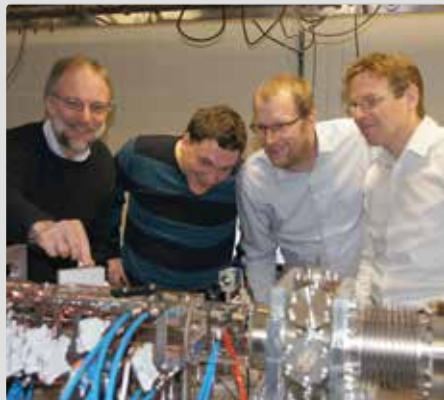


Quantum
physics of
interacting
Rydberg
atoms

Ryding high

Professor Dr Tilman Pfau explores the physics of Rydberg atoms and aims to unlock the benefits of small vapour cells. Here, he describes their current and potential application in quantum devices and some of the challenges his team faces



Pfau with his team members: Dr Sebastian Hofferberth, Dr Robert Löw and Professor Hans Peter Büchler

To start, could you provide some background of what Rydberg atoms are and how you can excite atoms to the Rydberg state?

Highly excited atoms, so-called Rydberg atoms, are quantum objects like normal atoms but with exaggerated properties: they are very large, sensitive and provide a lot of flexibility in the control over their properties. They are readily available at ultra-low temperatures but also room temperature and above, and compared to manmade objects they are perfectly identical, which allows the study of networks of identical nodes. Rydberg atoms can be excited in a coherent way by laser pulses.

What progress have you made in your investigation of Rydberg atoms and molecules?

A fascinating field of research based on Rydberg atoms is Rydberg molecules. We have found novel binding mechanisms for molecules as soon as a Rydberg atom is involved. The new binding mechanism does not fall into the usual categories of van der Waals, ionic or covalent. From the fundamental point of view it is important to understand binding mechanisms that keep things together.

You are now moving from two-body interactions to collective quantum behaviour in many-body physics. Is there a limit to how far you can continue along this path of proliferation?

We want to understand quantum physics stepwise from two to few to many particles. Whether there is a technical or fundamental

limit to this effort is an open question right now. Currently, we investigate collective quantum states involving thousands of atoms. We will try to push the limit.

As the Director of the 5th Institute of Physics at the University of Stuttgart, could you give an insight into some of its latest investigations regarding Rydberg atoms?

From our initial investigations of ultracold interacting Rydberg atoms, we have recently extended the work to Rydberg atoms in vapour cells at or above room temperature. We see that although temperatures are 100 million times higher than in ultracold atoms, the same interaction mechanisms are at work. We hope that this can be used to build quantum devices that do not need refrigeration. If this is so, then there is also potential for integration into photonic circuits.

Is there a possibility that, by choosing Rydberg states through tuning laser parameters, novel states of matter might be created?

Indeed, the character of the interaction between Rydberg atoms can be chosen from dipolar (like between two magnets) to van der Waals (like between two noble gas atoms), and from isotropic to anisotropic. As a consequence, many new states of quantum matter have been predicted, and we are just starting to understand and explore them.

Your team recently fabricated and characterised a device – the electrically contacted vapour cell – which could be used in future applications such as atom clocks or magnetic field sensors. Could you briefly describe this device and how you created it?

To read out the number of Rydberg atoms in a vapour cell, one traditionally uses optical spectroscopy. However for integration in circuits, electrical readout is much more favourable. So we contacted the inside of the cells with transparent electrodes. To our surprise and rather unexpectedly we learned that the electrical readout works even better than optical readout.

What other devices are you planning to create within this focus area?

One of our next goals is the design and characterisation of a deterministic single photon source from our work on microcells. This means a single quantum

of light, the smallest portion of energy is produced on demand.

Do you think the public is familiar with your research field and what would you say should be done to improve awareness?

Quantum physics is thought to be hard to understand and to convey to the general public. In my Institute, we have a tradition which involves going out to present physics in public and invite people and high school kids to our labs. Over the years, we have set up a high school lab where we also present topics related to quantum physics. Our experience is that people lose their mostly negative attitude towards physics as soon as you offer hands-on experiments to them.

A quantum matter

A team from the 5th Institute of Physics at the **University of Stuttgart** is fervently working to elucidate the rich behaviour of Rydberg atoms and establish their potential in the future of quantum devices

FOR MOST PEOPLE, quantum computing is a strange concept that sits in the grey area between reality and science fiction, but for quantum physicists it is the business of day to day life. A future of quantum computers is fast approaching. Scientists are looking at a range of quantum objects as potential candidates for the central communicative nodes within these devices. One of the most promising candidates are Rydberg atoms; suitable atoms in a highly excited state. They are very large and have hugely exaggerated properties. In the world of quantum physics they are strange objects and a subject of notable research.

