CURIOUSER AND CURIOUSER, by Michael Brooks

New Scientist, 10 May 2003

WE HAVE always been aware that quantum stuff moves in mysterious ways. A quantum particle such as an electron can spin clockwise and anticlockwise at the same time, for example, or exist simultaneously in two places. We've also known that these strange "superpositions" are extremely fragile. Indeed, it is a tenet of quantum theory that as soon as anyone tries to observe a superposition, it collapses back to some kind of normality. Make a measurement of, say, an electron spinning both ways at once and the electron appears to have just one spin.

That is why Schrödinger's famous cat can only be both alive and dead at the same time in its box so long as no one looks inside. Lifting the lid forces the cat to either live or die. And so this mysterious quantum world has remained impossible to explore. Until now, that is.

Yakir Aharonov, an influential physicist at Tel Aviv University and the University of South Carolina, believes he has discovered a way to observe the quantum world without destroying superpositions. This is a stunning claim and flies in the face of 80 years of teaching about quantum theory. But Aharonov says a technique he has invented, called "weak measurement", shows that looking at something doesn't have to change it. "Weak measurement finds what is there without disturbing it," he says.

Although Aharonov has been working on weak measurement for 15 years, his confidence has recently grown enormously. Last year he published a paper showing that weak measurement can give us new insight into a previously inexplicable paradox in quantum mechanics (Physics Letters A, vol 301, p 130). The result of this work is "strange and surprising", Aharonov says, but shows quantum theory to be logical and self-consistent. Weak measurement, he believes, will be the tool that finally opens up the weirdness of quantum theory for inspection.

The paradox in question is a thought experiment described in 1992 by Lucien Hardy, then at the University of Oxford, which shows how quantum theory makes a nonsense of the interaction between matter and anti-matter. First Hardy considered a Mach-Zender interferometer, an instrument in which a quantum particle hits a half-silvered mirror. This sends it into a superposition of states, in that it travels down two separate arms at once.

The interferometer later reunites the two paths, although what happens then depends on what happened en route. The arms of the interferometer meet at another half-silvered mirror, which is arranged so that if the particle has had an undisturbed journey - that is, it doesn't encounter any other particles or fields - it is collected in a detector "C". But if something disturbs the particle while it is on its way through the interferometer, it may arrive at a second detector, "D".

Hardy imagined two such interferometers positioned so that one arm of the first overlaps with one arm of the second (see Diagram). Then he imagined sending a positron - the antiparticle of an electron - through one interferometer, and an electron through the other at the same time. If the two particles travel along the overlapping arms they should meet in an "annihilation region" and destroy one another.

Hardy showed that something much stranger happens: in rare cases, quantum theory predicts that both D detectors could click simultaneously. Somehow both particle and antiparticle could disturb, yet fail to annihilate, each other in the overlapping arms.

The situation arises because quantum theory deals with probabilities amassed from the multiple existences of particles. Since the particles can simultaneously be in and not in the overlapping arms, the probabilistic nature of quantum theory allows an improbable - yet possible - outcome that makes no sense. This is Hardy's paradox.

In the decade since Hardy described it, people have "resolved" the paradox by saying that the thought experiment doesn't correspond to any possible real experiment, and is therefore meaningless. The only way to find out what really happens to the particles in the experiment would be to measure their routes, rather than simply inferring them from the final result. But as soon as a particle detector is placed in any of the paths, standard quantum theory says the particles will be disturbed, guaranteeing that the D detectors will fire. So you can no longer infer the particles' positions: the paradox is lost.

"The general attitude is 'since the paradox disappears when measurements are performed, the whole paradox is a red herring and doesn't deserve much attention'," says Sandu Popescu of the University of Bristol and Hewlett-Packard Labs, Bristol. But Popescu and Aharonov think otherwise. Working with Tel Aviv Unversity's Benni Rezni, Alonso Botero of Texas A&M University, and Jeff Tollaksen of Boston University, they have devised a modified version of Hardy's thought experiment that could be performed in a lab. By their calculations, the paradox will still exist, but because the experiment can actually be done, it means the paradox cannot be dismissed as abstract reasoning: it must be an objective truth of quantum theory.

