Heaven on Earth

Bringing the heavens to the lab is difficult. Setting up the heavens in the lab, on the other hand, is a bit easier. That's exactly what researchers working with **Andreas Wolf** are doing. At the **Max Planck Institute for Nuclear Physics** in Heidelberg, they reproduce chemical reactions that take place in distant interstellar clouds.

TEXT **THOMAS BÜHRKE**

The Test Storage Ring (TSR) has been in operation at the Max Planck Institute for Nuclear Physics for some 20 years now. It is a racetrack of sorts, with a 55-meter circumference, on which charged particles race around, guided by magnets. Compared with its big brothers, such as the new super-accelerator LHC at the European particle physics lab in Geneva, the TSR is quite modest. But by no means is it ready for the scrap pile yet – quite the contrary. Equipped with sophisticated technology, the apparatus continues to deliver excellent measurement data.

A few years ago, for instance, physicists in Heidelberg used the storage ring to test Einstein's theory of relativity with unparalleled precision (MaxPlanckResearch 2/2004, page 20 ff.). And for Andreas Wolf's research group, the TSR has also been serving a very different purpose for several years: the study of chemical and physical reactions that lead to the formation of molecules in space.

The most productive chemistry labs in space are giant clouds composed of gas and dust. In photos, they make a very dense impression: they appear to be impenetrable, and attenuate the light of stars located behind them. Nevertheless, with an average of 10,000 particles per cubic centimeter, the densities are much lower than in a cleanroom lab on Earth. It is the clouds' enormous expanse of several light-years that makes them opaque to light.

