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Quantum Rebel

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Has a simple experiment unravelled our most cherished notions of reality? Marcus Chown investigates

WHEN you look at your reflection in the bathroom mirror every morning, you could be doing yourself a favour. After all, some physicists believe that the most fundamental aspects of the universe do not really exist until they are observed. So you could argue that getting up and stumbling to the bathroom each day is vital to your well-being.

That is absurd, of course. But is it any more absurd than the standard interpretation of quantum theory, our most successful description of the microscopic world of atoms and their constituents? The theory's weirdness has grown to be accepted as the way things are: a bizarre scheme in which reality manifests itself in different ways depending on whether - and how - you measure it.

It now seems that our acceptance of such strangeness may be a mistake. An audacious and highly controversial experiment suggests that is not how things are at all. Shahriar S. Afshar, a 33-year-old Iranian-American physicist, has carried out a novel version of the "double-slit" experiment held by physicists to embody the central mystery of quantum theory's weirdness - and he says he has contradicted the standard result. "According to my experiment, one of our key assumptions about quantum theory is wrong," says Afshar. It's not a claim to make lightly. If he is right, it will reopen an argument that has lain dormant since the birth of quantum theory.

The Danish physicist Niels Bohr claimed that the only way to interpret the theory - the only way to understand what the mathematics of quantum theory has to say about how quantum things manifest in the familiar, classical world of our experiment - is to assume that nothing really exists until it is measured. To Bohr, it made no sense to talk about an objective reality independent of observers because our observations make a difference to what we will see.

This "Copenhagen interpretation" of quantum theory came from Bohr's conviction that, though the fundamental building blocks of reality might seem to be both particles and waves - a phenomenon physicists call wave-particle duality - it is more likely they are something else entirely, something for which there is no analogue in the familiar classical world in which we carry out our experiments. When faced with our classical apparatus these mysterious quantum entities will show either a particle-like or a wave-like face.

Bohr proposed that the face you see depends on how you set up your experiment. And, he said, you'll never see both at the same time in one experiment. He called this the "principle of complementarity". Einstein took exception to this: he refused to believe that the very fabric of the observable universe could change depending on our choice of measuring equipment. But he never managed to find an experimental way to refute complementarity, and Bohr's influence ensured that it gradually became the accepted view of how the quantum world will manifest in our classical experiments. Afshar, however, may have succeeded where Einstein failed.

His experiment centres on shining laser light onto two nearby apertures. This light emerges from the apertures as two spreading beams. Where the beams overlap, they interfere, producing alternating bands, or fringes, of light and dark. You can easily explain this interference pattern if you think of the light as waves. When two wave crests meet, they combine to produce even brighter light; when crests and troughs meet, there is darkness. The exact geometry of the interference pattern - the width and separation of the light and dark fringes, for instance - depends on the position of the slits, the frequency of the laser, and so on.

Nothing mysterious so far; the physicist Thomas Young first demonstrated this phenomenon in 1801 using sunlight. The problem arises because of quantum theory, which says you can consider the light beams as streams of particles called photons. Each photon is a packet of light energy. How do particles produce an interference pattern?

The short answer is they can't - yet they do. And the mystery deepens when you turn the laser right down so that only one photon travels through the apparatus at a time. It takes a lot longer, but the interference pattern builds up, one photon at a time. For this to happen, each photon must somehow pass through both slits and interfere with itself. Observing an interference pattern in these circumstances is the equivalent of hearing the sound of one hand clapping. The particles - whose defining characteristic is that they are localised at a particular point in space - are behaving like waves, which are smeared through a relatively large region of space. The Caltech physicist Richard Feynman once called this hybrid behaviour "the only mystery" in physics.

It certainly is mysterious: if you set the experiment up to follow the path of the particles - using, say, a photon detector to see which slit the light goes through - you'll be rewarded with a view of the particle-like face: your photon detector will register a photon. And if you look for evidence of waves, by looking for an interference pattern for example, you'll see that instead. Experiments have shown that attempts to locate the photon on its way through the apparatus always result in a washed-out interference pattern. Bohr's interpretation of the double-slit experiment appears to be right: nature does not permit us to know which slit a particle passed through - "which way" information - and also see an interference pattern. This has become the orthodox view, reprinted in thousands of physics textbooks.