The "weak measurement" technique they propose exploits quantum uncertainty - the fact that in any quantum system there is always an intrinsic uncertainty about properties such as a particle's position and energy. Aharonov's quantum detector is so weakly linked to the experiment that any measurement moves the detector's "pointer" by less than the level of uncertainty. In return, the detector has an imperceptible impact on the experiment. Astonishingly, this means any superpositions are preserved.

There is a price to pay for these delicate readings, however: they are extraordinarily inaccurate. But while this might appear to make the whole process pointless, Aharonov has calculated that when repeated many times, the average of these measurements approximates to the true value of the thing being measured.

Imagine a set of scales designed to measure the weight of an electron. In a weak measurement, quantum uncertainty means that the position of the scales' pointer will always be uncertain by a small amount, and the size of that discrepancy will be larger than the weight of the electron. This makes it impossible to say for certain what an electron weighs. But if billions of electrons land one at a time on the scales, the average of all the measurements will reveal the weight.

Of course, if it is not clear that an electron is on the scales or not, taking an average of all the readings won't give a true indication of its weight. The average will be skewed to a lower value by the occasions when no electron was present. But Aharonov and Popescu get round this problem: they know which runs of the experiment make both D detectors click and so can choose which measurements to throw into their average, and which to ignore.

In their thought experiment, Aharonov and Popescu "post-select" the results: they focus on just the paradoxical incidents when both D detectors click. The weak measurements then build up a picture of what is going on, all without disturbing the system. The reward is a result that presents the paradox in a fully logical, self-consistent way.

The apparatus in their thought experiment includes an array of detectors that make one of two different types of weak measurement. One type counts the number of electrons or positrons that pass along each arm. This could be a gravitational field detector fixed strongly in place so the particle's presence transfers almost no momentum. The second weak measurement comes from "pair detectors" that can record an electron and a positron passing simultaneously past two separate points. These "pairs" might be measured by two boxes connected by a rigid spring - the attraction between a pair would slightly compress it. The exact methods are not as important as the fact that they could be physically performed in the lab. All these weak, inaccurate results are recorded only when both D detectors click, and the results are then averaged over many runs of the experiment.

With the mental apparatus assembled, the physicists "run" the experiment. The results are predictable - at least in quantum terms. First they calculate the number of electrons passing through the annihilation region every time both D detectors click. The average is 1. The number of positrons passing through the region is also 1. The same measurements made for the non-overlapping arms of the interferometer give 0. This is exactly what would be expected with both D detectors clicking: both particles must have been in the annihilation region for them to disturb each other. So why didn't they annihilate? Another calculation reveals a rather puzzling answer to this question. The pair detectors show that the number of electron-positron pairs in the annihilation region is 0.

Other pair detectors reveal even stranger results. One indicates the presence of an electron in the annihilation region at the same time as a positron travels down the non-overlapping arm. Another shows a positron in the annihilation region while an electron is in the non-overlapping arm.

So with weak measurements, the paradox remains: we have an electron and a positron disturbing each other in the annihilation zone, yet pair measurements tell us they were not there together, so could not have disturbed each other. But there's now an additional difficulty: the results imply that there are two pairs of particles in the apparatus at the same time. And we know that's not true. It seemed like a fundamental flaw - until, that is, Aharonov and Popescu looked at a final pair-measuring device in the non-overlapping arms of the interferometer. The reading there was -1. Somehow, there was a "negative presence".

Aharonov says that when he first saw the negative number come out of the pair measurement, he was rather taken aback. Nobody had seen anything like it before. "It looks impossible. But then I realised it was the only way to see it. It's beautiful."

What exactly a -1 result means is still up for grabs, but Aharonov and Popescu believe they have shown that there is a way to carry out experiments on the counter-intuitive predictions of quantum theory without destroying all the interesting results. A single quantum particle could have measurable effects on physical systems in two places at once, for instance. Indeed, Aharonov and Popescu say, when you get a look inside, quantum theory is even more bizarre than we thought. Quantum particles can assume far more complex identities than simply being in two places at once: pairs of particles are fundamentally different from single particles and they can assume a negative presence.

And the fact that weak measurements transform the paradox from a mere technicality into an unavoidable truth suggests that they could provide a springboard for new understanding in quantum mechanics. "It shows there are extraordinary things within ordinary quantum mechanics," Popescu says. The negative presence result might be just the tip of the iceberg: every paradox in quantum theory may simply be a manifestation of other strange behaviours of quantum objects that we have not yet detected - or even thought of. "Many of the well-known paradoxes of quantum mechanics have properties like this," Popescu says.

