The properties of one particle can determine those of another even though the two are miles apart and don’t exchange any information. What appears to be a spooky phenomenon is what physicists call entanglement, and they have already observed it in small particles. Now Roman Schnabel, a professor at Leibniz University Hannover and at the nearby Max Planck Institute for Gravitational Physics (Albert Einstein Institute), aims to entangle two heavy mirrors.
Clear, lucid thinking is probably the best defense against the meanderings to which even physicists can succumb the moment they attempt to formulate quantum physics in comprehensible imagery. This, at least, is the impression Roman Schnabel conveys as he patiently explains his research in his tidy office at the Max Planck Institute for Gravitational Physics in Hanover. In any case, the young professor of experimental physics has no use for hip quantum mysticism. But he certainly doesn’t shy away from contact with other schools of thought. He recently gave a lecture on quantum physics at an event that was hosted by an Asia institute and that highlighted the relationship between the natural sciences and Buddhism.

“In contrast to the Buddhist teachings presented there, quantum physics allows for true randomness,” says Schnabel. That things can happen for absolutely no reason is just one of the quirks of the quantum world. An even stranger phenomenon is the one that Viennese quantum physicist Erwin Schrödinger dubbed entanglement in the 1930s. It allows two particles to form a quantum object even when they are far apart.

In addition, in the quantum world, every measurement changes the object that is measured. So if one measures, on one particle, the quantum property through which that particle is entangled with other particles, the same property will promptly be determined for each of the particles involved. And it doesn’t matter how far apart these particles are. For entangled light quanta (photons) in air, it even works across a distance of 144 kilometers, as Austrian physicists showed in 2007. Such spectacular demonstrations trace back to thought experiments from the 1930s. Back then, the smartest minds in physics argued heatedly about the consequences of the still young quantum mechanics. Albert Einstein, in particular, wanted to dissect the alleged weaknesses with a razor-sharp knife. Now experimenters can realize these thought experiments – and what do you know: nature is just as crazy as quantum theory describes it.

An Elaborate Plan for a Bold Idea

Since the 1970s, experimental quantum physics has been developing into a fascinating research field, focusing particularly on entanglement. Although quantum mechanics describes this phenomenon mathematically precisely, its consequences contradict everything we know from our everyday experiences. In our environment, we perceive only large things for which subtle quantum effects normally go under in the flood of physical interactions. Only the most modern experimental skill can prepare the delicate entanglement and maintain it for awhile.

In principle, quantum mechanics imposes no limits – neither on the spatial distance between the entangled objects nor on their size. Roman Schnabel now wants to investigate, together with colleagues in his 18-member research group, whether it is possible to entangle also really large, heavy objects. Other working groups are also attempting this with larger objects than photons or atomic components of matter, for instance with giant molecules. But Schnabel’s idea is far bolder: intense laser light will be used to entangle two massive mirrors. He plans to start with mirrors...
weighing “maybe 100 grams” and then increase the weight to a good kilogram. If that succeeds, then entanglement will have finally reached our world of large, tangible objects.

The plan has been thought out so thoroughly that the critical reviewers of Physical Review Letters, the most highly renowned journal of physics, have given it their stamp of approval. If it succeeds, it will be a major sensation. Schnabel is optimistic, as he can use a unique precision technology that was developed at the Albert Einstein Institute for the major gravitational wave experiment GEO600.

When asked how he would explain entanglement to his hairdresser, Schnabel can’t suppress a hearty laugh. It’s not easy to come up with understandable images. A thought experiment with two players who can’t see each other gives an initial impression. A referee places two dice in a cup and shakes them. Now the referee gives each player one die. They each toss their die and write down what number they see. In the quantum world, however, the toss corresponds to a measurement, which destroys the entanglement. So the referee collects the dice again after each round, entangles them, and passes them out again. After a few rounds, he ends the game.

**No Tricks in the Quantum Dice Game**

The three now first look at one of the two notepads. As expected, they see a list of randomly rolled numbers. But when they lay the two notepads side by side, they discover something astounding: the columns of numbers are identical! The quantum dice apparently produced random numbers, but in the exact same order. This must be due to entanglement, as the experienced referee ruled out all tricks and collusion between the players. Furthermore, the dice were neither loaded, nor did they exert any hidden forces on each other.