So how come Afshar is claiming Bohr was wrong - that you can track the photons' paths and not destroy the interference pattern? Because, he says, he's done it.

He carried out his original experiment at the Institute for Radiation-Induced Mass Studies, a privately funded organisation in Boston, where Afshar is principal investigator. The set-up is relatively simple (see Diagram). Laser light falls on two pinholes in an opaque screen. On the far side of the screen is a lens that takes the light coming through each of the pinholes (another opaque screen stops all other light hitting the lens) and refocuses the spreading beams onto a mirror that reflects each onto a separate photon detector. In this way, Afshar gets a record of the rate at which photons are coming through each pinhole. According to complementarity, that means there should be no evidence of an interference pattern. But there is, Afshar says.

He doesn't look at the pattern directly, but has designed the experiment to test for its presence. He places a series of wires exactly where the dark fringes of the interference pattern ought to be. Then he closes one of the pinholes. This, of course, prevents any interference pattern from forming, and the light simply spreads out as it emerges from the single pinhole. A portion of the light will hit the metal wires, which scatter it in all directions, meaning less light will reach the photon detector corresponding to that pinhole.

But Afshar claims that when he opens up the closed pinhole, the light intensity at each detector returns to its value before the wires were set in place. Why? Because the wires sit in the dark fringes of the interference pattern, no light hits them, and so none of the photons are scattered. That shows the interference pattern is there, says Afshar, which exposes the wave-like face of light. And yet he can also measure the intensity of light from each slit with a photon detector, so he can tell how many photons pass through each slit - the particle-like face is there too.

"This flies in the face of complementarity, which says that knowledge of the interference pattern always destroys the which-way information and vice versa," says Afshar. "Something everyone believed and nobody questioned for 80 years appears to be wrong."

When Christopher Stubbs of Harvard University invited Afshar to repeat the experiment as a visiting scientist in Stubbs's lab earlier this year, the result was the same. Afshar has now submitted his work for peer-reviewed publication. What ought to happen now is that the journal's review process will either find some flaw in Afshar's reasoning or else uphold his position and throw Bohr's ideas onto the scrap heap.

In reality, things are unlikely to be quite that clear-cut. That is because Afshar is not only challenging the orthodox interpretation of quantum theory, he is also challenging the orthodox interpretation of interpretations.

There are at least half a dozen different interpretations of quantum theory. Each one is a way of relating the mathematics of quantum theory to what might be going on in the real world. Most physicists believe that, because they are derived from the same mathematics, the various interpretations all predict identical outcomes in all conceivable experiments: no experiment can rule just one of them out. Nonsense, says Afshar. "The key phrase here is 'all conceivable experiments'," he says. "How can you ever say you've considered all conceivable experiments? You can't. I mean, I've just conceived of one where some interpretations predict a demonstrably wrong outcome, and my experiment is repeatable and verifiable."

John Cramer of the University of Washington in Seattle agrees. He says he used to believe that experiments could never distinguish between quantum interpretations - right up until he heard about Afshar's experiment. But he now believes Afshar has found a loophole. By testing for the interference pattern indirectly while concentrating on the particle measurement, he has discovered a simple, repeatable experiment where the Copenhagen interpretation predicts a different outcome from other interpretations. "Afshar's experiment could actually have been done at any time since Thomas Young demonstrated the wave nature of light with a double-slit experiment," says Cramer. "But no one thought of it."

So what does it mean for quantum theory? Antony Valentini of the Perimeter Institute for Theoretical Physics in Waterloo, Canada, believes that Afshar's experiment shows complementarity to be a piece of historical baggage that should have been discarded many decades ago. "Bohr's views were at best simplistic," Valentini says. "Some people have tried to update the principle of complementarity, but it's still a hopelessly vague idea that's difficult to make sense of - as Afshar's experiments highlights." He believes it is time to admit that Bohr's views have no role to play in quantum theory.

