FASTER THAN THE SPEED OF LIGHT

Einstein came up with the ultimate speed limit—nothing moves faster than light. But was he wrong?

Julian Brown **investigates**

QUANTUM MECHANICS has been with us for over sixty years and has been thoroughly put through its paces both experimentally and theoretically. Yet physicists continue to be haunted by its strange implications—virtual particles, antimatter, negative energy, Schrödinger's cat. Now it appears there is something else to add to the list: light that travels faster than light.

Such an idea sounds paradoxical if not downright nonsensical. Einstein's special theory of relativity says that anything that travelled faster than light would also have to travel backwards in time. So if light can travel faster than light, shouldn't it be possible to send signals backwards in time, causing all sorts of mayhem, with effects taking place before anything ought to have caused them?

Well, not exactly. It turns out that the quantum world is so strange that it is, after all, possible to break Einstein's speed limit. Until very recently the consensus was that this would not violate Einstein's theories. But some tantalising new results reported at a meeting last month are not so easy to explain away. If they prove true, relativity theory could be in trouble.

'If light can travel faster than light, shouldn't it be possible to send signals backwards in time, causing all sorts of mayhem?'

Most of the attempts to send light faster than light involve a phenomenon called quantum tunnelling. In particular, there is the work of Raymond Chiao and colleagues at the University of California at Berkeley. Chiao has been pioneering a range of experiments that probe the twilight zone of quantum mechanics—an alien world where ghostly particles can spontaneously appear and disappear, where objects can pass through solid walls and where everything seems to dance to a different tune depending on whether or not you happen to be watching.

Quantum tunnelling is, in itself, a remarkable phenomenon because it involves particles travelling through barriers that ought to be impenetrable. If you throw a ball at a wall you expect the ball to bounce back, not to pass straight through it. Yet subatomic particles pull off the quantum equivalent of this feat with consummate ease.

According to quantum theory there is a distinct, albeit small, probability that a particle can tunnel its way through a barrier even if it does not have enough energy to jump over. The probability declines exponentially with barrier thickness so for all practical purposes quantum tunnelling is usually observed only when barriers are no thicker than a few atomic layers. Nevertheless, quantum tunnelling has many practical applications—playing a major role in nuclear fusion, in electronic devices such as the tunnel diode, and in tunnelling electron microscopes, the highest-resolution microscopes in existence.

What Chiao and others have done is measure how long it takes particles of light—photons—to tunnel through a barrier. Their rationale was a pile of theoretical calculations, some performed as long ago as the 1930s, which suggested a strange idea. In 1932, L. MacColl of Bell Labs wrote: "When a particle tunnels through a barrier, it does so without any appreciable delay."