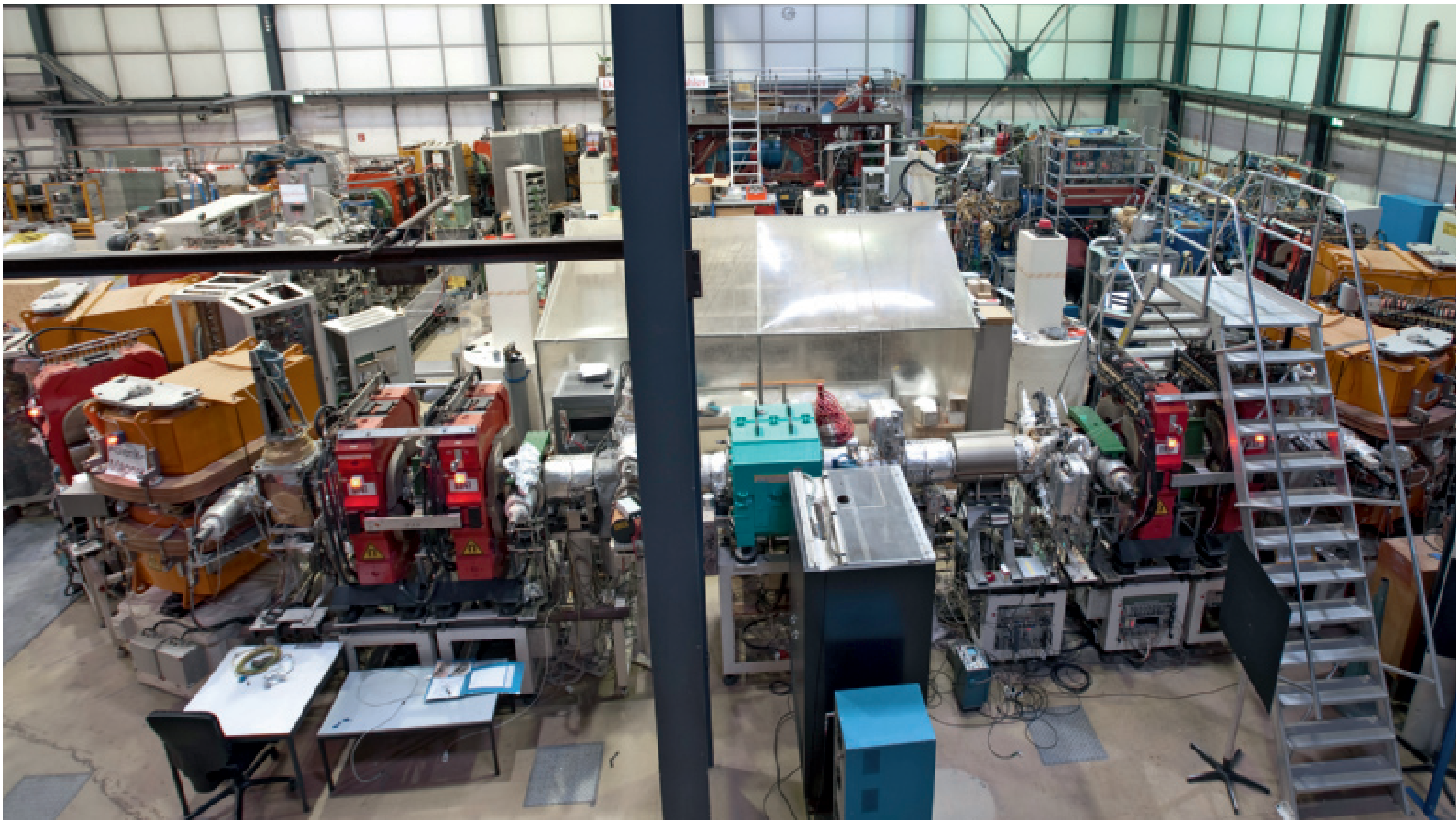
MOLECULES CONTRIBUTE TO STAR FORMATION

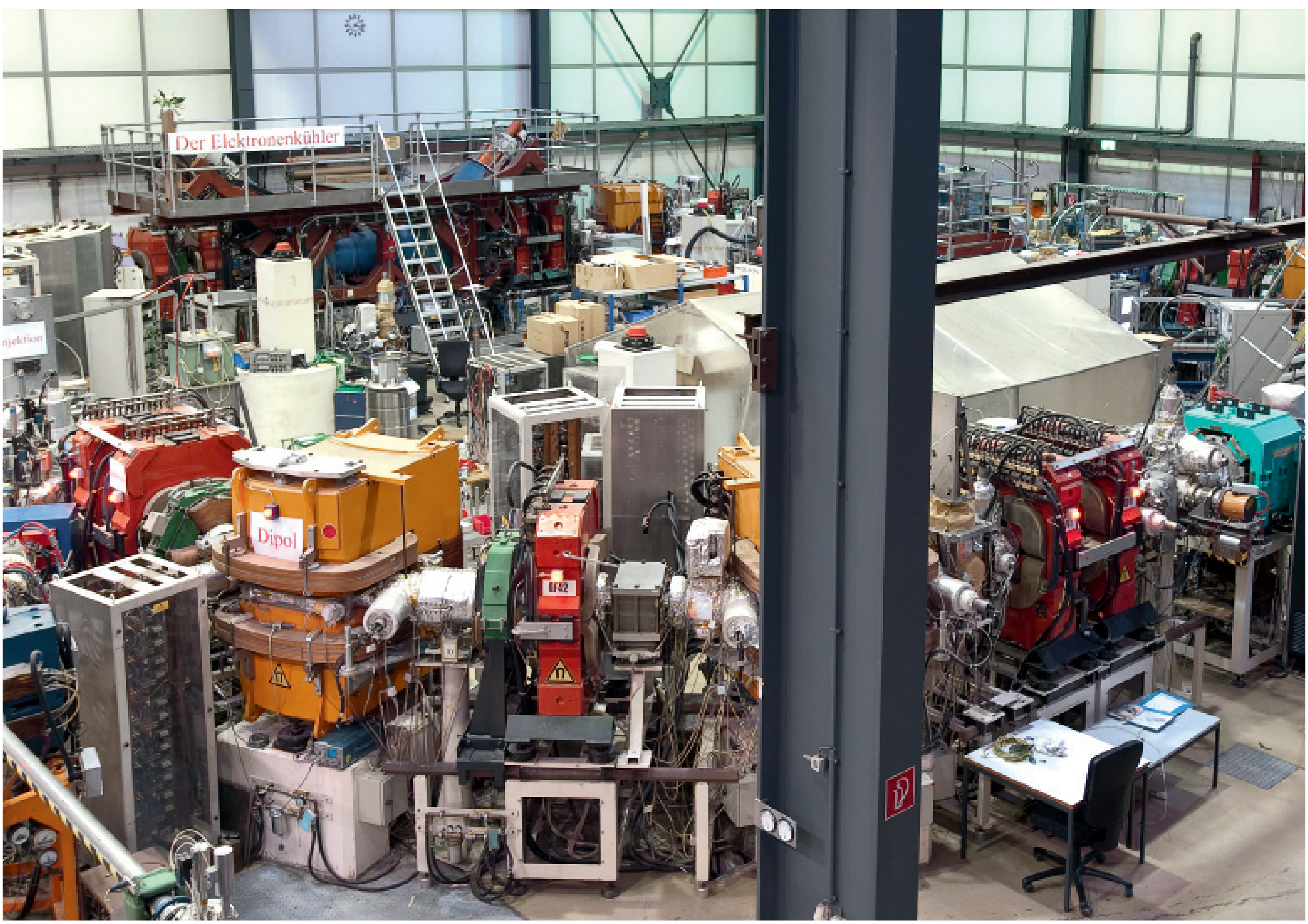
These clouds of gas and dust are the birthplaces of stars and the production plants of molecules. In recent decades, astronomers have discovered a great variety of molecules there. Today, they know of some 150 species, from simple compounds, such as the hydroxyl radical (OH), water (H_2O) and carbon monoxide (CO), to such complex organic substances as glycolaldehyde (CH_2OHCHO), a sugar, and ethylene glycol ($HOCH_2CH_2OH$). The search for glycine, the simplest amino acid and one of the basic building blocks of DNA, is running at full speed worldwide.

