HELLO KITTY!

Curiosity doesn't have to kill the quantum cat – just be careful how you open the box, says **Amanda Gefter**

IT MAY not have the swirling cameras and intense music of a TV emergency room, but John Martinis's laboratory is about to provide just as much drama. Martinis, a physicist at the University of California, Santa Barbara, is preparing a landmark experiment. The objective? To bring an animal back from the brink of death.

It is not just any animal. This is Schrödinger's cat, the most famous feline in physics. In a macabre thought experiment first mooted by Erwin Schrödinger in 1935, the cat's life is endangered by a quirk of quantum theory. Contained within a closed box, the cat either lives or dies depending on the quantum state of an atom, which is rigged up to a vial of poison gas. In one quantum state the vial breaks, killing the cat. In the other it remains sealed. The twist is that the atom's quantum state only takes a definite value when someone looks at it. Before the box is opened, the cat is in a "superposition" of being both alive and dead, and opening the box and looking in either kills the cat or saves it.

At least, that's the standard view. It now seems that the equations of quantum theory offer a startling alternative, according to Andrew Jordan of the University of Rochester in New York. Even when perilously close to death, the cat can be saved.

There is more than an imaginary cat's life at stake here. Martinis's experiment offers an insight into the fundamental nature of quantum measurement, and could bring enormous pay-offs: the cat-in-a-box experiment might help the development of computers that use quantum rules to dramatically speed up their calculations, for example. The predicament of Schrödinger's cat may even have implications for national security. What's more, discovering exactly how this quantum drama unfolds may prove vital to our understanding of how the universe really works. Even if our curiosity does ultimately kill the quantum cat, at least we'll know it didn't die in vain.

At the centre of the Schrödinger's cat dilemma is the phenomenon of superposition. In everyday life, we imagine a particle or object can exist only in one particular state or position: either in position A or position B, say. In the quantum realm, however, things can exist at both A and B simultaneously.

The only trouble is, we can never see this phenomenon. Experiments have indirectly proved that superpositions really do occur, yet we never seem to happen upon a cat that is both dead and alive. The act of observation or measurement somehow forces the superposition to revert to the "classical" state, in which the quantum particle takes one position or the other, but not both. Two of the biggest questions in quantum physics are exactly how measurement achieves this and whether there is a way to undo its effects. The answers, it seems, are related, and are both to do with the fact that, in quantum mechanics, nothing happens in a magic flash.

Physicists have long assumed that, like the death of a cat, measurements on quantum systems are irreversible. But it turns out that is only because they have made a simplifying assumption – one that they are now rejecting. "Quantum measurement is usually taught in textbooks as an instantaneous process," Jordan says. "What we've learned in the last few years is that real measurements don't work that way. In nature, all processes take a finite time."

The breakthrough proof came last year, when Nadav Katz of the University of California, Santa Barbara, working with some UCSB colleagues and Alexander Korotkov of the University of California, Riverside, used an array of impressive technologies to take a quick peek inside the box and glimpse the cat's state (*Science*, vol 312, p 1498). They discovered that, rather than collapsing in an instant, the superposition marches toward collapse one step at a time.