A team led by Professor Dr Tilman Pfau at the 5th Institute of Physics, University of Stuttgart is studying the creation and behaviour of interacting Rydberg atoms. In doing so, they are increasing our knowledge of these quantum objects as a candidate for future quantum devices. While the group has clear objectives and the research at the Institute is subdivided into a range of projects, the overarching aim is impressively ambitious: "We want to push the limits of experimental quantum physics, from fundamental questions about quantum phenomena to applications of quantum devices," explains Pfau.

Rubidium plays a central role in the group's investigations. It is an alkali atom which is a suitable candidate for Rydberg excitation as it has only one electron in its outer shell. The researchers excite rubidium to the Rydberg state using lasers. Once in this state, the Rydberg atom shows dramatically exaggerated behaviours. For example, the polarisability of the atom and its size causes

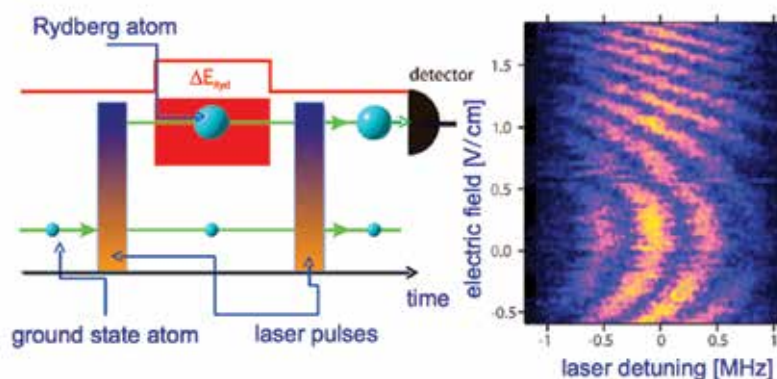
some groups of Rydberg atoms to interact via van der Waals forces. In contrast to normal atoms, the strength of those forces is of the order of 10 billion times stronger than the same bonding between atoms in their normal state.

EXAGGERATED BEHAVIOUR

This example of the increase in the strength of van der Waals forces illustrates the scale of the behavioural change in the atom when excited to the Rydberg state, but it is far from the complete picture. Perhaps more important are the changes in atomic

Perhaps the most startling discovery made by Pfau's group has been the identification of an entirely new form of atomic bonding

sensitivity: "Rydberg atoms are large atomic quantum antennas and therefore sensitive to external fields but also to the presence of other Rydberg atoms," highlights Pfau. This makes these curious atoms suitable for use in detailed sensing devices, for example in the detection of electrical fields. Interestingly, Professor Serge Haroche – joint winner of the 2012 Noble Prize in Physics – was able to show that Rydberg atoms are so sensitive they can detect the presence of a single photon. Such incredible sensitivity coupled with strong bonding between atoms identifies Rydberg atoms as candidates for quantum computing:



Rydberg atom interferometry: ground state and Rydberg atoms interfere in a so-called Ramsey interferometer for Rydberg atoms (left). The interferogram (right) shows a phase shift due to an applied electric field and proves the coherence of the excitation.

"This is the basis for applications in quantum information processing, where networks of interacting nodes are required," enthuses Pfau.

While researchers like Haroche and Pfau are significantly contributing to our knowledge of these strange atoms, there is far more that lies undiscovered. The Stuttgart team is now in the process of studying the detailed behaviour of the Rydberg atom individually and in networks at different temperatures. They are particularly interested in building up a picture of the coherence between atoms across a range of temperatures and in coalition with various surface materials and coatings. By doing so, they may be able to identify materials or processes which improve the coherence of Rydberg atomic networks and thus their suitability in quantum devices.