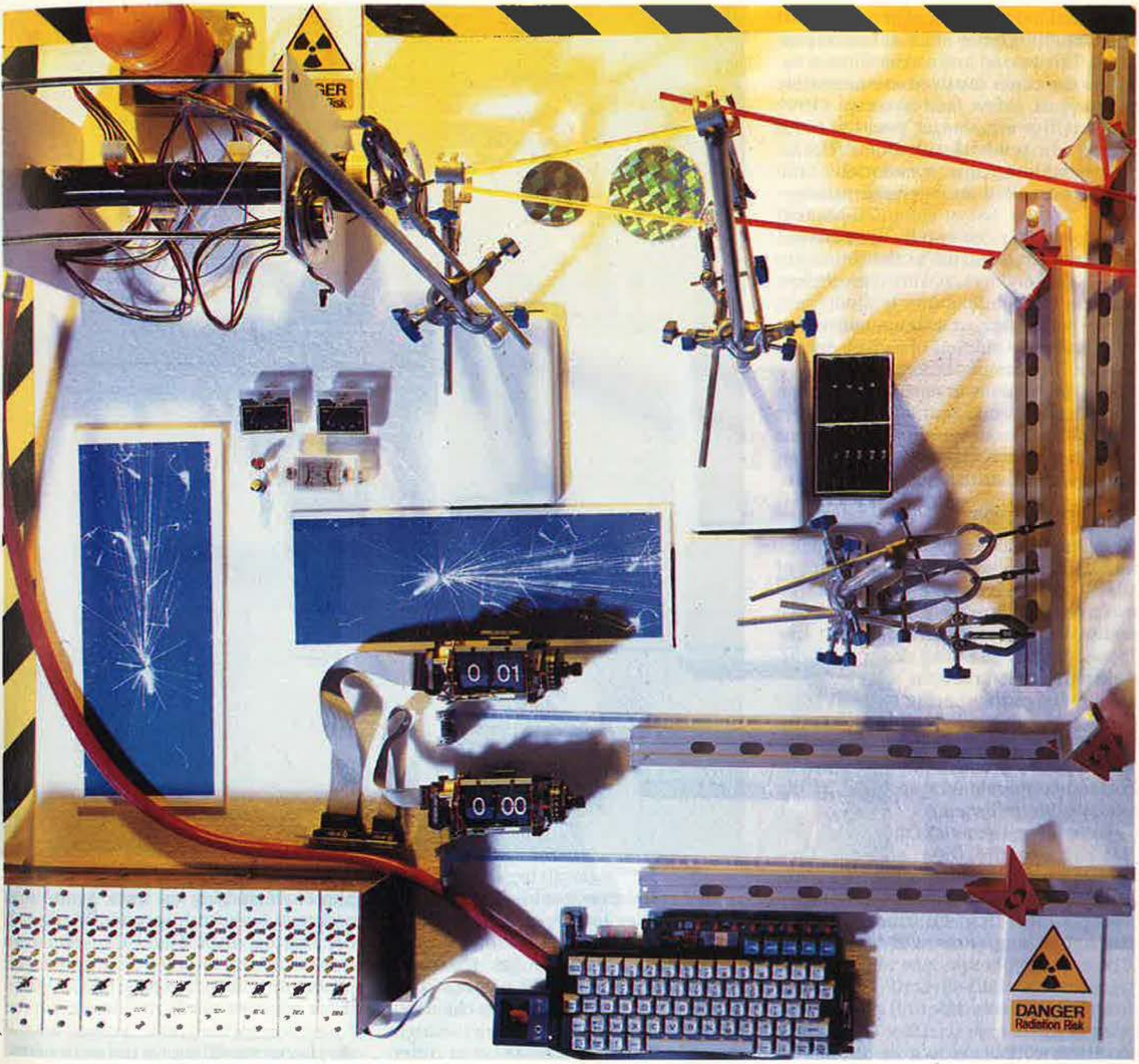
The implications of this, though, did not become apparent until 1955 when Eugene Wigner and his student L. Eisenbud at Princeton analysed the problem and concluded that under some circumstances tunnelling particles could actually travel faster than light.

This bizarre conclusion has been reexamined and argued about by theoreticians over the decades. The problem is that many ways of looking at it seem to leave common sense behind. For example, one approach is to say that a tunnelling particle has to borrow energy to overcome the barrier it is penetrating. In effect, the particle runs an energy deficit while it is tunnelling—it has a negative kinetic energy. Classically, kinetic energy is related to the square of the speed so, if the energy is negative, the speed will be the square root of a negative number, which sounds like nonsense.

Peaks and packets

Of course, tiny quantum particles do not behave like ordinary balls so the classical calculation is probably inappropriate. Another way of looking at the time it takes the particles to tunnel is to take advantage of the fact that quantum particles can also be viewed as spread-out waves, where the size of the wave at any particular place is related to the likelihood of finding the particle there. There are many different ways of calculating the speed of such a "wave packet": the group velocity which corresponds to the way the peak of the packet moves, the phase velocity which corresponds to the movement of an individual oscillation within the packet, the energy velocity corresponding to the speed at which energy is transported, and so on. All of them can be very different.

Wigner and Eisenbud's analysis calculated the tunnelling time in terms of the peak of the wave packet and concluded that it could be anomalously short. These calculations also suggested the tunnelling time would become "saturated". In other words, it would reach a maximum beyond which it would stay the same no matter how thick the barrier. This would imply that the effective



Andy White

tunnelling velocity can, in principle, increase without limit as the thickness of the barrier increases. Although the probability of travelling though the barrier also falls rapidly with increasing thickness, the few particles that were able to pass through would do so without regard to Einstein's ultimate speed limit of the speed of light.

