RESEARCH *in Brief*

Biomathematics

A Biological Generator of Prime Numbers

Fig. 1: Cicadas during reproduction

Photo: Leon Higley, Department of Entomology, University of Nebraska-Lincoln. We would like to thank the US-American scientists for providing us with the photographs and map.

In large areas of North America, cicadas emerge every 13 or 17 years from their underground homes to reproduce on a massive scale – living thereafter underground for another 13 or 17 years in the form of larvae. Scientists from the Max Planck Institute of Molecular Physiology, Dortmund and the Universidad de Chile believe that they have now solved the mystery surrounding the unusual life cycle of these insects: the researchers working with Prof. Mario Markus have developed a predator-prey model, in which only those life cycles that have the length in years of a prime number are stable. The researchers are also using the model to produce arbitrarily large prime numbers, thus bridging the gap for the very first time between number theory and biology – two otherwise completely separate disciplines.

In 1634, European settlers in East Tennessee first encountered the frightening experience of a cicada plague. The mass reproduction of these insects has taken place regularly at intervals of 17 years ever since – and was recorded right on target for the 22nd time in 1991. In each case, the plague begins with the soil in plantations or forests becoming riddled with holes overnight. The larvae emerge out of these small, closely adjacent holes in the soil – up to 40,000 holes can be counted around one single tree alone; the subsequent transformation of these larvae into chirping insects and the processes of mating, egg laying, and ultimate death all take place within a period of just a few weeks (Fig. 1 and 2). The larvae then hatch from the eggs, bury themselves into the soil, and live on the juice of roots until another 17 years have passed by.

Cicadas with a 17-year life cycle live in the region marked blue on the map (Fig. 3); the red region on the map refers to cicadas with a 13-year life cycle. What is truly remarkable about these creatures is their punctuality (the predicted dates are only one week out at the very most), the level of noise they make (at 100 decibels it is no longer possible to hear the road traffic), the extent to which they attract tourists and journalists, their sheer abundance (several million insects per hectare), as well as the mystery surrounding their mass-scale reproduction at intervals of 13 or 17 years.

The evolutionary biological explanation for the occurrence of the cicadas on this massive scale is that the potential predators of the cicadas (for example, birds or wasps) become satiated, so that a sufficient number of cicadas will always survive to preserve the species. The reproduction cycle at intervals of 13 or 17 years can also be explained using the predator-prey model: if the life cycle were twelve years, for example, then the cicadas could be eaten by all synchronized predators that appear every 1, 2, 3, 4, 6 and 12 years. However, if the cicadas mutate to 13-year cycles, then only those species that appear every year or every 13 years will be predators. In general terms, it should follow that prime numbers – that is to say numbers that are only divisible by themselves and by one – represent the favoured intervals of reproduction. The next largest prime number after 13 is 17 – the precise length of the life cycle of the cicadas that live in the biotope shown in blue on the map. Although this evolutionary biological explanation had been around for some time, a mathematical model of the evolution of these insects had still not been devised.

Fig. 2: Cicada plagues occur every 13 or 17 years.

Photo: Lee Jenkins, Department of Entomology, University of Missouri

Mario Markus and Oliver Schulz from the Max Planck Institute of Molecular Physiology, and Eric Goles (Universidad de Chile) have now developed an evolutionary model (Complexity 6, pg. 33-38, 2001; Mathematical Intelligencer 24, pg. 30-33, 2002) that produces prime cycles of the prey through mutation and selection of predators and prey. The German-Chilean research group was able to show in mathematical terms that a prime cycle of the prey is stable with respect to cycle-changing mutations of predators or prey, and that a non-prime cycle of the prey is changed following a finite number of mutations. The researchers then pursued two courses of investigation. Firstly, in addition to the chronological development, they examined the spatial aspects of the insect reproduction process, taking into consideration the interaction between neighbouring populations. In the course of these investigations, they came up with territories that had arisen through self-organisation – as occurs in nature – in which the favoured length of cycles is 13 and 17 years. Secondly, they turned their backs on nature, and used as their initial conditions cycles with a length that reached the limits of computing capacity, even if these were completely unrealistic in biological terms. In these cases, the simulation was stable in the case of extremely large prime numbers, which also means that the model generates extremely large prime numbers. This, however, is of general interest: in the hunt for ever larger prime numbers, new records are constantly being achieved (see, for example, Paulo Ribenboim, "The New Book of Prime Number Records", Springer, 1996). What is unique about the German-Chilean work is the fact that the prime numbers are produced using a biological model. The evolutionary model therefore links number theory and biological modelling for the very first time.

Gaps still exist in the biological assumptions of the model, as the predators of the cicadas have not yet been found. The biologist Christine Simon from the University of Connecticut speculates that one predator could have been an extinct parasitic wasp; Californian scientists believe that a possible predator is the fungus Massopora cicadina that affects cicadas. Following on from the work of the physicists and the computer scientists, it is now once again the turn of the biologists to undertake further research. ●

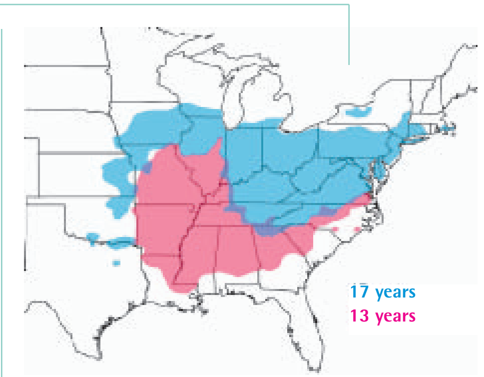

Fig. 3: Geographical distribution of the cicadas. Altogether there are three species of cicada which have life cycles of 13 or 17 years.

Map: John Cooley, Department of Ecol. and Evol. Biol., University of Connecticut.