Cramer believes Afshar's experiment also falsifies the "many worlds interpretation". This claims that particles can do many things at once, such as simultaneously pass through two slits, but they do each in a separate universe. So when an experimenter determines that a photon has gone through one slit, it means we are in a universe in which that, and that alone, has happened. The photon did also go through the other slit, and it went through both, but those events happened in other, entirely separate universes. "Afshar has identified a place where the Copenhagen and the many worlds interpretations are inconsistent with the formalism of quantum mechanics itself," Cramer says.

However, Afshar is aware that each person's opinion of his experiment depends on their own view of how quantum theory should be interpreted. Valentini, for example, believes that there must be something behind quantum theory, and that things do have properties with well-defined values (New Scientist, 29 June 2002, p 30), so it is unsurprising that he finds a refutation of Bohr's ideas so appealing. Cramer, too, has a vested interest in Afshar's experiment. He has developed his own interpretation of quantum theory, called the transactional interpretation. This uses waves that travel backwards in time to allow quantum particles to interact and, Cramer says, it stands up to Afshar's experimental test.

Afshar is about to embark on a photon-by-photon version of his experiment at Rowan University in New Jersey, where he is now a visiting research professor. Since the detectors can distinguish the origin of the photons, and since there will be only one photon in the set-up at any one time, Afshar can glean which-way information about each of the photons. "The experiment performed at Harvard is essentially the same as running the single-photon version for a very long time," he says.

He fully expects the experiment to produce the same result. That will be a relief for many, he says. "Many physicists have found Bohr's ideas either vague or intolerable, but until now nobody has been able to show in an experiment that complementarity fails."

Afshar admits that, in the end, he is unsure what his experiment means in detail for quantum theory. "We are back at the fork in the road encountered by Bohr and Einstein, and avoided entirely due to Bohr's ingenious complementarity," he says.

But we've still got a wave that's a particle, and a particle that's a wave. What are we to make of that? Well, Afshar says, there are two choices. The first is to shrug your shoulders and concede that human logic and language will never explain what is going on. The second option is to conclude that the particle phenomenon isn't really there, and to use the wave picture for the entire experiment. In this interpretation, the interference pattern and which-way information are not logically inconsistent - the waves do go through both slits, while the "image" each detector sees corresponds to light waves from only one of the pinholes.

Afshar believes the second option is the simpler and better choice, which leaves a big question: is there any such thing as a photon?

The photon detectors in Afshar's experiment "click" when they detect a photon. But if there is no photon, what are they seeing? It comes down to the interpretation of Einstein's photoelectric effect, the experiment that "proved" the existence of the photon - and won him the 1921 Nobel prize. Afshar says the American physicist Willis Lamb and others have explained these particle-like clicks as a result of the interaction of unquantised electromagnetic waves and quantised matter particles in the detector. So although Einstein was right to doubt Bohr's complementarity, he was "right for the wrong reasons", Afshar says. "In order to declare Einstein the winner of the Bohr-Einstein debate, we must take back his Nobel prize. We have no other choice but to declare the idea of Einstein's photon dead."

Afshar has long doubted the existence of the photon. Indeed, like other physicists, Afshar brings his own prejudices to the interpretation of his experiment. For 18 years he has been developing a fundamental theory of physics designed to unite the incompatible theories of quantum mechanics and general relativity, in which electromagnetic fields such as light simply cannot be quantised and there is no such thing as a photon. "It was to test this that I did my experiment," says Afshar.

If he is right about the photon, where will it end? He has already designed another experiment that he believes could resolve the light quantisation issue once and for all. "If in that experiment we find that there are no photons - quanta of light - then all of us will have to get back to the drawing board," he says. But that's not the end of it. Interference experiments using other quantum entities, such as electrons and atoms, have also been used to support complementarity. A further goal is to adapt his experiment to show whether these "particles" are also illusions. "If the same results are obtained in analogous experiments using particles other than photons then the debate would cover the whole of quantum mechanics," Afshar says.

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