From thought to reality

Klaus Mølmer of Aarhus University in Denmark was initially sceptical about weak measurement, but his own examination of Aharonov and Popescu's work has convinced him it has to be taken seriously. He even thinks he knows how to demonstrate it in a real experiment. It could even be done now, since it exploits the same techniques that quantum computing researchers use (see "Paradox lost").

Hardy, now at Ontario's Perimeter Institute, is also impressed by Aharonov and Popescu's work, but questions its meaning. "In spite of the consistency with which the apparatus gives these negative readings, it is quite a jump to infer that there really are a negative number of particles," he says. Instead, Hardy suggests, it might just be a form of error. But, he concedes, there is definitely a case to answer because the apparatus consistently gives the same error - a negative number of particles whenever both D detectors click. "This error is consistent with what might otherwise be regarded as some kind of naive reasoning about otherwise paradoxical situations."

While Hardy remains noncommittal about weak measurements, Popescu insists that there's nothing unusual about them. They are not a magic trick, and not even a convenient "interpretation" of quantum mechanics. "They are a particular type of measurement, and their results are just ordinary experimental results," he says. "Unusual experimental results, to be sure, but not fiction."

Aharonov admits that his ideas about weak measurements remain "widely unaccepted", but he's not cowed by that. Everyone will talk in terms of weak measurements in the future, he says; some are already learning the language.

Raymond Chiao of the University of California at Berkeley and Aephraim Steinberg of the University of Toronto, for example, are looking at weak measurement as a way to explain photon tunnelling. It is widely accepted that quantum objects such as atoms and photons can "tunnel" through barriers that they don't strictly have enough energy to get over. Experiments show that photons really can do this - and at speeds greater than the speed of light. Chiao and Steinberg, who performed the first experiments to demonstrate photon tunnelling, are exploring the idea that, since the photon's chances of accomplishing this feat are tiny for a wide barrier, their experiment might have been a post-selected weak measurement, allowing them to observe a strange quantum event that defies ordinary logic. It may involve negative energies or even negative time. They are exploring these possibilities in further experiments that use weak measurements.

Howard Wiseman of Griffith University in Queensland, Australia, also believes weak measurements can help shed light on strange quantum phenomena. In a forthcoming paper in Physics Letters A, Wiseman shows how weak measurement and negative presence can interpret double-slit interferometer experiments. Fire an electron at a pair of parallel slits and, if left undisturbed, the electron produces a pattern on a screen behind the slits that is created by interference between two electron states in superposition.

Some have suggested it might be possible to determine which slit the electron went through to find out what is really going on with the electron's simultaneous wave and particle existence. But this has generally been deemed impossible because any attempt to look at the electron gives it extra momentum, which affects the outcome and washes away the interference pattern. But Wiseman has shown that weak measurement reveals that such momenta can take on a negative value, giving a net momentum of 0 to the electron and letting researchers determine which slit the electron went through. It is, he says, possible to do this with existing technology.