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Astronomy

Conica Surpasses Hubble

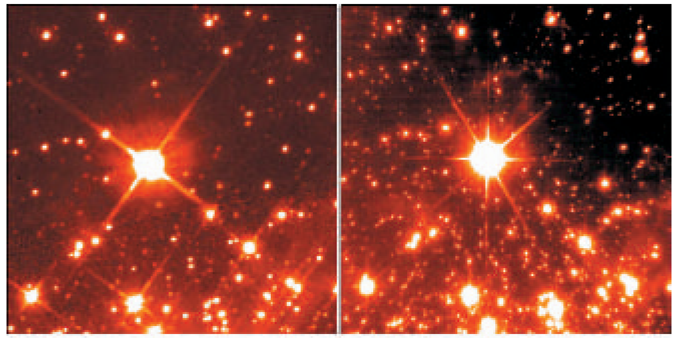
Using Conica, the new infrared camera on the Very Large Telescope (VLT) at the European Southern Observatory (ESO), a team of German and French astronomers has succeeded in achieving images with a level of resolution that has never before been accomplished. The first observational target for this camera that features adaptive optics was the open star cluster NGC 3603 on November 29, 2001. Conica made it possible for numerous newly formed stars to be observed in this cluster. Conica is now the world's most efficient infrared camera. This high-precision instrument, weighing around one ton, was developed under the overall leadership of the Max Planck Institute for Astronomy (MPIA) in Heidelberg, in collaboration with colleagues from the Max Planck Institute for Extraterrestrial Physics (MPE) in Garching and the ESO.

Conica operates on the 2,600-metre high Cerro Paranal in the Chilean Andes, on the fourth 8-metre telescope of the VLT. An instrument for adaptive optics (NAOS), built under French management, was installed with the camera, and this continuously corrects the blurring effect caused by air turbulence. In this way, Conica and Naos are together able to provide astronomical images which greatly surpass the Hubble Space Telescope (HST) in terms of both sensitivity and sharpness.

In the near infrared spectral range (wavelength approximately one micrometre) during optimum conditions, Conica and Naos are together able to show details right down to a few hundredths of a second of arc – three times the level of focus achieved using the Hubble telescope. This would enable a fifty-metre rock on the moon to be visible. How-

The new 1-ton camera on the Very Large Telescope (VLT). The blue connecting flange that resembles a gearwheel can be seen on the left. The adaptive optics facility NAOS is located in the centre (light blue) and Conica is on the right (red).

Photo: MPI for Astronomy



The star cluster NGC 3603 in the Carina constellation, on the left taken with the Hubble Space Telescope (Wide Field Planetary Camera 2), on the right with Conica and NAOS on the VLT. The comparison shows that the new camera provides images that are considerably sharper than those from the HST. In each case, the image field is approximately 25 x 25 seconds of arc, which corresponds to 2.5 x 2.5 light years at the distance of the star cluster. The exposure times is 400 seconds (HST) and 300 seconds (CONICA).

PHOTO: NASA (LEFT), ESO (RIGHT)

ever, this does not mean that the Space Telescope has become redundant: on the one hand, the atmosphere in some regions of the near infrared swallows up part of the light, whilst on the other hand Naos requires a comparatively bright star in the field of vision to correct the air disturbance – therefore, not every field in the sky can be optimally imaged.
The project was launched at the beginning of 1992 with an agreement between the two Max Planck Institutes and the ESO. Since then an estimated 40 man-years of work have been invested in the construction of CONICA. The ESO agreed to pay for the material costs of around 2.3 million German marks, whilst the Max Planck Institutes provided the expertise. "Many engineers, PhD candidates and diploma students from our institute have worked on the development and construction of our camera with total commitment. Now we are reaping the benefits of long-term development", explains Project Leader Rainer Lenzen from the Max Planck Institute of Astronomy in Heidelberg.
CONICA is not just a camera, it is an extremely versatile scientific instrument: the scientists have a choice of seven individual cameras inside CONICA, and this is similar to the way in which lenses with varying focal lengths can be interchanged in a photographic camera. They are positioned on a large wheel and are rotated on this wheel into the light path. This enables images with varying resolution to be obtained. This is necessary, above all, because CONICA is sensitive in the infrared range at wavelengths between approximately one and five micrometres. Each camera has the optimum design for each particular section of this range.
Carrying out observations in the infrared range places particular demands on the instruments due to the fact that all bodies radiate heat at room temperature in this wavelength range. It is necessary to "freeze" the instrument to prevent it from being dazzled by its own heat radiation. CONICA is equipped with a double cooling system, which reduces the temperature of the optical system and the camera to minus 210 degrees Celsius, and reduces the temperature of the detector to minus 240 degrees Celsius. During CONICA's construction, this cryosystem posed one of the biggest problems for the stability of the entire instrument. During a lengthy exposure time, the telescope rotates with the camera to equalize the visible movement of the sky from East to West. "We had to ensure that the device, which weighs around a ton, did not bend more than a few thousandths of a millimetre during this movement", says Lenzen.
The fact that the astronomers overcame all the problems is demonstrated in the initial images. CONICA can be used for almost all areas of astronomical research. One particular area of focus is the birth of stars. In galaxies such as the Milky Way enormous clouds exist that are made up of dust and gas. In certain conditions, individual areas within these clouds can be drawn together by their own gravitational force and condense to form new stars. Our own Sun was also created in this way. Only when a star starts to shine brightly does it sweep the surrounding environment clean of residual dust and gas and become visible. The early stages of the birth of a star cannot be observed in the region of the visible light as they take place deep within the cloud. Only in the infrared range that is accessible to CONICA does the emitted radiation penetrate the dust and provide a glimpse into the "childhood" of young stars.
One example of this type of region is the area that surrounds the young star cluster NGC 3603. The numerous small light spots that become visible on the CONICA image taken on the VLT are low-mass stars, which in astronomical terms are remarkably young, i.e. only a few hundred million years. Most of these are not visible on the Hubble image. The ability to observe stars using this level of accuracy will lead to an improved understanding of the processes involved in the formation of stars.
A second, central area of research is the formation and evolution of galaxies and quasars. Quasars are also visible from the furthest distances, as they are the brightest celestial bodies in the universe. It is highly likely that their tremendous radiation is produced in the vicinity of a black hole that is located at the centre of every quasar. The youngest galaxies and quasars are many billion light years away. They have a high recession velocity due to cosmic expansion and their light is therefore strongly displaced towards longer wavelengths. Although they emit most light in the visible and ultraviolet range, when observed from the Earth, they therefore appear most brightly in the close infrared range. CONICA will consequently be able to glance far back into the early development stages of our Universe (see MAX PLANCK RESEARCH 4/2001, pg. 22 ff.). ●

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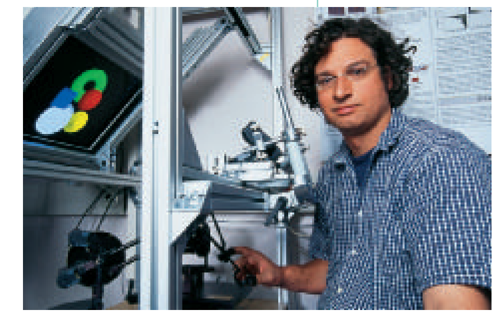
BIOLOGICAL CYBERNETICS