The interstellar molecules intervene in cosmic activities in various ways. For instance, in the formation of many molecules, energy is released in the form of radiation and discharged into space. This causes the cloud to cool down and contract further – a process that is necessary in order for the matter to ultimately be able to coalesce to form stars. This also raises the question of whether the organic molecules involved here played a causal role in the formation of life on Earth.

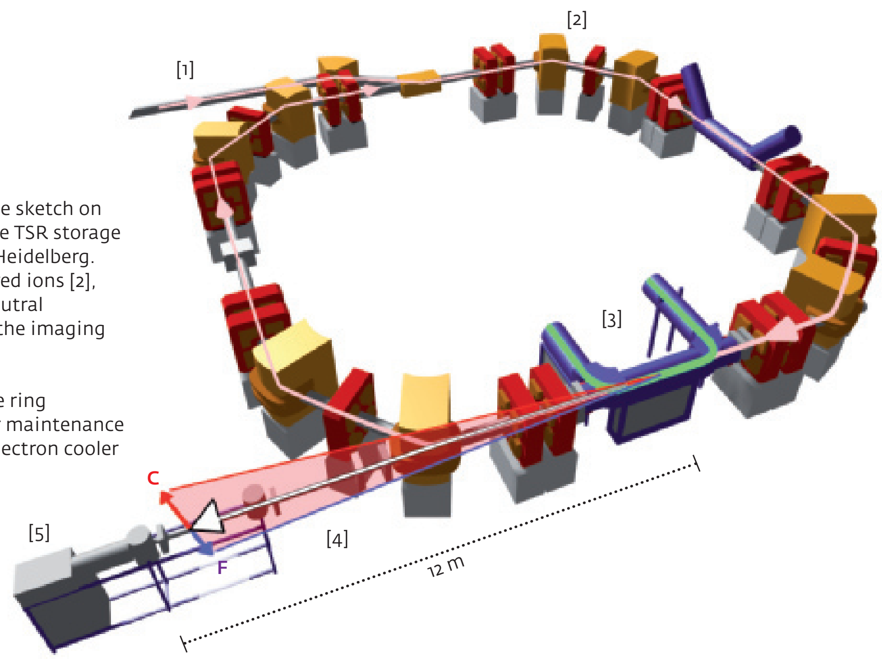
Molecules can form in space in two ways: for one, atoms and molecules accumulate on dust particles and react there with other atoms. For another, these particles collide with each other and aggregate in free space. "We are using the storage ring to study such gaseous-phase reactions," says Andreas Wolf. >

A glimpse of a delivery room for stars: Cold interstellar clouds – in this image the Eagle Nebula – are home to a complex network of chemical reactions. Researchers are trying to decode this network in their terrestrial labs.





Der Elektronenkühler
Dipol



right: Molecular dissociation upon electron capture: The sketch on the right shows what happens at various stations in the TSR storage ring at the Max Planck Institute for Nuclear Physics in Heidelberg. Injection of CF+ ions [1], magnetic deflection of the stored ions [2], merger with the cold electron beam [3], dissociating neutral fragments following electron capture [4]. At the end is the imaging detector [5].

left: The interior of the building that houses the storage ring resembles a shop floor. All parts are freely accessible for maintenance work or for installing experiments and detectors. The electron cooler can be seen in back in the bottom image.