It is this gradual collapse that might ▶

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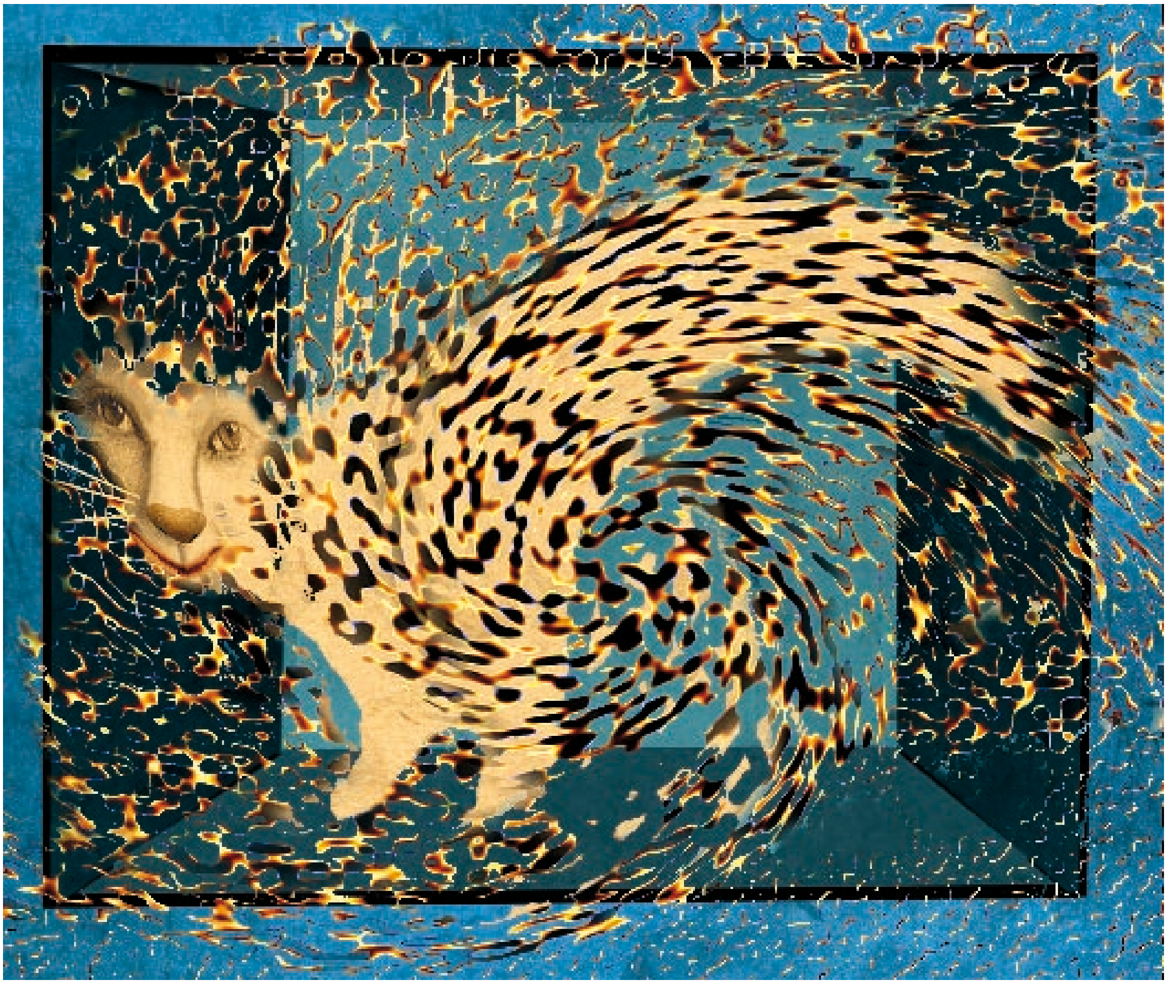

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"Even if our curiosity kills the quantum cat, at least we will know it did not die in vain"

Cracking the uncrackable code

If we really can perform "weak" quantum measurements whose disturbing effects can be undone, it might have serious implications for the security of nations. Quantum cryptography has been hailed as the future of cryptography because its codes are impossible to crack; the US government and some major financial institutions are already looking at ways to implement the technology. Commercial quantum cryptography systems are available off the shelf for those with concerns about corporate security. The unhackable nature of the technology, though, relies upon the fact that a measurement of a quantum system changes the system indelibly. If measurements can be undone, quantum cryptography could be in big trouble.

In quantum cryptography, two people (usually referred to as Alice and Bob) must agree upon a secret key that will be used to decipher a message. They do this by exchanging entangled photon pairs – particles of light in a quantum state that is extremely sensitive to disturbance by a standard quantum measurement. An eavesdropper, Eve, might attempt to intercept the message, but this will disturb the entanglement and Alice and Bob will become aware of her presence.

That all changes if Eve is able to make a weak measurement and then undo it without leaving a trace. "An Eve who makes only a weak measurement will probably be hard to detect by Bob and Alice," says Markus Buttiker, a theoretical physicist at the University of Geneva in Switzerland.

There is a catch for Eve, though: with a weak measurement she will only gain a small amount of information and so can't be certain what a message says. However, she might get enough clues to decide whether to keep that information – and risk getting caught – or use another weak measurement procedure to undo her original measurement and remain undetected.

Quantum cryptography researchers are now trying to work out how to defeat this threat. According to Andrew Jordan of the University of Rochester in New York, it is not yet clear just how big a problem weak measurement might pose. "We're working on that at the moment," he says.

save Schrödinger's cat. Korotkov, this time working with Jordan, has figured out how one could monitor the cat's state and then undo any damage that monitoring has done (*Physical Review Letters,* vol 97, p 166805). Martinis will soon be putting the idea to the test. "We think we can do the experiment readily in the next few months," he says.

Performing the experiment will involve manipulating the quantum state of a loop of superconducting wire known as a phase qubit. First, the researchers fire a finely tuned microwave pulse at the loop. This puts the qubit into a "cat state", akin to the dead-and-alive state of Schrödinger's cat, in which it sits in an equal superposition of both of the qubit's possible energy states.

Until, that is, the measurement begins. As soon as the researchers begin to perform a measurement, the superposition slides towards one state or the other. The question is, which one? Is the cat going to live or die?