Mathematics of the Senses

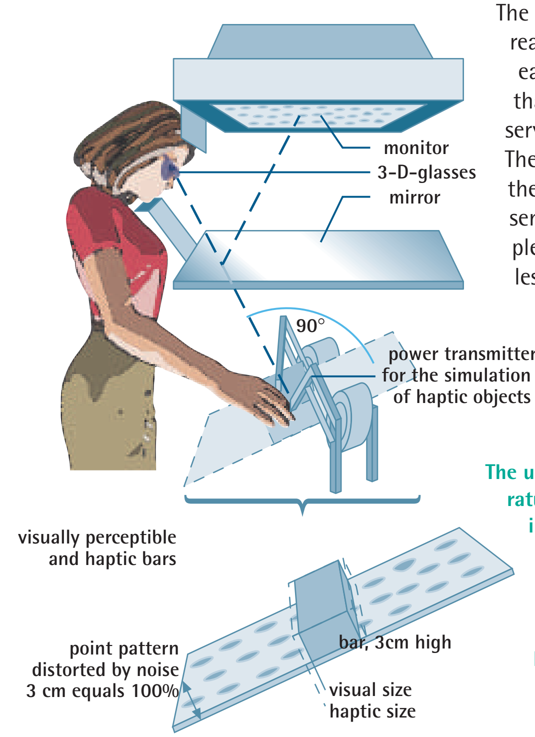


Marc O. Ernst investigates the way in which the brain calculates different sensory perceptions.

PHOTO: WOLFGANG FILSER

Humans use all of their senses to perceive an object. In this way, we can hear an apple when it falls to the ground, we can see it lying there, grasp hold of it and pick it up, smell it and then bite into it. Our brain integrates all these sensory perceptions to create a complex perception of the apple. Marc Ernst from the Max Planck Institute for Biological Cybernetics in Tübingen, together with his colleague Martin Banks from the University of California in Berkeley, has now discovered that our brain processes visual and haptic information in a statistically optimal manner (NATURE 24 January 2002).

Which particular sensory data will dominate depends on the specific situation and on what we do with the object. If we assess the size of the object, then we are more likely to be visually oriented. On the other hand, if we assess the roughness of its surface, then our sense of touch will be our best guide. According to each particular task, we therefore place a varying degree of importance on the sensory data that is supplied by the eyes and the hands – and this is dependent on how reliable these perceptions are.
Physical measuring instruments will always have a small fault tolerance and our sensory organs are similarly not entirely perfect: all the perceptory signals that are transmitted to the brain are "noisy" in one way or another. However, during perception, the brain is meant to use all available information sources in as optimal a manner as possible.



GRAPHICS: ROHRER, BASED ON A MODEL FROM THE MPI FOR BIOLOGICAL CYBERNETICS

The upper sectional image shows the test apparatus; the test object is shown in the lower image. A computer monitor mounted upside down above a mirror creates the image of a test object. Observers are able to see the test object in the mirror. The bar that is to be touched is simulated below the mirror by means of two power transmitters (PHANToMs from the firm SensAble Technologies). The lower sectional image shows how a discrepancy between the haptic and the visual perception of the bars can be produced using this apparatus. The "visible" bars consist of a random point pattern that can be distorted by noise so that the reliability of the visual signal can be manipulated.

The researchers had already demonstrated in earlier experiments that our hands can also serve as "visual aids". The more noisy and therefore uncertain the sensory data, for example during touch, the less dominant the data will be in competition with the other information sources (for example sight). A statistical model – the "maximum likelihood" method – would provide the optimum combination for processing the signals, which have a varying degree of reliability, so that the overall noise is minimized. Only in this way could all available sensory information relating to an object be utilized in a manner which is as meaningful as possible.
Using the following experiment, the scientists have now shown that during perception our brain really does operate along the lines of a skilled mathematician: those undertaking the test had the task of comparing the size of two bar-shaped objects. They were able to both see and touch the bars. From the errors in the comparisons made by those undertaking the tests, the researchers were able to determine the degree of reliability with which the sensory signals of the different senses in the brain are processed.
Using an ingenious experimental set-up, which created a virtual image of the test objects on the computer, the researchers were able to independently manipulate the visually perceptible object and the haptic object. They produced a discrepancy between the two objects and then investigated whether the test persons were oriented more towards the visual or the haptic perception. In this way the scientists established the weighting of the signals in relation to each other and determined that the behaviour of the test person matched the predictions of the statistical model precisely: when the size of the object was clearly and obviously visible, then the visual perception was dominant; if, however, the experimenters "blurred" the image by superimposing noise, then the haptic size was dominant – and to the exact extent predicted by the statistical model.
Further research work at the Max Planck Institute for Biological Cybernetics in Tübingen should now reveal how we actually carry out this statistically optimal procedure and what the neuronal representation of this interaction between sight and touch looks like in the brain. ●