It is only in recent years that the technology existed to test these ideas experimentally. The first hints came ten years ago from Steven Chu and Stephen Wong at AT&T Bell Labs in New Jersey. They measured superluminal velocities for light pulses travelling though an absorbing material. Despite the surprising nature of their findings, it seems that few people took any notice. One reason, perhaps, was that absorption, though interesting, was not the same thing as quantum tunnelling. When particles hit a quantum barrier, most of them are reflected rather than absorbed. So the physics is quite different.

The forbidden zone

In 1991, Anedio Ranfagni and his colleagues at the National Institute for Research into Electromagnetic Waves in Florence came up with an idea for investigating a phenomenon that was more closely related to quantum tunnelling. They looked at the way microwaves can stray into "forbidden" zones inside waveguides. Waveguides are square metal tubes used for conveying microwaves. If the cross section of the waveguide is too small to fit a complete number of half-wavelengths, the microwaves are almost entirely reflected. But like tunnelling particles, some microwaves can still penetrate the forbidden region.

The Italian group measured the speed of propagation through the forbidden zone but reported values less than the speed of light. But when in 1992 Günter Nimtz and colleagues at the University of Cologne reported superluminal speeds for microwaves traversing the forbidden region, the Italian team realised that they had not used thick enough barriers. When they redid the experiments, they also found evidence for microwaves travelling faster than light.

The following year, the matter was clinched when Chiao and his colleagues Aephraim Steinberg and Paul Kwiat at the University of California at Berkeley provided the most direct evidence yet for superluminal transport. They measured the tunnelling times of photons of visible light. This was no mean achievement because the times involved are incredibly short—just a few femtoseconds (10^{-15} seconds)—much shorter than the times that can be resolved with atomic clocks.

To achieve this resolution, the researchers used an ingenious arrangement known as a Hong-Ou-Mandel interferometer invented by Leonard Mandel and colleagues at the University of Rochester in New York (see below left). In this a laser beam is shone onto a crystal known as a down-converter, which absorbs photons of a given energy and emits pairs of photons of lower energy. The photons in each pair are then raced against each another along different tracks. On one track, the photons pass though a barrier, an optical filter, and on the other they pass through air.

Speed bumps

The filter, which is around a micrometre thick, consists of alternating layers of glass, each layer made up of material with either a low or a high refractive index. The layers individually act like "speed bumps", slowing down the light. Taken together, when the wavelength of light matches the spacing of the bumps, they block out the light almost entirely. The researchers deliberately tune their laser light to produce photons with the forbidden wavelength so most of the photons are reflected.

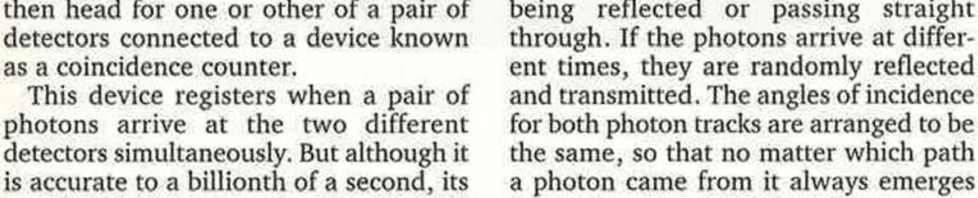
But a few photons still manage to tunnel through the filter and are then directed towards a half-silvered mirror, which acts as a beam splitter. Some of the photons that hit this will pass through it and some will bounce off. The partner photons are also directed towards the half-silvered mirror but from the opposite side. All the photons then head for one or other of a pair of detectors connected to a device known as a coincidence counter.

This device registers when a pair of photons arrive at the two different detectors simultaneously. But although it is accurate to a billionth of a second, its reactions are too slow for it to measure the time the light take to tunnel through the barrier. In fact, a billionth of a second is the time it takes for the entire race, which is a metre or so in length.