To answer that question without killing the cat, the researchers will look to see whether or not the qubit performs a quantum trick called tunnelling. Faced with an insurmountable barrier, there is nothing that a classical particle can do. A quantum particle, on the other hand, can take advantage of the uncertainty principle, which says you can never precisely define all the particle's properties. That means that in certain circumstances there is a small probability you will find it on the far side of this apparently insurmountable barrier. The more energy a particle has, the more likely it is to tunnel when given the opportunity; if the researchers see the qubit has tunnelled they will know it has collapsed to the higher energy state.

In itself, that is disastrous, of course: if the researchers see the burst of magnetic energy that indicates the particle has tunnelled to a higher energy state, it means the measurement was completed and the cat is dead or alive. The trick is to catch the qubit before it actually gets there.

To sneak a peek at the qubit's state midway through its collapse, the researchers induce a steadily increasing voltage across the wire ring. This is like teasing the qubit into "thinking" about tunnelling by making it easier to cross the barrier. Then, at a certain threshold, they drop the voltage back down again. It is equivalent to opening the box and then quickly closing the lid again.

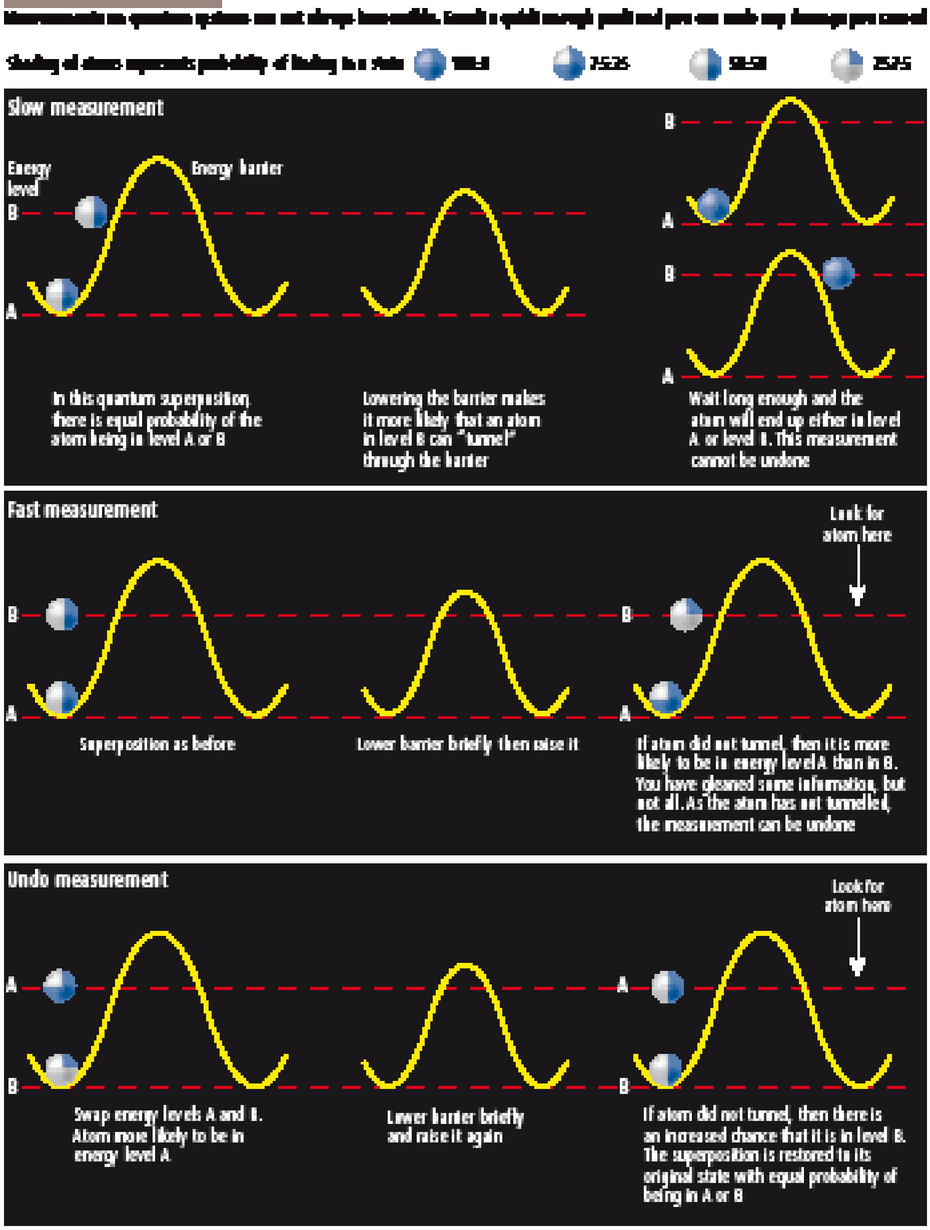
Because quantum processes take a finite time, lowering the energy barrier then raising it again acts as a "weak" form of measurement (*New Scientist*, 10 May 2003, p 28). If we don't see the qubit tunnel, we learn that there is some finite probability that it is in the lower energy state. In other words, we have gained information about a quantum system without destroying its delicate superposition. The more time we risk leaving the barrier down without the qubit tunnelling, the more certain we are of its low energy state.