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BIOPHYSICAL CHEMISTRY

Proteins Are the Perfect Water Filters

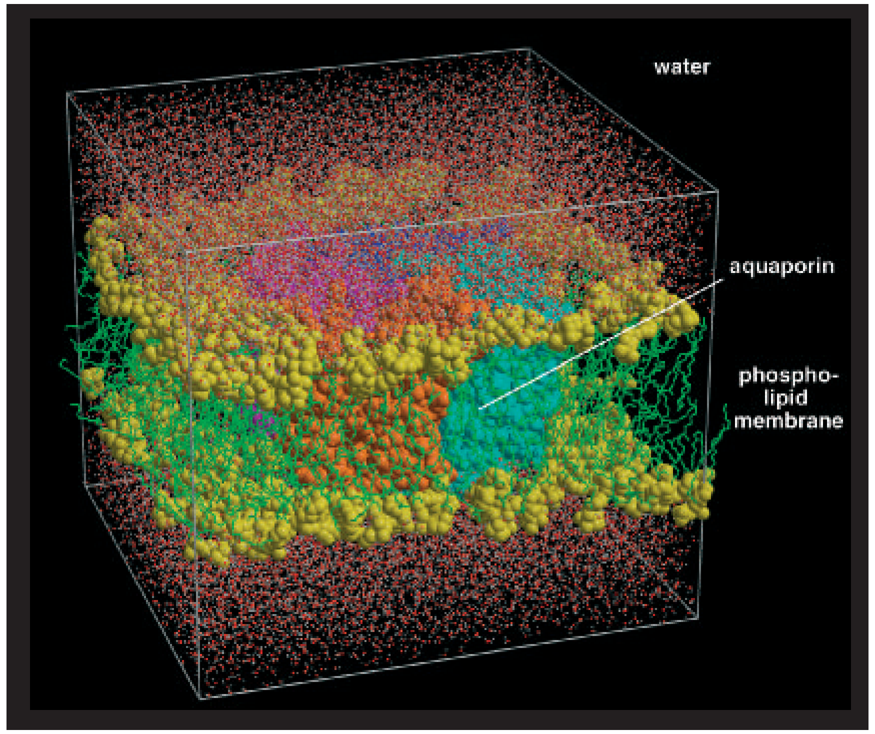

Fig 1.: The aquaporin/membrane system computer model used in the simulations. The biologically active form of aquaporin is a tetramer, a complex made up of four aquaporin molecules (orange/cyan/magenta/blue), which is embedded in the cell membrane (green/yellow). Liquid water (red/white) was simulated on the inside and outside of the membrane and this water passed through the four aquaporin molecules. The whole system involved approximately 100,000 atoms.

Achieving a flux of clean water between cells is one of the fundamental problems of life. The solution has now been explained in detail for the very first time: using extensive computer simulations, scientists from the Max Planck Institute for Biophysical Chemistry in Göttingen have revealed the structure and function of proteins, which build microfine channels in the membrane of cells – channels which are only permeable to the purest water.

Water regulation plays a crucial role in the human body. Almost all biochemical reactions, that is to say all fundamental living processes which take place inside cells, are carried out in aqueous solutions. A controlled system of water flux is correspondingly important for each cell: depending on the conditions inside and outside the cell, the necessary quantity of solvent required in each case must always be transported into or out of the cell. This exchange of water takes place via special proteins called aquaporines, which form microfine channels in the otherwise waterimpermeable cell membranes.

Aquaporines can be found in the cell membranes of many plants and animals; they prevent the cell from bursting, for example due to changes in the exterior salt concentration (osmotic regulation). In humans, aquaporines regulate the water balance in the kidneys, red blood cells, in the eye lens, and in the brain, to name just a few. A defect or a malfunction in these proteins causes diseases such as diabetes insipidus, congenital cataracts, or neurone-related hearing loss.

In all cases, a highly efficient, yet selective water transport system that excludes the permeation of other molecules, is of central importance. In this way, the aquaporines allow water molecules to permeate, but prevent the cell from losing nutritional molecules or salt ions. Although these filters are extremely fine-pored, aquaporines achieve a remarkable level of water conductivity of up to three billion water molecules per second and channel. A membrane patch of 10 x 10 cm2 with embedded aquaporines could filter and desalinate one litre of water in approximately seven seconds.

How does the protein fulfil these conflicting requirements? The first clues came from the spatial atomic structure of an aquaporin (AQP1) that was recently decoded using electron microscopic techniques in a collaboration between a Japanese working group led by Yoshinori Fujiyoshi, a group in Basel led by Andreas Engel, and the "Theoretical Molecular Biophysics" working group at the Max Planck Institute in Göttingen. The structure showed that the protein forms a channel in the membrane that is 2 nanometres (two millionths of a millimetre) long and at its narrowest point only 0.3 nanometres wide – just large enough to allow a single water molecule to pass through. Larger molecules are not able to permeate this narrow channel.

Evolution has also solved the problem of how to block the permeation of smaller ions in this channel. It is vital, above all, to prevent the permeation of protons (hydrogen ions), so that a difference in the proton concentration (pH value) between the interior and the exterior of the cell can be maintained as an important short-term energy store. Similar to an electrical battery, this store would short-circuit and discharge if protons were allowed to permeate.

Water itself is also known to conduct protons relatively well; the protons hop at great speed over so-called hydrogen bonds from one water molecule to the next. So, how does aquaporin prevent the flow of protons through this membrane channel? Up until now, scientists could only speculate over the answer to this question on the basis of the static spatial structure of the water channel protein. Above all, it was not possible to observe the movement of the water molecules through the channel. It also did not resolve the question of how the extraordinarily high speed of water flow was achieved.

GRAPHICS: MPI FOR BIOPHYSICAL CHEMISTRY

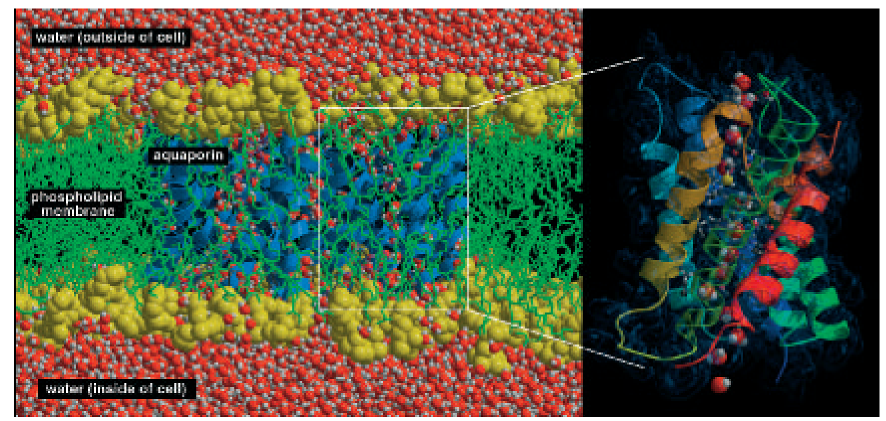

Fig. 2: Snapshot of the aquaporin during simulation. Left: water molecules (red/white) diffuse via the aquaporin (blue) through the cell membrane (yellow/green). The section on the right illustrates the "dance" of an individual water molecule on its journey through the channel.

The scientists at the Max Planck Institute for Biophysical Chemistry have now succeeded in tracing, in detail and in "real time", the movement of individual water molecules through an aquaporin channel using atomic resolution computer simulations (SCIENCE, 14 December 2001). For these simulations the researchers "reproduced" the protein in the computer atom for atom (Fig. 1).

