by the sun, you don't notice it, but actually the sun is pushing on you with radiation pressure, you don't even feel it. But for objects that are as small as atoms, you can really push them strongly. In the case of our drums, hitting them with microwave radiation, actually steers their motion, moves them around, pushes them around. And when we did that to the two drums simultaneously, we were able to steer them into an entangled state, and once they were in an entangled state, we used a different microwave pulse. This time just to probe their state, we shined the microwave pulse, it hit the two drums and as it reflected off of them, it carried information, Doppler shifted information about their state.

0:19:08.9 SC: We've been talking about entangling two macro-scale objects, but they're still pretty small. How much bigger can we go? Is there a limit on the size of entangled objects?

0:19:19.2 SK: That is more than a million-dollar question. [laughter]

0:19:23.1 SK: Because there is no limit to how big things can behave quantum mechanically. And it creates tension because we know that it works for atoms and electrons, we know that on a daily basis, you don't need quantum mechanics, you don't see anything that's quantum mechanical really on a daily basis. And then the theory says nothing, it says, "Quantum mechanics is supposed to be true all the way from the smallest scale to the largest scale of the universe." And so experimentalists are living in this gap, they start with atoms, and then they entangle them. And they say, "Okay,
what's the next big thing that I can go ahead and try and entangle?” And they entangle that. You just set the bar higher. Now, the next thing will be to entangle something bigger. Every time we've tried in the past, say three decades, we were successful. The bigger we go, the harder we try, we are able to entangle. So we are not seeing a bound experimentally, do not see a bound to quantum mechanics. If anyone at some point makes an experiment, tries to entangle, I love that phrase, entangle a cucumber.

0:20:30.1 SC: [laughter] yes I like it too.

0:20:31.8 SK: Take a cucumber from the grocery store, and another cucumber and entangle them. If at some point you fail, and you fail not because you didn't work hard enough, you failed because of an intrinsic reason. That means we will see experimentally, evidence that quantum mechanics doesn't work at all scales, that will be one of the most exciting results. The problem is, every time we try, we succeed. And so in principle, we can entangle two cucumbers to the best of our knowledge. And what experimentalists like myself are doing, we're just pushing the envelope on how big the objects are.

0:21:12.7 SC: There are a few different ways to talk about the result of this paper. And we just talked about how this is pushing ever upwards, the size, or the scale of things that can be entangled. But this can also be used in technology. Can you talk about how entangled microscopic objects might be used?

0:21:32.1 SK: Yes, let's think about our single element, which is the drum. Those tiny drums, they're small, they're compact, and they can store quantum information for a long period, long time. So you can treat them as a quantum memory. That's a bit surprising, because usually, when you think about mechanical objects, you don't think about a mechanical thing as being a good quantum memory. But as it turns out, we know today in 2021, we know how to engineer very high quality, mechanical resonators that retain their information, you can think of a platform that has many of those, an array of these drums, and you have a memory. Each one of them stores quantum information, you have multiple elements, so you have a memory. What entanglement brings to the table is the ability to now weave them together into something more interesting. Entanglement is exactly the process where you start to make them interact, and correlate with each other, and generate a state that is spread all over that array of drums. And that will be one of the building blocks of turning an array of drums or an array of mechanical resonators into a unit that processes quantum information. In fact, the industry has been looking at mechanical resonators, and at least one of the known efforts in the industry is to use mechanical resonators as the building blocks of a scalable quantum information platform.

0:23:09.5 SC: What's the advantage of using mechanical objects rather than, say superconducting qubits?

0:23:15.1 SK: I'll give you my kind of philosophical point of view. Superconducting qubits, for example, are basically artificial atoms that tend to interact with the electromagnetic surrounding. Because they are essentially spins or dipoles. They see electromagnetic radiation around them and they respond, it's a good thing, because then you can control them. But it's also a bad thing, because then they can radiate and they can interact, and then they can lose their quantum information. In
fact, one of the efforts in the field is how do I make superconducting qubits that are well isolated from their environment? And the answer is, it's hard. It's hard because they talk to electromagnetic fields. Now the electromagnetic laws of motion, Maxwell's equation generate strong forces. On the other hand, mechanical elements don't radiate anything to the electromagnetic field if you don't want them to. They're just mechanical. They abide by Newton's laws of motion. And if you build it well enough, they just don't talk to their surrounding. Because of that they can be used as good memory elements.

0:24:33.0 SC: What other uses could you see for entangled macroscopic objects?

0:24:38.0 SK: On a fundamental level, I think it's an obligation of quantum physicists to push the envelope on the mass of objects that exhibit quantum mechanical properties. Every time we push that envelope, we know that quantum mechanics is relevant to a larger scale. And if we never challenge the boundaries of quantum mechanics, we will never know. That's on a fundamental level. And I think that's important. No one 100 years ago, when quantum mechanics was being debated, and it was a fairly young theory, no one in their mind could ever imagine that you would entangle two drums. Einstein, Podolsky, and Rosen gave entanglement as a counter argument for the completeness of quantum mechanics.

0:25:26.3 SC: Right. They said, "Look at this crazy idea that comes out of this. Do you think this is a real thing?"

0:25:32.0 SK: Yeah, 85 years later, you can see it. You can see it with your own eyes. But technologically, larger objects are objects that you and I can manipulate and use for our daily use. For example, to store information. For example, to do quantum key distribution. For example, if you wanna build some sort of a quantum illuminator, like shine light on something that has quantum properties. And so is not that we like bigger objects is that we, [chuckle] we can produce them easily, we can interconnect them easily. And so we would really, really like to be able to create big objects that conform to quantum mechanics. And if you look at superconducting chips, or our drums, for that matter, they're large, they have a size scale that's 10, 20, or even more microns. It's something that we can put wires next to, it's something that we can put inductors next to, it's something that we can talk with using regular electronics. And so I have an easy interface, it really, really would benefit us if we can control these larger objects quantum mechanically.

0:26:43.3 SC: Thanks, Shlomi.

0:26:44.6 SK: Thank you.

0:26:45.1 SC: Shlomi Kotler is an Assistant Professor in the Department of Applied Physics at the Hebrew University of Jerusalem. You can find a link to the paper we discussed and a related insight at sciencemag.org/podcast.

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