Now it is time to undo any harm we have inflicted in the process. To do this, the physicists fire another kind of microwave pulse, known as a pi-pulse, at the qubit. This inverts the quantum states of the qubit: the higher energy level is now the lower level and vice versa. The voltage is then ramped up and dropped again. If the qubit doesn't tunnel this time, it becomes more likely that it is in what is now the lower energy level. Where the first weak measurement pushed the superposition one way, the second pushes it by the same amount the other way, which means we end up right where we started. It is as if the qubit, or the cat, had never been disturbed at all.

Jordan and Korotkov say that their prescription will work to undo any weak quantum measurement, regardless of the experimental apparatus. Step one: take a weak measurement that shifts a superposition state toward one definite state or the other. Step two: swap the states around and take an identical second weak measurement. Because the states have been swapped around in the interim, the second measurement only serves to cancel out the effects of the first. You got to see the cat, and without doing it any harm.

Not that it is a guaranteed success: if the qubit does tunnel during either the first or the second weak measurement, the researchers have to begin again. The other drawback is that you have to repeat the process many ▶

BACK FROM THE BRINK



times to get the information you want: each repeat only gets you a little more certainty about the state of the cat. "From a single weak measurement we cannot say with certainty that the cat is dead or alive," says Markus Buttiker, a theoretical physicist at the University of Geneva in Switzerland. The more you repeat this process, however, the more information you gain about the most likely configuration of the superposition. In other words, you can satisfy your curiosity without (for the most part) killing the cat.

If confirmed by experiment, the researchers believe they will have ruled out one of the most popular explanations for how quantum things turn classical. "Decoherence theory" suggests that the superposition never really collapses – it only appears to collapse. What actually happens, according to this idea, is that all the information about the system disperses into the environment: when a quantum system interacts with a classical measuring device, it becomes irreversibly entangled with all the particles that make up the measuring device and its surroundings. All the information about the original state of the system in superposition is then spread so thinly throughout the massively bigger environment that it is, essentially, lost. The odds of identifying the original state become far worse than the odds of randomly shuffling a deck of cards back into perfect order.

According to Jordan, the weak measurement experiment should demonstrate that decoherence theory cannot be correct. Weak measurements make superpositions evolve towards one of the well-defined original states of the isolated system, not into an ever-bigger mess of entanglements with everything around it. "In our analysis of continuous weak measurements, we see that the system gets drawn to one state or another," Jordan says. "That rules out decoherence theory." The reversibility of weak measurements also stands against decoherence: if information does spread into the environment, it shouldn't be possible to get it back.

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"We wanted to find out, is quantum measurement written in pen or pencil?"

It would be useful to know whether decoherence is real or not, as it is seen as one of the major obstacles to building a useful quantum computer (*New Scientist*, 26 June 2005, p 18). Also the reversibility of weak measurements may have implications for cryptography based on quantum rules (see "Cracking the code", page 34). But, more fundamentally, what will this all mean for Schrödinger's hapless cat?

Well, like doctors and surgeons, we still can't work miracles. If the quantum state has tunnelled – if we find the cat completely dead, in other words – then we will know the superposition has collapsed and we can't bring the cat back to life.

However, weak measurements seem to indicate that if we peek into the box just long enough to partially determine the cat's fate – say, if we find it very close to dying – we can undo our weak measurement and restore the cat to the relative safety of the original unknown state. "We wanted to find out, is quantum measurement written in pen or pencil?" Jordan says. "Now we know it is written in pencil."

This could be a very profound discovery. Since the birth of quantum theory we have become used to thinking of quantum measurements as creating reality: until things are measured, they don't have an absolute, independent existence. But if some forms of measurement, such as weak measurement, are reversible, then the fundamentals of quantum mechanics go even deeper than we realised. If you create reality with weak quantum measurements, does undoing them erase the reality you created?

It seems that Martinis's experiment might have a shocking twist just before the end. To save the quantum cat, we might have to be willing to throw away the idea that we live in a real, permanent cosmos that can't unravel before our eyes. It's a true cliffhanger: will Martinis save Schrödinger's cat or the durable fabric of your universe? Stay tuned for the next episode... ●