The virtual protein was embedded in a membrane and surrounded by a large number of water molecules, the protein's natural environment. The model contained a total of approximately 100,000 atoms and the movements of these were accurately calculated by means of a subsequent so-called molecular dynamics simulation. The simulation required several months worth of calculations carried out on an 80-processor, high-performance parallel computer. In this way, a film sequence has been created, in which every detail of the movement of individual water molecules can be observed and analysed on screen (Fig. 2). The simulation also accurately reproduced the water permeation rate – an important test for the accuracy of the calculation. The computer simulations reveal a fascinating, finely choreographed "dance of the molecules", directed by protein building blocks (amino acids) that are carefully positioned on the inside of the channel. This precise control of the movement of the water molecules was found to have two functions: firstly, the water molecules are "passed on" from one site to the next, in an orderly manner, on their journey through the channel, which drastically increases their water permeation rate. Secondly, the permeation of protons is blocked by the temporary breakage of hydrogen bonds between the passing water molecules. The breakage of these bonds would usually be energetically unfavourable (the reason why water does not boil until it reaches a temperature of 100 degrees Celsius, whilst carbon dioxide will already boil at minus 78 degrees Celsius). Aquaporin compensates for this energy expenditure: its individual amino acids form highly ordered transient hydrogen bonds with passing water molecules. This bonding is also only possible because the water molecules are very precisely aligned and "passed on". The permeation of water molecules is a spectacular example of biological molecular nano-engineering developed by nature over millions of years.

In follow-up work, within the framework of an international project sponsored by the European Union, the Göttingen group would like to attempt to construct molecules that can regulate or even block water permeation through the aquaporin and to test these molecules in simulations. The precise understanding of such substances could provide an encouraging starting point for the development of new medicines.

Computer simulations of proteins on an atomic level are currently being carried out with increasing success, not least as a result of rapidly increasing computer capacity. Over and above traditional bioinformatics, such simulations provide a thorough physical and chemical understanding of fundamental biological processes. ●

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RESEARCH *in Brief*

EVOLUTIONARY BIOLOGY

A Good Reputation is Priceless

Researchers led by Prof. Manfred Milinski, Director of the Max Planck Institute for Limnology in Plön, have provided experimental evidence that a public resource will be cooperatively managed, and that the "tragedy of the commons" will no longer exist, if the ways and means by which the resource is used are linked to the reputation of the user (NATURE, 24 January 2002). If this succeeds, then the public resource will provide high profits for all users.

Many problems facing human society, such as overfishing of the seas, or our inability to sustain the global climate, are cooperation problems. If individuals, groups, or states are free to overuse a publicly managed resource, then this is indeed how they will usually behave. This problem, known as the "tragedy of the commons", has been extensively investigated by social, political and economic scientists for decades, and has recently also come under the close scrutiny of the evolutionary biologists. Up until now, apart from the possibility of directly punishing the unwillingness to cooperate, no cooperative solution to the "tragedy of the commons" had been discovered. The usual way of investigating the "tragedy of the commons" is by carrying out "public goods" experiments: this involves, for example, four students, each being given a starting capital of five Euros. They have the choice of investing some of this money in a public fund, in which case they place an amount of up to five Euros in an envelope without discussion. The person conducting the test collects the envelopes, doubles the total sum of the contributions and redistributes the money equally amongst all four players. The four students would then make the most profit if each one of them were to contribute their full five Euros and then receive ten Euros in return (double the amount).

However, it would be more "economical" to contribute nothing and to make a profit by relying on the contributions made by the other players: the total income is doubled and shared out amongst the four players. In this way, for every Euro that is personally donated by a player, only half a Euro in received in return. The amount that each player receives does not depend on the amount that they themselves have invested. This disparity between investment and profit is a true "tragedy of the commons" problem: egoistic self-interest stands in conflict with communal interest.

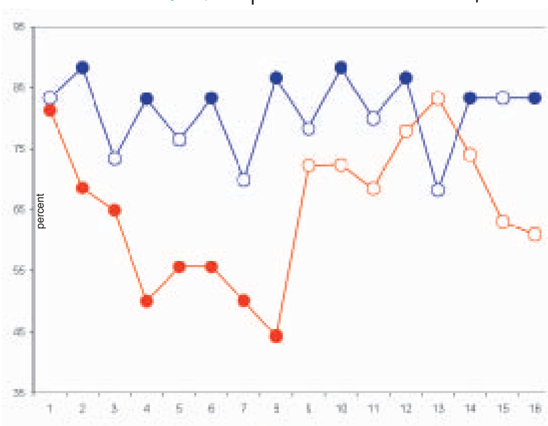
These types of experiments usually begin with the players behaving in a highly cooperative manner. However, this cooperation breaks down after only a few rounds and no one continues to invest in the public resource. Each player who attempts to cooperate would lose money, as they would receive only half a Euro for each one personally invested. In contrast to the "tragedy of the commons", humans have clearly found a solution to a different cooperation problem: that of indirect reciprocity or "give and you shall receive". Here, cooperation is shown towards those fellow humans who are known to have helped others. Confirmation of this solution had already been provided some years ago on an evolutionary-theoretical and experimental basis. Manfred Milinski, Dirk Semman and Hans-Jürgen Krambeck from the Max Planck Institute for Limnology in Plön based their work on the following hypothesis: if it is important, for the purposes of indirect reciprocity, to establish a highly generous profile, that is to say an "esteemed reputation", and to maintain this reputation, then this should also apply to the "public goods" situation if one is to constantly encounter the same social partners in both situations.

If a player does not cooperate in the "public goods" game, then it is possible that he would subsequently lose the reputation that he had painstakingly built up in the reciprocity game. In the game the students are also given starting capital. In each round, each player is once a potential giver (-1.25 Euro) and once a potential receiver (+2 Euro), but never in reciprocation with the same person. The Max Planck researchers then carried out a computer-aided experiment with groups of six students from the University of Hamburg, whereby ten groups played 16 rounds, alternating between one round of "indirect reciprocity" and one round of "public goods" games. In each round of the "public goods" games, the six players were all asked at the same time if they wished to pay into the public fund. Nine other groups played firstly eight rounds of "public goods" and then eight rounds of "indirect reciprocity". The students played anonymously under a pseudonym and, as is usual practice in these types of experiments, they received actual cash payments in line with their final bank balance.

The graphics below on Page 10 illustrate the result: the groups that started off by playing eight successive rounds of the "public goods" game initially behaved, as expected, in a cooperative manner, but this cooperation soon broke down. In contrast, those groups that played alternating rounds of "public goods" and "indirect reciprocity", maintained their high level of cooperation right up to the 16th round. A player who did not contribute to the public fund received little support in the subsequent round of the "indirect reciprocity" game and therefore cooperated once again in the next "public goods" game. In this way, the students receive large payments at the end of the game. In contrast, the view that cooperation in the "public goods" game would be the best for all parties involved, does not suffice on its own to maintain the initial cooperation throughout the block of eight rounds of the "public goods" game. Manfred Milinski explains the results: "The effects of these findings on human society will not, of course, result in all parties behaving in a purely cooperative manner at the next world climate conference. However, it is certainly beneficial for states or social groups to interact in as diverse a manner as possible. On the other hand, we must also be wary of the unknown "tragedies of the commons" which only clearly emerge as such when other interactions, for example between states, break down, where previously cooperation between the parties has been maintained."