There isn’t (yet) such a thing as quantum dice, but entangled quantum particles behave similarly: there seems to be a strange connection between them. However, even this image is misleading, as there are no physical forces in play. In addition, only certain properties are ever entangled. For light quanta, for instance, this can be what is known as polarization, which can be imagined as a small pointer. If two entangled photons are prepared in a certain way, then the polarizations of both photons must point in exactly the same direction.

In physics, this process is called entanglement collapse. Quantum mechanics sets no limit whatsoever on the speed with which it assimilates all entangled particles. In light of such oddities, Albert Einstein criticized that it was as if there were “spooky action at a distance.” “Of course that does not exist – that image would be completely wrong in physics terms,” stresses Roman Schnabel.

A radar gun in the police car measures either the distance between the cars (position measurement; green), or the sum of their speeds (momentum measurement; blue).
Physicists in Geneva recently showed that the collapse actually propagates at least ten thousand times faster than light. This raises the question of whether, through measurements on the first photon, one could use the second photon to morse information to a recipient faster than the speed of light. This would fundamentally contradict Einstein’s special theory of relativity, which puts an absolute speed limit of the speed of light on all physical interactions.

**Gravity Comes into Play**

Quantum theory actually saves this situation, though theoretical physics has been trying in vain for more than seventy years to unite it with the (general) theory of relativity. This is where we see the greatest gap in the premises of modern physics. Very strangely, quantum theory follows the rules of the theory of relativity. That is to say, it prohibits any possibility of an “entanglement chat” at superluminal speed by incorporating randomness – essentially as an interfering transmitter. If, for instance, someone were to attempt to morse bits of information to a communication partner through polarization of entangled photons, he would notice the following annoying effect: any measurement on one’s own photon does not produce a specific intended bit, but rather a completely random result, just like throwing dice. This effectively prevents any transmission of meaningful information.

Roman Schnabel and his colleagues will have an eye on the critical gap between quantum theory and the theory of relativity when they attempt to entangle heavy objects, as this is where the gravitational force comes into play. It is the only one of the four fundamental forces of physics that still continues to stubbornly defy description in quantum theory terms. On the other hand, it is closely tied to the general theory of relativity: gravity is created by warps in space-time, which are caused by objects having mass. So Schnabel’s mirrors, which are indeed quite heavy, sit in a small but possibly momentous space-time indentation.

The well-known British theoretician Sir Roger Penrose from the University of Oxford raised the question of whether this indentation could destroy the highly sensitive entanglement. “Most physicists think, as I do, that it won’t change the quantum character,” explains Schnabel. So the

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**ILLUSTRATION**: Roland Würgler/Wangenmühle | *Photo*: MPI für Gravitationsphysik
entanglement of the mirrors should be successful, but the sensitive quantum state may indeed feel the effects of gravity. That might open up completely new there and initially exchange no information whatsoever with the rest of the universe,” explains Schnabel. But they are closely connected with each other, which manifests itself in their entanglement.

“It’s as if the two particles know only of each other in the beginning,” says Schnabel. A variety of external forces gradually begin to act on them and thus define their properties with respect to their environment. Only then do they really show up in our cosmos, so to speak. In doing so, they lose their quantum entanglement relationship to each other and become separate particles with individual properties.

The mirrors, in contrast, are initially isolated, individual objects that know nothing of each other. So Schnabel’s team must take the reverse approach: they must suppress the disruptive influences of the environment on the properties to be entangled, and in this way turn the mirrors into a quantum object. The researchers in Hanover hope to entangle the mirrors’ centers of mass using a strong laser beam whose photons exert light pressure on the mirrors. Thanks to this force, the laser acts like a mechanical spring.

“The position and speed of the center of mass of one mirror should then be determined only by the corresponding properties of the center of mass of the other mirror,” explains Schnabel. Position and speed here are specified relative to the axis between the two centers of mass. So the mirrors are to be entangled in one spatial dimension. To this end, they will be suspended on superfine quartz threads like pendulums – a technique originally used in GEO600. When they oscillate only minutely, their motions in the axis direction are practically as free as if they were floating.

If the experiment succeeds, the positions and the speeds of the mirrors’ centers of mass should seem to disappear in the axis direction. They dissolve into approximations and aren’t perceptible again until the moment they are measured – and the result of any measurement is only vaguely predictable. In the floating state prior to measurement, the mirrors are entangled. After the laser light is turned off – and as with the quantum dice, it is not allowed to maintain any secret connection between the mirrors – the entanglement should theoretically survive for about a hundredth of a second. In physics, that is a wonderfully long time for experimenting.