At first glance, the idea seems paradoxical. Prevailing temperatures in the molecular clouds are around 10 Kelvin (minus 263 degrees Celsius), so that the atoms and molecules there move very slowly. In the TSR, however, the particles circulate at around 20,000 kilometers per second, which is about 7 percent of the speed of light. That is why a trick is needed in order to imitate certain interstellar reactions in the TSR.

What reaches the storage ring are positively charged ions – atoms or molecules that have lost an electron from their shell. One section of the storage ring contains an electron cooler. This is where electrons are fed in at a very specific speed. They accompany the ion beam for nearly two meters before being guided back out of the ring. In this electron bath, the particles collide and influence each other with their electrical forces.

As a result, ions that are faster than the electrons are slowed down, and slower ones are sped up. In this way, the particle speeds gradually align with one another. This happens for each revolution, or several hundred thousand times per second, until finally all electrons and ions are traveling at nearly the same speed.

A COLD BEAM MADE UP OF A HUNDRED MILLION IONS

If we imagine riding on one of the ions, the surrounding electrons would appear to be hardly moving at all. This is the same phenomenon we experience on the highway when two vehicles are traveling alongside each other at nearly the same speed. This almost negligible relative speed means, from a physics perspective, that ions and electrons together form a surprisingly cool gas – just like in an interstellar cloud at a temperature near absolute zero, or minus 273.15 degrees Celsius (0 Kelvin). For this reason, physicists also refer to it as a cold beam, which, in the TSR, can contain as many as a hundred million ions.

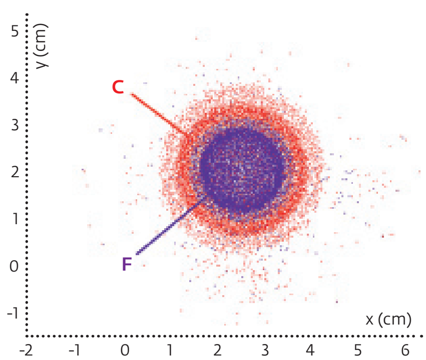
As if that weren't enough, in the TSR, not only can ions and electrons be brought to the same speed, but they can also fly past each other at almost any speed. "We use this to simulate different temperatures at which the reactions take place," explains Wolf. This is based on the physical notion that atoms and molecules move increasingly quickly as temperatures rise.

However, the electrons are not only responsible for cooling the ion beam – they are simultaneously their reaction partners. In other words, in the TSR, Wolf and his colleagues do not reproduce just any reactions, but exclusively electron attachments. These, however, play an important role in the web of interstellar chemistry. A key position here is that held by the H_3^+ ion. On one hand, it can react with an oxygen atom and then form a water molecule in later steps. If, instead of the oxygen, it reacts with a carbon atom, then this can entail complex organic molecules. "The H_3^+ ion is located at a central branch of the reaction tree," says Andreas Wolf.

Theorists had long wondered what happens when an H_3^+ ion takes on a negatively charged electron. In a naive view, one would suspect that the two particles join to form a neutral H_3 molecule, because opposite charges attract. But it isn't quite that simple. Whether an electron can attach or not

1 | With a circumference of 35 meters, the cryogenic electrostatic storage ring is more compact than its predecessor. The first components – in the image a portion of the outer shell – are already being mounted. The new storage ring is set to go into operation in 2012.

2 | Fine-tuning the detector: Michael Lestinsky from Columbia University, New York, regulates the electronics for counting individual ions.



Composite image of the impact sites of C and F atoms in many thousand individually detected molecular dissociation processes. The size of the ring shows the fragments' kinetic energy that is released upon dissociation.

depends on whether the electrons can take on an appropriate state in the attachment process.

Theorists concluded, following calculations of electron energies, that such a "gateway" does not open up for cold electrons at H_3^+, and the attachment process should thus occur extremely rarely in space. "Based on their observations, astrophysicists have long been skeptical about this statement," says Wolf. That is why the Max Planck researchers in Heidelberg decided to study this reaction in the TSR.