Games in the name of research: Manfred Milinski during the experiments with the students.

Cooperation (in percent) within the groups during the 16-round test. The dots represent the "public goods" game, the circles the "indirect reciprocity" game (see text for more detail).



GRAPHICS: MPI FOR LIMNOLOGY / PHOTO: WOLFGANG FILSER

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QUANTUM OPTICS

Ultracold Atoms are Captured in an Optical Lattice

Researchers at the Max Planck Institute for Quantum Optics in Garching, the Ludwig Maximilian University in Munich and the ETH Zurich have produced a new state of matter close to the temperature of absolute zero (NATURE, 3 January 2002). Using a three-dimensional light crystal, the scientists succeeded in converting a superfluid Bose-Einstein condensate into a so-called Mott insulator state and back again. In a Bose-Einstein condensate, the atoms are spread out over the entire lattice in a wave-like manner, whilst in the Mott insulator they are localized at individual lattice sites with an exact number of atoms and, in this way, form a particle lattice.

The state was first predicted by the physicist Sir Neville Mott within the framework of metal-insulating transitions in solids. Among other accolades, Mott was awarded the Nobel Prize for Physics in 1977 for this work. The Mott insulator that has now been produced at absolute zero (at 10 nanokelvins) enables fundamental questions of solid-state-physics, quantum optics, and atomic physics to be investigated in an ideal manner and opens up new perspectives for quantum computing.

In 2001, the Nobel Prize for Physics was awarded for pioneering work on the production of Bose-Einstein condensates (MAX PLANCK RESEARCH 1/2002, pg. 62ff). In this type of condensate, at temperatures close to absolute zero, all atoms lose their individuality. A wave-like state of matter is created, that can be compared in many ways to laser light. Using this type of atomic Bose-Einstein condensate as a starting point, it has now been possible to reach a new state of matter in atomic physics.

In order to achieve this, the scientists stored a Bose-Einstein condensate in a three-dimensional lattice of microscopic, tweezer-like laser light traps. By changing the light intensity of this lattice, the researchers were able to dramatically alter the properties of the condensate and induce a transition from the superfluid phase of the Bose-Einstein condensate to a so-called Mott insulator phase. If the light intensity of the lattice in which the atoms are captured is only weak, then all atoms will still remain in the superfluid phase of the Bose-Einstein condensate. In this phase, each individual atom is spread out over the entire lattice in a wave-like manner, as predicted by the laws of quantum mechanics. This atom gas can move freely through the lattice.

However, when the researchers increased the intensity of the optical lattice, they were able

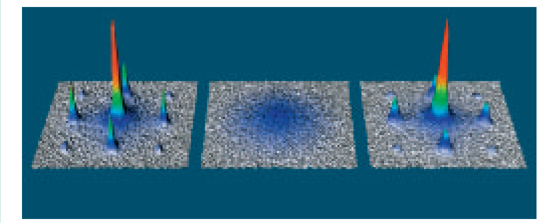

Fig. 1: The matter wave interference pattern of a quantum gas stored in a three-dimensional optical lattice with more than 100,000 occupied lattice sites. From left to right: high-contrast interference pattern in the superfluid regime of a Bose-Einstein condensate; interference pattern following a quantum phase transition into a Mott insulator without phase coherence; restored coherence following a quantum phase transition from a Mott insulator back to a Bose-Einstein condensate.

FIG.: MPI FOR QUANTUM PHYSICS

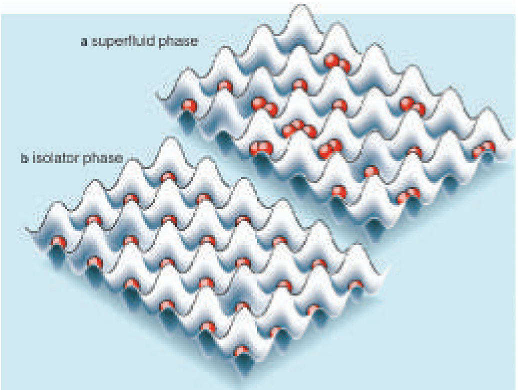

Fig. 2: A quantum phase transition in an ultracold gas. Superimposed laser beams create an optical lattice which forms a potential mountain with peaks and valleys. The gas, consisting of rubidium atoms, can be reversibly crossed between the superfluid and the insulator phase. a) At a temperature of only a few nanokelvins, all atoms find themselves in the same quantum state and form a superfluid phase where they are able to switch freely between the valleys. b) If the intensity of the laser beams is increased, the gas will move into an insulating phase where each atom is "captured" at its own lattice site. This control possibility is essential for achieving quantum computing.

FIG.: NATURE

to observe a transition of the superfluid condensate into an insulating state, with an exact number of atoms at each lattice site (Fig. 1 and 2). In this case, the movement of the atoms through the lattice is blocked due to the repulsive interaction between them. The physicists Markus Greiner, Olaf Mandel, Tilman Essingler, Theodor W. Hänsch, and Immanuel Bloch have demonstrated in their experiments that the phase transition between the superfluid and the Mott insulator phase can take place in both directions.

This transition is called a quantum phase transition, as it can take place at temperatures of absolute zero. The transition between the phases occurs as a direct consequence of the quantum fluctuations predicted by Heisenberg's uncertainty relation, as all thermal fluctuations, which normally create a phase transition, are then already "frozen out". With these experiments, the researchers in Munich have succeeded in opening up a new chapter in the physics of ultracold atoms. "With this experiment we are taking a significant step beyond a Bose-Einstein condensate", says Immanuel Bloch. "In the Mott insulator state, the atoms can no longer be described using the highly successful theory for Bose-Einstein condensates, but as a result of their interaction need instead to be described using new theories. The experiments provide valuable impetus for the development of these further theories.