The precision laser serves not only to induce entanglement, but also to detect it. This is because its light can be used as a superfine ruler with which the motion of the mirrors’ centers of mass can be measured extremely precisely. The physicists can register even oscillations of just one attometer – an unimaginably tiny 0.000000000000000001 or \(10^{-18}\) meters. “That is a thousandth of the diameter of a proton,” Schnabel proudly points out.

**Mysterious Results in Quantum Car Racing**

Two measurement results that appear to contradict one another will prove whether the mirrors are entangled. Paradoxically, they are completely correct in quantum mechanics terms. To explain this, Schnabel describes a somewhat peculiar quantum car race: “Imagine three cars on a three-lane racetrack.” The observer sits in a quantum police car that drives at a constant 100 km/h in the right lane.
In the left lanes, on a level with the police car, are the two other cars, which correspond to the two mirrors. They are supposed to try to drive exactly 100 km/h, as well.

The observer can capture the motion of the two with a radar gun. He first notices that they are subject to fluctuations: apparently they aren’t able to constantly stay exactly on a level with him. Now he notices something strange. With his radar gun set so that he can determine the precise position of the cars, he measures that the two cars oscillate back and forth in synch. “So they are sometimes in front of him together, and sometimes behind him together,” explains Schnabel. But this measurement says nothing about the speed of the cars.

The second measurement setting shows the policeman the sum of the speeds. Despite the fluctuations, the two cars are always driving at a combined speed of exactly 200 km/h! That allows just one conclusion: as soon as one car speeds up, the other must slow down accordingly – or vice versa. The two cars thus oscillate asynchronously against each other. But this measurement doesn’t reveal how far apart they are at the moment this speed is measured.

Each measurement contradicts the other, but which one is correct? The amazing answer is: they both are! It just depends on which radar gun setting the policeman uses when measuring. This is because the two cars are entangled in this direction of motion.

That is exactly the kind of contradictory oscillation behavior Schnabel expects to see with the entangled mirrors. Two detectors will monitor this mirror motion in the axis direction, while the laser light will assume the role of the radar waves. One detector will measure the precise speed at which the mirrors move relative to each other, and the other detector the distance of the centers of mass relative to each other – right down to the exact attometer. The speed measurement will generate a perfectly asynchronous oscillation and the position measurement a perfectly synchronous one.

With this, the researchers in Hanover aim to realize a famous thought experiment devised by Albert Einstein, together with Boris Podolsky and Nathan Rosen, at Princeton University in 1935. The three scientists wanted to show that quantum physics is incomplete, because their experiment seems to suggest that it is possible to simultaneously measure the positions and the speeds of two entangled objects with precision.

**A First Glimpse of Quantum Gravity**

In our quantum car race, any radar measurement would destroy the entanglement of the two cars, but it can be set up in exactly the same way. So the quantum policeman can freely decide whether to occasionally measure the position first and then the speed: by measuring like that, he could, in principle, determine the precise positions and speeds of the entangled cars, even if it would apply only to the overall system, namely the distance between the cars and their speed relative to each other.

But that seems to contradict Heisenberg’s well-tested and confirmed uncertainty principle, which states that the position and speed of an object can never be determined simultaneously with precision. Within quantum mechanics, there is only one completely logical – if radical – way out of this dilemma. In the quantum car race, it is indeed not possible to say anything precise about the position and the speed of each individual car. “The entangled objects, in our case the two mirrors, no longer have any individual properties in terms of position and speed,” explains Schnabel.

Einstein did not accept this point of view because it contradicted his understanding of a physical reality, which required each individual system of the entangled object – so here each mirror or each car – to have a speed and a position, even if they cannot be determined simultaneously with precision. But apparently physics must bid farewell to this Einsteinian understanding of reality – at least until there is a better interpretation. So far, only one thing is certain: in this case, quantum theory describes nature without any contradiction of any previous experiments.

Now Roger Penrose’s question about gravity, which could help unify quantum theory and the theory of relativity, can be understood: if an entangled mirror no longer has a precise position, then it can end up effectively next to its own space-time indentation – whose position the general theory of relativity describes precisely. So it should feel the effect of its own gravity. If this affects its quantum state, the experimental physicists may get the first glimpse of quantum gravity effects.

To date, theoreticians can only speculate about the world of quantum gravity, for instance in the form of string theory. However, it will take a few years yet before the mirror experiment is realized. In any case, Schnabel is convinced that it will confirm the predictions of quantum physics: “It’s just right in a way that Einstein could not accept.”

Roland Wengenmayer