ENERGY CAUSES MOLECULES TO SPIN LIKE TOPS

The experiment required the production of an extremely cold H_3^+ gas. Wolf's colleague Holger Kreckel took on this task. He built a device that allowed ions to be trapped in an electromagnetic field. Then they were cooled with helium to temperatures found in space, and only then guided into the TSR. The result left no doubt: the experiments produced much higher attachment rates than predicted. What had the theorists forgotten?

When considering chemical reactions, one normally focuses on what happens in the electron shells of the participating atoms or molecules. In reality, however, there is more going on: when an electron approaching from outside begins to penetrate the electron shell of a positive ion, it has already gained kinetic energy. It must release this energy if it wants to remain in the molecule. The experiments permit only one explanation: a portion of this energy sets the molecule's nuclei in motion, causing it to spin like a top. While the theorists were hesitant to consider this process, the results confirm its existence and, in fact, its crucial importance for the attachment of cold electrons.

The second thrust of the Heidelberg experiments is clearly evident here: not only astrophysics will benefit from the results, but also the quantum physics description of atoms and molecules. And it goes even further: As already mentioned, in the TSR, it is possible to set the speed difference with which electrons and ions fly past each other. In this way, it is also possible to define how much energy the electrons transfer to the ions upon attachment.

When Wolf and his colleagues then varied this energy within a certain range, they noticed that the attachment rate did not change continuously, but rather exhibited maxima and minima. Again, quantum physics provides the explanation: while a humming top can spin at any speed, a molecule can change its speed only stepwise – in quanta. Any time an elec-

Graphic: MPI for Nuclear Physics (left), photos: Andreas Varnhorn (2, right)

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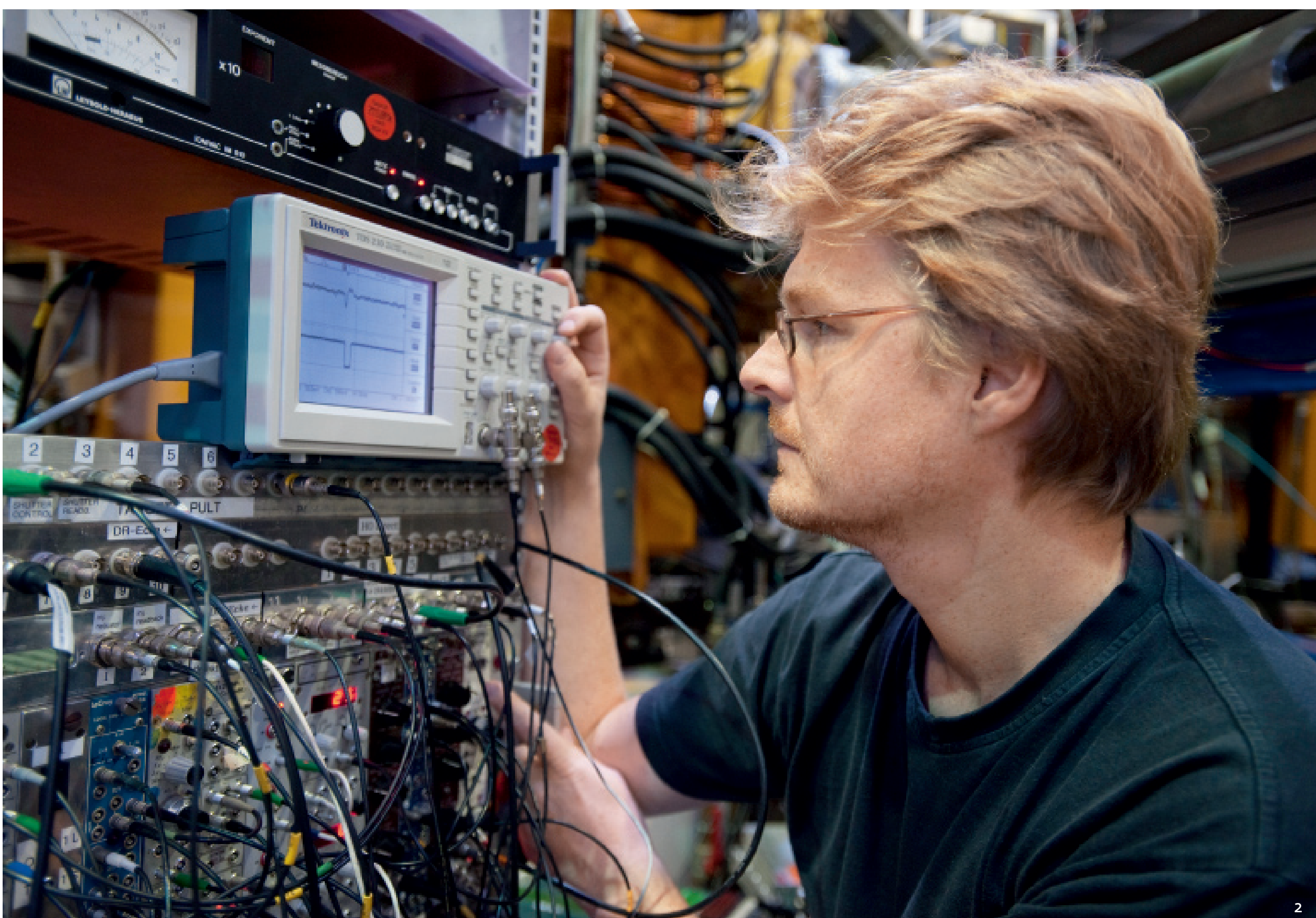