The new Mott insulator state will help the scientists to explain fundamental questions concerning the physics of strongly correlated systems, which among other things form the basis for our understanding of superconductivity. Furthermore, the Mott insulator state opens up a variety of new perspectives for high-precision matter-wave interferometry and quantum computing. ●

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LIMNOLOGY

Water Fleas Have Perfect Timing

Water fleas influence the readiness of their parthenogenetically produced offspring to reproduce bisexually and to form resistant resting eggs. Scientists from the Max Planck Institute for Limnology in Plön have discovered that female water fleas transmit information on the feeding conditions and photoperiod in which they live to their female offspring during embryonic development (NATURE, 20 December 2001). This allows the next generation to adapt its reproductive strategy to the seasons in the most effective manner.

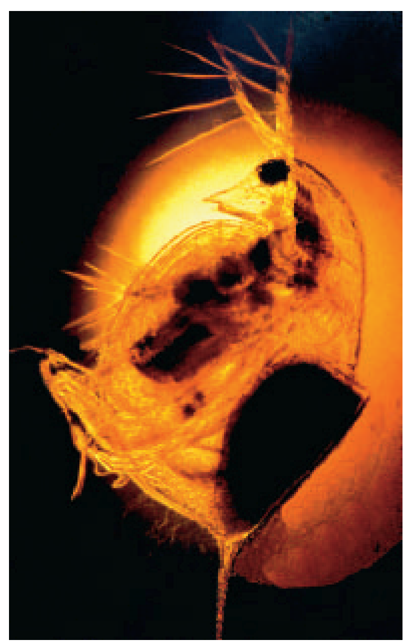

PHOTO: MPI FOR LIMNOLOGY

A female Daphnia sheds a saddle-shaped structure (ephippium) that it has formed on its brood pouch. The ephippium contains two resting eggs produced by bisexual reproduction – a form of reproduction that only occurs rarely in Daphnia. In unfavourable conditions, the ephippium can survive for decades before new Daphnia emerge from the resting eggs.

Critical view of the offspring: Winfried Lampert checks the development of the water fleas.

PHOTO: WOLFGANG FILSER

Water fleas (Daphnia) play an important role in freshwater lake communities. Their ability to assert themselves within this ecosystem is primarily due to their flexible method of reproduction: during parthenogenetic reproduction, the number of formed embryos is controlled, they can form resting eggs and alternate between unisexual and bisexual reproduction. As a result of their ability to reproduce parthenogenetically, they can be easily cultivated as clones (i.e. a group of genetically identical individuals). This characteristic has made them into a closely studied model organism in aquatic ecology. The scientific investigations focus on the strategies employed by these extremely short-lived organisms (Daphnia live only a few weeks) to adapt their life cycle to changing environmental conditions.

At specific times, female water fleas switch to bisexual reproduction. A saddle-shaped structure (ephippium) containing two resting eggs then develops on the brood pouch of the female water flea. If environmental conditions are unfavourable, these eggs can survive for many years, settling for instance in lake sediments. Resting eggs are mainly formed during late autumn, as the feeding conditions for Daphnia significantly deteriorate at this time of year. The switch from parthenogenetic egg production to bisexual reproduction requires various cues from the environment.

The researchers were interested in discovering which environmental stimuli were decisive for the precise "timing". On the one hand, the switch in the reproduction cycle must take place before it is too late for the water flea population and they risk death from food shortage; on the other hand, it would be extremely ineffective if the female were to react to short periods of food shortage or cold spells in summer by switching to resting egg production.

Viktor Alekseev, guest researcher from St. Petersburg, and Winfried Lampert from the Max Planck Institute for Limnology in Plön, have now discovered a mechanism that explains why the production of resting eggs can occur in phases both in late spring and in autumn. In controlled laboratory experiments, the largest quantities of resting eggs were produced by the offspring when the mother had a plentiful food supply, but the offspring had only little food, and both generations lived in short photoperiod conditions (i.e. 10 hours light/14 hours darkness) at the same time. This situation only exists outdoors in autumn, when massive-scale resting-egg production actually takes place.

The laboratory results also explain the occasional occurrence of a second phase of resting-egg production in spring: in this case, the filtering action of the Daphnia can produce a "clear water stage" in the lake and can also lead to a food shortage. When the second generation lives in conditions where the food supply is abundant, then no resting eggs are ever produced. The readiness of the offspring to produce resting eggs is therefore not only significantly influenced by their own environment, but also by the food and light conditions (photoperiod) in which their mother has lived. Female water fleas transmit this information in a manner that is still unknown. The transmission of environmental information to the next generation is an interesting opportunity for short-lived organisms to adapt their life cycle to environmental conditions in the most effective way: these "maternal effects" are becoming an increasingly exciting subject for evolutionary ecology. ●

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SOLID STATE RESEARCH

First Steps towards Spin Electronics

In spin electronics, scientists are planning to use not only the electrical charge, but also the self-rotation (spin) of the electrons and the atomic nuclei for processing and coding information. Researchers from the Max Planck Institute for Solid State Research in Stuttgart and the Garching Walter Schottky Institute of the Technical University Munich, have succeeded in measuring and controlling the spin interaction between free electrons and atomic nuclei by means of purely electrical methods using a complicated field-effect transistor arrangement (NATURE, 17 January 2002). These results open up new perspectives for the research on nuclear and electron spin interactions in nanostructures, and also for new information technology concepts.

Semiconductors are extensively used in the fields of electronics and information technology, as the free charge carriers, which are responsible for their conductivity, can be flexibly manipulated or transported back and forth using an applied voltage to perform logical switching operations. However, in the longer term, the spin of the electrons, and even that of the individual atomic nuclei, may become increasingly important in information technology. Spin is a quantum mechanical property of elementary particles. It can be viewed in a simplified form as a rotation around their own axis – either in a clockwise or anti-clockwise direction.

Experts use the terms "spin up" and "spin down". As only two elementary spin directions are possible, it seems reasonable to assume that these can be used as binary information carriers. Hard disks are everyday examples of how spin can be "flipped" from one direction to the other using magnetic fields to store digital information.

We would derive particular advantages from being able to electrically influence the spin direction of elementary particles in an arbitrary manner – just like the charge carriers in semiconductors – through the application of voltages alone. We would then expect to achieve more efficient components which could combine several functions simultaneously, such as storage, logic, and communication for data processing. The use of manipulated spin for so-called quantum computing is still very much a concept for the future and has so far been the subject of speculative and controversial debate. In quantum computing, both spin states would no longer serve only as "0" or "1" of a standard bit. The quantum mechanical superposition of both spin states produces a quantum bit, in which a continual variation of the spin direction is possible. Computers that are based on these principles could achieve a high level of parallel processing for some specific problems.