The secret of the million-fold improvement in resolution lies in the half-silvered mirror. When the photons hit its surface they have a fifty-fifty chance of being reflected or passing straight through. If the photons arrive at different times, they are randomly reflected and transmitted. The angles of incidence for both photon tracks are arranged to be the same, so that no matter which path a photon came from it always emerges on one heading towards a detector.

If we call these emerging tracks 1 and 2, there are four possible outcomes: both photons emerging on track 1, the first on track 1 and the second on track 2, the first on track 2 and the second on track 1 or both on track 2, all with equal probability (see below right). When these photons reach the detectors, the counter registers their arrival only if they were travelling on different paths. So the counter "sees" 50 per cent of the emerging photon pairs.

But something quite different occurs if the two photons arrive simultaneously (within around 20 femtoseconds of one another) at the half-silvered mirror. Because the photons were generated simultaneously with the same energy



Left: The apparatus for Chiao's photon race. Right: If each photon arrives separately at the half-silvered mirror it is then equally likely to follow path 1 or 2 (A and B). But if both photons arrive simultaneously (C and D) they must then travel together down the same path, either 1 or 2, registering a "null" on the coincidence counter

and phase they are said to be "correlated". When the photon wavepackets meet, quantum mechanics steps in, causing them to "interfere" with one another. The upshot is that the two correlated photons always travel away from the mirror together along either path 1 or 2, and so hit only one detector on the coincidence counter. In this case, nothing is registered on the counter.

Chiao and his team first used this apparatus without the filter, so that both photons were racing through air. The idea was to adjust the track lengths of each photon until the signal suddenly disappeared from the coincidence counter. At that point, the two racing photons must have arrived at the half-silvered mirror at the same time, within 20 femtoseconds or so. By searching for the centre of the null, the researchers managed to narrow the time resolution to within a quarter of a femtosecond. This way, they made sure that the race would be fair.

They then inserted the optical filter, and measured how much one path length needed to be increased or decreased to restore the null. The size of the adjustment indicates the size of the time difference. Using this technique, the researchers found that the photons that tunnelled their way through the optical filter arrived 1·5 femtoseconds sooner than the ones that travelled through air. The tunnelling photons seemed to have travelled at 1·7 times the speed of light.

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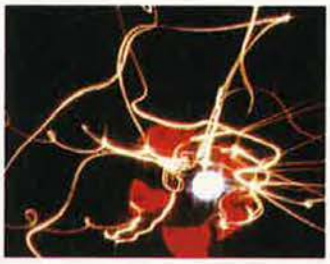


Even so, Chiao steadfastly maintains that these superluminal photons do not violate Einstein's special theory of relativity. The important thing, he says, is whether it is possible to send a signal by this route. "These experiments do not mean that you can send a signal faster than light. Only a few photons get through the barrier. Because tunnelling is probabilistic, we've no way of knowing which ones they will be. So it would not be possible to send any useful information."

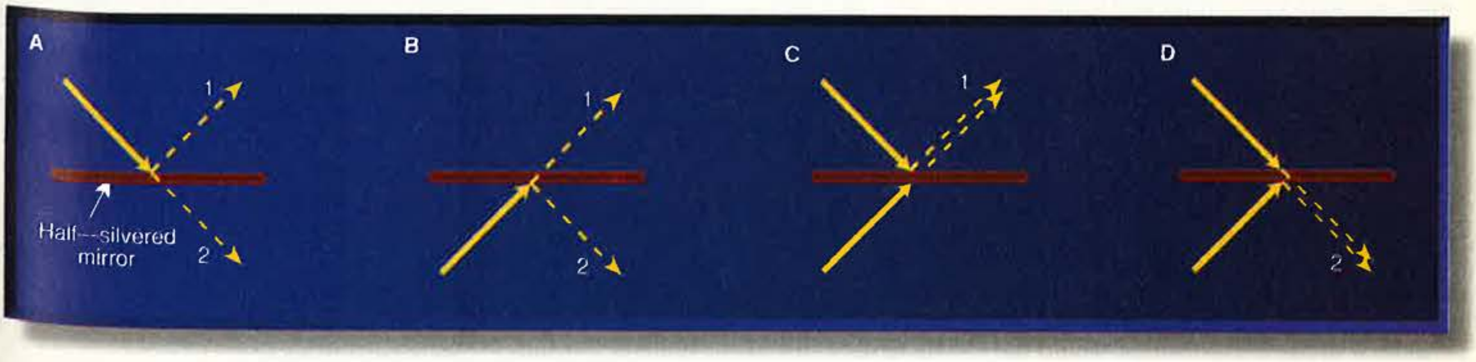
To understand what is happening, we need to go back to the wave packet description of photons. The wave packet represents a probability distribution where the peak corresponds to the most likely position of detecting the particle. However, because such wave packets are spread out, there is a chance of detecting the particles in other places which means some photons will appear to arrive early and some will arrive late.