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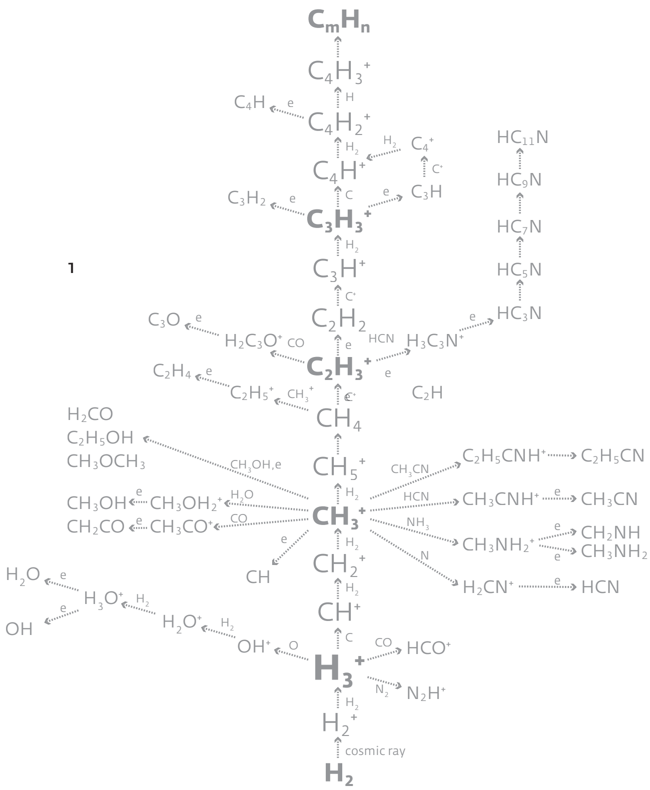
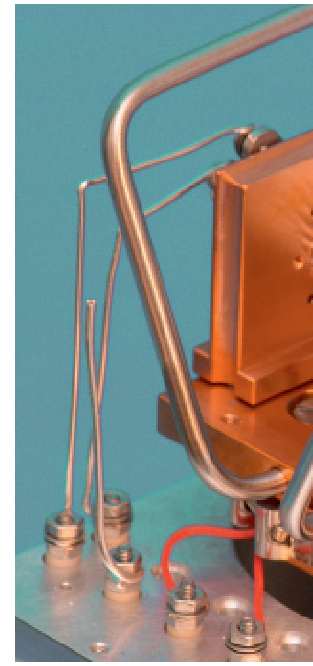


1 The H_3^+ ion is located at a central site of the tree-like structure of chemical reactions. In this way, it can, for instance, take on an oxygen atom and then, in further steps, form a water molecule. If, instead, it takes on a carbon atom, then complex organic molecules can form.

2 The ion trap for cold H_3^+ ions is an important aid for preparing cold molecules at the storage ring at the Max Planck Institute for Nuclear Physics in Heidelberg.

3 Andreas Wolf and his team bring the heavens to the lab, studying quantum physics effects in the process.



tron carries precisely the right excitation energy for the rotation, the attachment rate increases.

Wolf's experiments thus contribute to a complete quantum physics description of molecules. And a difficult one it is – already failing for even the simplest molecules, such as H_3^+. However, the researchers attach such great importance to this that they have, in recent years, organized several conferences specifically on this topic.