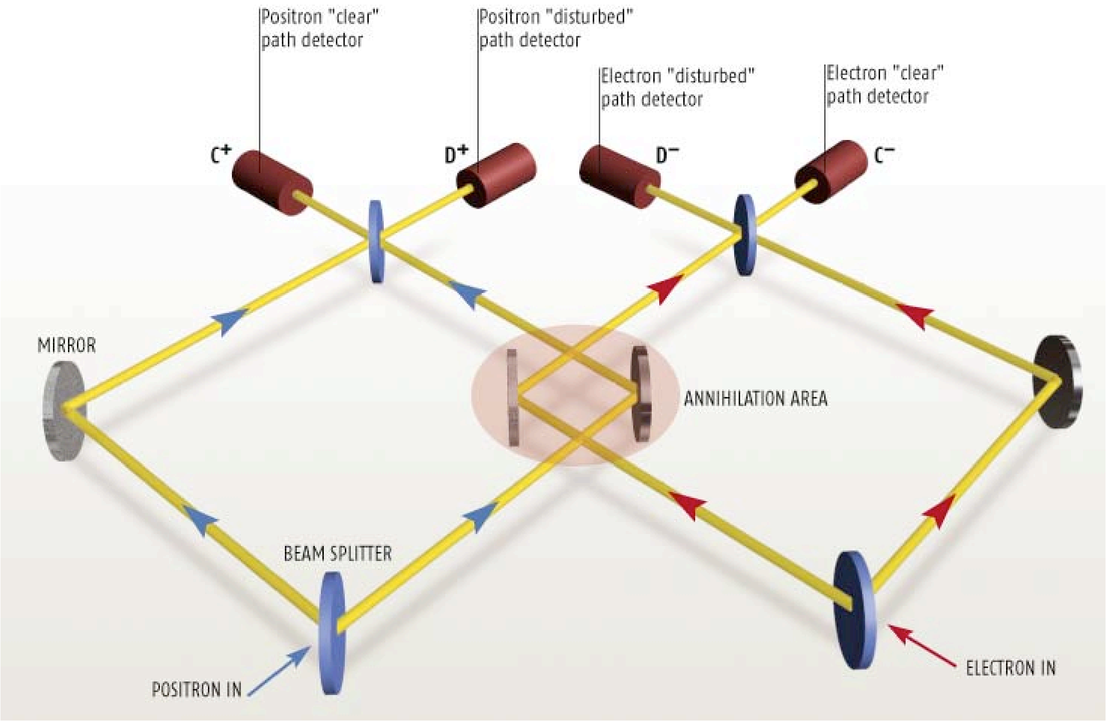
Mølmer's experience with translating weak measurements into a real lab experiment makes him think that most of what has been done to date with quantum systems employs weak measurement - physicists just haven't realised it. He now believes weak measurements might even have practical repercussions. They could, for example, expose flaws in quantum cryptography, in which disturbance caused by measurement is supposed to prevent eavesdroppers decoding messages. "A weak measurement used by an eavesdropper could be an interesting strategy," Mølmer says.

Whatever the implications - and Popescu and Aharonov are sure they've only begun to scratch the surface - a new door has opened. Weak measurement should give us a view inside the processes of quantum mechanics that we once thought impossible. It has already uncovered a negative presence that we never knew existed, and there could be plenty more surprises waiting to be found.

Eventually, Aharonov believes, weak measurement may dispel all our present notions of the weirdness of the quantum world. Aharonov claims that when the Nobel laureate Richard Feynman famously pronounced that we can never truly comprehend quantum mechanics, he was "too hasty". "I think people will remove the mystery that Feynman said could never be removed," he says. "You should never say never."

HARDY'S PARADOX

The positron and electron go down both arms of each of their interferometers. If they meet in the overlapping arms, they should annihilate each other. But, bizarrely, they are still registered as arriving at the D detectors



Paradox lost

YAKIR AHARONOV has shown that in quantum systems, two contradictary things really can happen at once. His exploration of Hardy's paradox (see Graphic below) using "weak measurement" is more than an abstract thought experiment: with a twist, it can be done in the lab.

Klaus Mølmer of Aarhus University in Denmark suggests probing the locations of a pair of ions instead of the electron and positron. First, cool the ions down to their lowest energy state and hit them with two carefully engineered laser pulses. This should send the ions into a superposition that is analogous to the state of the electron and positron passing through Hardy's experiment on their way to hitting the D detectors. In Mølmer's version, the ions move to positions they should never occupy.

Mølmer sets the ions up so that they will always fluoresce, except when they are in this paradoxical superposition. As soon as the fluorescence vanishes, he carries out a weak measurement on the ions' position using another laser - equivalent to measuring the positions of the electrons and positrons in Hardy's experiment. The laser light forces the ions apart by less than the intrinsic quantum uncertainty in their position. Repeated many times, this tiny push is enough to expose the strange shift in the ions' position (Physics Letters A, vol 292, p 151).

The centre of mass of the pair should lie somewhere between them. But the weak measurements show that, in the paradoxical quantum state, the ions' centre of mass lies outside this region. If the ions were at coordinates 0 and 1, the centre of mass is at -1. "It's like you're weighing yourself and it shows -60 kg," Mølmer says.

It's not that weird, though, he insists. Quantum theory allows the particles to be considered also as waves, and the experiment simply reflects the destructive interference of those waves. Nevertheless, he believes it is a brilliant resolution. In a physical realisation of the Hardy paradox, you would expect all hell to break loose and everything to become nonsensical. But it doesn't.