Researchers in this field are already advertising search algorithms, which would be of practical significance for carrying out an exhaustive search of large databases, as well as algorithms for determining prime numbers. The boldest proposals, which are not yet achievable in technical terms, are based on mobile electrons in nanostructures made from semiconductor materials which can be controlled using electrical voltages and could sound out and manipulate the spin of isolated atomic nuclei.

These visions for the future have triggered a worldwide race towards new technology which would enable us to control and detect the direction of nuclear spin using mobile charge carriers in the smallest components achievable. However, progress will only be made when we know more about the microscopic interactions that take place between the electron spin and the atomic nuclei in these nanostructures and if we succeed in controlling these spins externally.

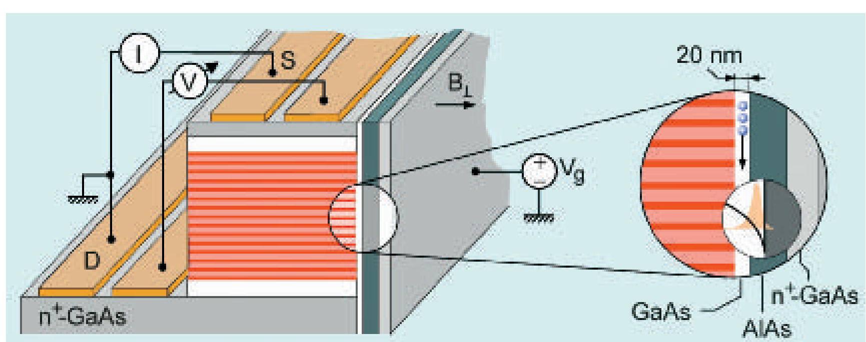

Fig 1: Schematic diagram of the device used by Jurgen Smet at the Max Planck Institute for Solid State Research. This device was developed and perfected by scientists working with Gerhard Abstreiter at the Walter Schottky Institute of the Technical University Munich. The technically refined electronic device functions essentially like a classic field-effect transistor. Through the application of a control voltage, electrons are able to fill a 20-nanometre thin channel, so that a current can flow between the source and the drain contacts. The movement of the electrons is restricted in two spatial directions and the amplitude of the gate voltage determines their density.

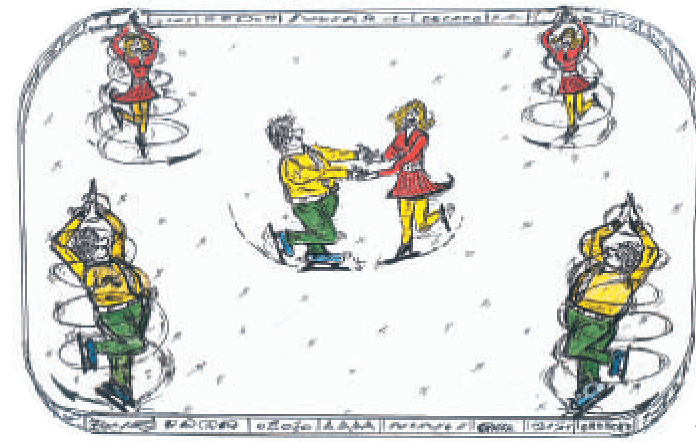

Fig. 2: A cartoon portrayal of flip-flop scattering between electrons and atomic nuclei. The ice skaters – electrons and atomic nuclei – exchange their spin direction on approaching each other. The maintenance of energy conservation is essential for this process.

FIGS.: MPI FOR SOLID STATE RESEARCH

Jurgen Smet and his colleagues at the Max Planck Institute for Solid State Research in Stuttgart are working on these fundamental questions, together with scientists from the group led by Gerhard Abstreiter at the Garching Walter Schottky Institute of the Technical University Munich. They have now jointly succeeded in determining, by measuring the electrical resistance, the strength of the spin interaction between the electrons and atomic nuclei of a semiconductor crystal subjected to an external magnetic field (Fig. 1).

A certain number of electrons is confined in an extremely thin channel of a field-effect transistor by means of a control voltage. At the same time, the amount of resistance encountered by these electrons is monitored. Scientists had previously already been aware of the fact that in certain circumstances electrons, which are restricted to moving in a two-dimensional plane, sense only a very low level of resistance. In this case, a simple correlation exists between the external magnetic field and the number of electrons: the so-called quantum Hall effect. However, the Stuttgart researchers have now discovered that the quantum Hall effect breaks down at a specific number of electrons (i.e. a specific control voltage) and that the alignment of the nuclear spin in the semiconductor crystal is crucial to this number of electrons needed to destroy this quantum Hall effect.

The researchers are exploiting this influence of the nuclear spin polarization on the electrical conductivity of the transistor as a type of "probe". By carrying out time-dependent resistance measurements, they succeed in obtaining precise information on the nuclear spin states. They can analyse the strength of the interactions between electron and nuclear spins. If the control voltage, at which the quantum Hall effect vanishes, quickly alters with time, the interaction is strong, and weak if this is not the case.

The information extracted from such time resolved measurements put the scientists in Stuttgart in a position to distill the appropriate conditions under which electrons and nuclei like to exchange their spins. The nuclear and electron spin mutually influence each other through the so-called "hyperfine interaction". This interaction allows a pair of spins to undergo spin-reversal or "flip-flop", whereby an electron can "flip" its spin by simultaneously "flipping" a nuclear spin in the other direction (Fig. 2).

This "flip-flop" process can only take place when the total energy is conserved. A thousand times more energy is usually required for "flipping" an electron spin than for reversing a nuclear spin.

Under normal circumstances, this discrepancy prevents flip-flop scattering. The spin exchange between the electrons and atomic nuclei in a crystal lattice is prohibited or at least takes place at an extremely slow speed. In other words, electron spins and nuclear spins are normally well isolated from one another. However, the Max Planck researchers have now proved that electrons flip their spin rapidly without significant energy supply if they occur in a specific number.

This phenomenon is based on a highly complex collective interaction of these electrons under the influence of the repulsive Coulomb forces between like charges, as well as on the tendency of neighbouring electrons to assume the same spin direction. The low-energy collective excitations of the electrons then enable their spin to be exchanged with that of the atomic nuclei of the crystal.

The flip-flop scattering is suppressed at a control voltage or an electron number where no such low-energy collective excitations exist. The interaction between nuclear and electronic spins can thus be turned on or off at will, merely by choosing an appropriate sequence of voltages. Through the ability to electrically manipulate nuclear spin, the Stuttgart scientists have reached an important milestone on the path towards spin electronics. ●

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