WATER SUPPLIER FOR THE COSMIC NETWORK

But electron attachment has yet another consequence: it destroys the molecule. Since the approaching electron transfers to the nuclei most of the energy released when it becomes bound, the molecule splits. As a result, an H_3^+ ion yields, for instance, an H_2 molecule and an H atom. The chemical composition of the products can easily be measured in the TSR.

Magnetic fields force the positively charged H_3^+ ions into their orbit in the TSR beam tube. Fragments such as H_2 and H, however, are electrically neutral, so they don't react to the field, and fly out of the storage ring. Last year, Wolf's group installed a detector here known as the EMU (energy-sensitive multistrip detector), which measures the mass and momentum of the penetrating particles. EMU was created in collaboration with colleagues from the Weizmann Institute in Rehovot, Israel.

With up to a thousand "images" per second, EMU can now register the momentum and molecular mass of all products for individual dissociation reactions – a major technological feat. This data can be used to reconstruct the processes that occur when electrons are attached, and when the molecule subsequently breaks apart like balls on a billiard table.

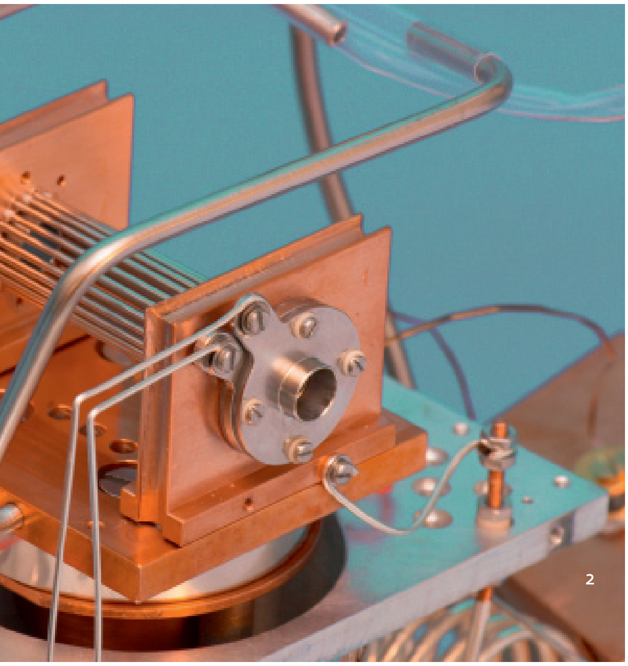
Andreas Wolf and his colleagues used this method to study a number of attachment reactions. One of the most recent examples is the hydronium ion H_3O^+. It is particularly interesting because, in electron attachment, it can decay into H_2O and OH, and is thus – at temperatures near absolute zero – one of the cosmic suppliers of water. The matter is complicated by the fact that it can also break into other fragments, such as OH plus two H atoms or O plus H plus H_2. This array of decay possibilities makes analyzing the EMU data a difficult puzzle. However, it can be solved. The result: in 20 percent of all decays, H_3O^+ yields water. What was surprising here was that the molecules are highly energetically excited. "In a sense, cold collisions create hot water," explains Wolf.

MANY FINGERPRINTS, BUT NO MATCHING CULPRIT

These findings contribute to sky research in two ways. On one hand, the measurement data become parameters in computer models with which the complex network of reactions in interstellar clouds are calculated; and on the other, they serve to identify molecules. Astronomers detect them with the help of their spectra. Particularly in the infrared and radio range, the various species make themselves known through an abundance of emission or absorption lines at very specific wavelengths – they leave behind characteristic fingerprints, as it were.

Identification is possible only by comparing these lines with lab spectra. However, many lines still cannot be matched to any known types of molecules. Some of them could stem from highly excited molecules that are released upon cold electron attachment to a parent molecule. That, at least, is what the Heidelberg experiments show.