Now when a photon approaches a barrier such as the optical filter, what happens is that the first part of the wave passes through the barrier relatively easily compared with the rest of the wave packet. The result is that the photon wave packet gets reshaped, so that its peak is shifted closer to the front. When raced against another photon travelling though air (or a vacuum) the leading edge of both wave packets arrive at the same time. However, because of reshaping the tunnelling photons appear on average to arrive earlier than their non- tunnelling partners. This gives the impression that they have travelled faster than light.

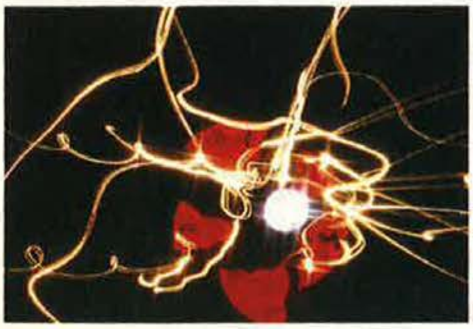
The reason the first part of the wave packet passes through the barrier more easily than the rest of it is that it takes a little time for the optical filter to block transmission. The filter works by building up coherent multiple reflections between its different layers. These reflections produce interference patterns which block transmission. But when the wave packet first arrives it takes a while to establish these patterns. In other words, preferential treatment of the leading edge of the wavepacket creates a sort of "optical illusion", shifting the transmitted peak earlier in time (see over page).

This is another reason why it wouldn't be possible to send a signal faster than light. "To send a signal a you need to open a shutter or do something to make a sharp break in the wave packet, says Chiao. "No matter how much reshaping a barrier produces, the wave peak can never overtake the front of the wavepacket." So it is this that really determines how quickly you can send a signal. No amount of wave reshaping will make the front of the wave packet arrive earlier than expected.

Although the results from Chiao's team helped to settle the question of super-

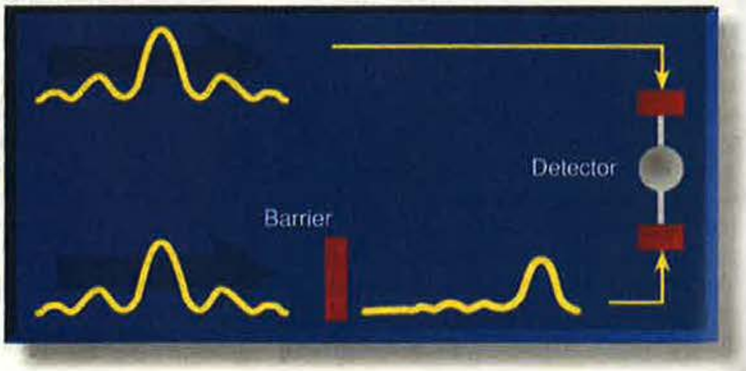


luminal velocities they had little to say about what happens as you make the barrier thicker. According to Nimtz, this issue had already been settled by his microwave work in 1992, but important confirmation came in October last year from experiments conducted by Ferenc Krauss and colleagues at the Technical University in Vienna. They have been able to use thicker barriers than Chiao's team because their light source is much more intense. They did not conduct their experiment with individual photons, but instead used very short bursts of laser light containing many photons. The Vienna team work with very short pulse lasers and at around 8 femtoseconds they have the fastest in the world.