Graphic: Illustration based on original material from B. J. McCall, Univ. of Illinois, Urbana, USA



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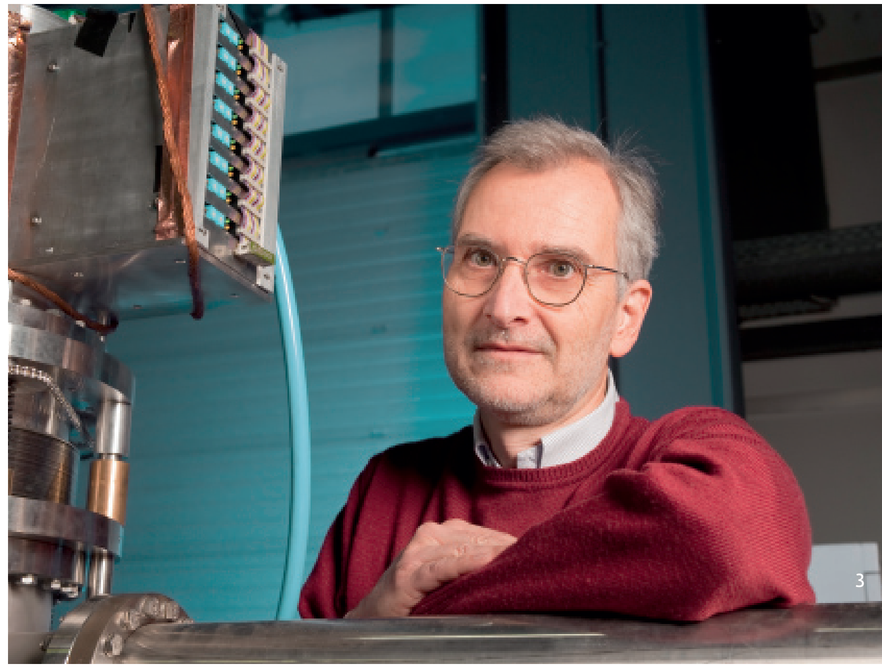

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Furthermore, there are even implications for biology. A few years ago, a team of scientists from Canada and the US found indications that the carrier of genetic information, the DNA molecule, can break apart when it takes on electrons. Here, too, it seems that, for reasons related to quantum physics, certain energies are preferred. The TSR experiments confirm this hypothesis.

But the experiments at the Max Planck Institute for Nuclear Physics are not possible with such large biomolecules, because the TSR can store only ions with a maximum mass of about 40 atomic mass units (abbreviated u). For comparison, the H_3O^+ ion has 19 u, and ethylene glycol ($HOCH_2CH_2OH$) already comes in at 62 u. Andreas Wolf wants to overcome this mass limitation with a new storage ring. The cryogenic electrostatic storage ring (CSR) will be more compact than its predecessor, with a circumference of 35 meters. But what really makes it stand out is its ability to cool to 2 Kelvin using liquid helium. This will make it possible to store molecular ions with larger masses, up to biological macromolecules. Cold electron attachment experiments will be possible for molecules measuring up to 160 u – not for DNA, but amino acids are well within reach.

A test facility has already made sufficient progress that it can be used for simple quantum physics experiments. Wolf anticipates the "first beam" in the cryogenic storage ring in 2012. Then, with special detectors, it will also be available to other groups from the Heidelberg-based institute for their experiments. With its helium cooling, the CSR has one thing in common with the LHC in Geneva. "We approach the technological challenges on the scale of this facility with targeted developments and step-by-step component testing," says Andreas Wolf.

The physicists in the Stored and Cooled Ions Division can thus continue contributing to a better understanding of the complex field of astrochemistry, uncover fundamental quantum physical aspects of molecules, and aid in the search for reliable theoretical models. ◂

GLOSSARY

Electron
An elementary particle with a negative charge. In atoms and molecules, electrons form the outer electron shell and govern chemical reactions.

Ion
An atom or molecule that has lost or gained one or more electrons and is thus electrically charged, either positively or negatively.

Opacity
Opacity (adjective: opaque) is a measure of a material's transparency. The greater the opacity of a substance, the less light is able to penetrate it and the cloudier it appears. In space, this cloudiness is apparent primarily as interstellar gas and dust clouds.

Proton
One of the building blocks of atomic nuclei, with a positive elementary charge. It consists of three quarks and is around 1,800 times heavier than the electron.

The research program came about through the close collaboration between Dirk Schwalm, as the Director of the heavy-ion physics division at the Max Planck Institute for Nuclear Physics until 2005, and Daniel Zajfman, as head of his research group at the Weizmann Institute of Science in Rehovot, Israel. It is based on the collaboration of many former and current members of the working group. Klaus Blaum's Stored and Cooled Ions Division, which was established in 2007, creates the ideal conditions for this research field and is expanding its options by building the cryogenic storage ring (CSR).