As the pulses were so short, they could achieve a very high time resolution. Their results strongly suggest that as they progressively increased the thickness of the barrier the tunnelling time saturated towards a maximum value. One way to explain this is to go back to the picture of the particles having to "borrow" energy to tunnel through the barrier.

According to Heisenberg's uncertainty principle, it's fine to borrow energy from the fuzziness of the quantum world, but you can do so for only a finite time—the greater the energy that you want to borrow, the less time you can have it for. The amount of energy the photons need to borrow, and hence the amount of time they can have it for, depends on the height of the barrier, but not the thickness. So any photons tunnelling through a barrier have to do it in the same time, no matter how thick the barrier.



Photon race: the photons that travel through the barrier have their wave packets reshaped, moving the peak, the likeliest place to find them, from the centre to the front end of the wave packet. This means that photons travelling through the barrier seem to arrive at the detector sooner than those travelling through air

A strange consequence of the Vienna results is that you could imagine a thought experiment in which you made the barrier arbitrarily large—say the size of our Galaxy. According to the theory, light that tunnelled through the barrier would jump across the Galaxy virtually instantly. Light that travelled the conventional, however, would take millions of years. As Chiao says: "It is as if the space in the barrier has disappeared".

Such a thought experiment would obviously be impossible to put into practice because even thin barriers allow only very few photons through. Yet it does put the phenomenon into stark relief. In fact, the rapid drop in tunnelling probability with barrier thickness would seem to place a severe limit on how far photons could actually travel at superluminal velocities. If the effect is of such short range, one might be tempted to write it off as little more than a curiosity.

'According to Nimtz, Mozart's 40th Symphony hopped across 12 centimetres of space at 4·7 times the speed of light. What's more, he actually had a recording to prove it'

Yet last month an extraordinary development in this tale unfolded at a special colloquium organised in Snowbird, Utah. Attending the meeting were some of the leading researchers in this field of faster-than-light quantum phenomena. To an astonished audience, Nimtz announced that his team at Cologne had not only measured superluminal speeds for their microwaves, but had actually sent a signal faster than light. The signal in question was Mozart's 40th Symphony. What they did was frequency modulate their microwave source with the music and then measure how quickly the music arrived after traversing the forbidden zone in a waveguide.

According to Nimtz, Mozart's 40th hopped across 12 centimetres of space at 4·7 times the speed of light. What's more, Nimtz actually had a recording to prove it. To his now bemused audience, he played a tape in which among the background hiss strains of Mozart could be heard. This was the "signal" that had travelled faster than light.

But that very word "signal" triggered heated discussion, with some participants claiming that the symphony could not be regarded as a signal. Among them was Chiao. "It's not a signal in Einstein's sense because of the timescales involved. I agree that when the music crosses the barrier it is shifted forward in time, compared with music that travels by a conventional path, but only by a very small amount. It is so small that you can predict what will happen to the music simply by looking at how the original audio waveform is changing. There is no threat to causality."

Nimtz is not so sure. "I don't have an opinion on whether this violates causality. However, I do not accept that Mozart's symphony isn't a signal. In principle, I could extend the path over much longer distances and then it would not be possible to predict the course of the music. Then you really would have a signal travelling faster than light."

Nimtz clearly believes he is onto something important. By contrast, Chiao and his colleagues, while happy to peer beyond the normal confines of scientific orthodoxy, are determined not to be lured over the edge. Their collective view remains firmly grounded in the sanctity of causality and Einstein's special theory of relativity. "Einstein causality," Chiao says, "rules out the propagation of any signal faster than light, but it does not limit the group velocity of electromagnetic propagation."

Chiao's colleague Steinberg puts it another way: "What stops you from sending a signal faster than light is that the calculation only works for smoothly varying pulses. If a smoothly varying pulse shows up at noon, it may have been possible to predict its shape from the shape of the pulse at 8 am. If at noon you suddenly have an important message and decide to change the shape of the pulse in order to convey this message, that change will not travel any faster than the speed of light."

Despite such reassurances, many physicists admit to being more than a little troubled by these faster than light phenomena. While few are prepared to accept Nimtz's more extravagant claims, many will doubtless want to see how much further theory and experiment can fly in the face of common sense. ☐

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