REWRITING THE TEXTBOOKS

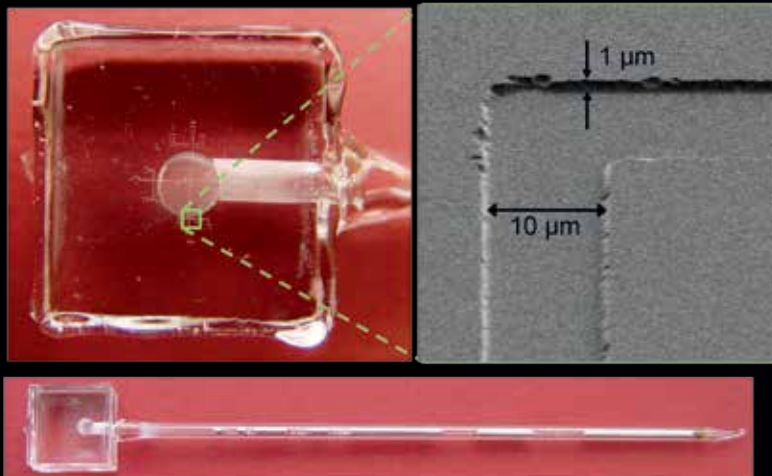
Perhaps the most startling discovery made by Pfau's group has been the identification of an entirely new form of atomic bonding. They found that molecules including Rydberg atoms have completely novel bonds with binding mechanisms that are neither van der Waals, ionic nor covalent bond. The team continues to work to understand the mechanism of these new bonds and their potential relevance in the behaviour of molecules involving Rydberg atoms, but in the meantime textbooks describing covalent, ionic and van der Waals as the only forms of atomic bonding are now outdated, representing a serious step forward in our understanding of physical chemistry.

The creation of Rydberg atoms involves the excitation of suitable elements by lasers. This process itself can be manipulated by the research team to create Rydberg atoms with differing behaviours. By adjusting laser parameters, the group is able to produce Rydberg atoms which interact in a variety of ways. So far, they have been able to create atoms which bond with van der Waals forces, dipolar type bonding (like the attraction between two magnets) and isotropic or anisotropic bonding. This variation in bonding has consequences for the behaviour of larger molecules and states of quantum matter – leading to the theoretical prediction that entirely new states of quantum matter will be produced as the technology and our understanding of these atoms grow.

Having explored single Rydberg atoms and two-body molecules, they are now looking at four- and six-body interactions. There is no known limit to this proliferation, but while Pfau and his colleagues are making important steps in this arena, they are all too aware that their efforts represent the beginning of a journey that will last many years.

AVOIDING REFRIGERATION

Rydberg atoms and interconnected molecules are good candidates for quantum

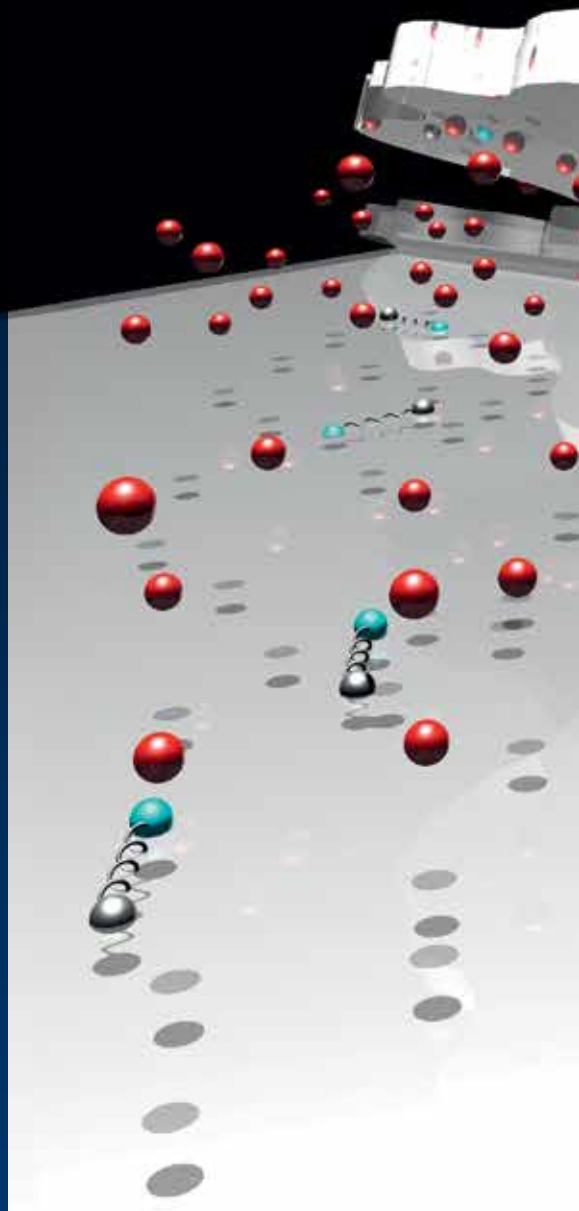


Fabrication method for micro vapour cells for alkali atoms (Baluktian T, Urban C, Bublat T, Giessen H, Löw R and Pfau T, 2010, *Opt. Lett.* **35**, 1950).

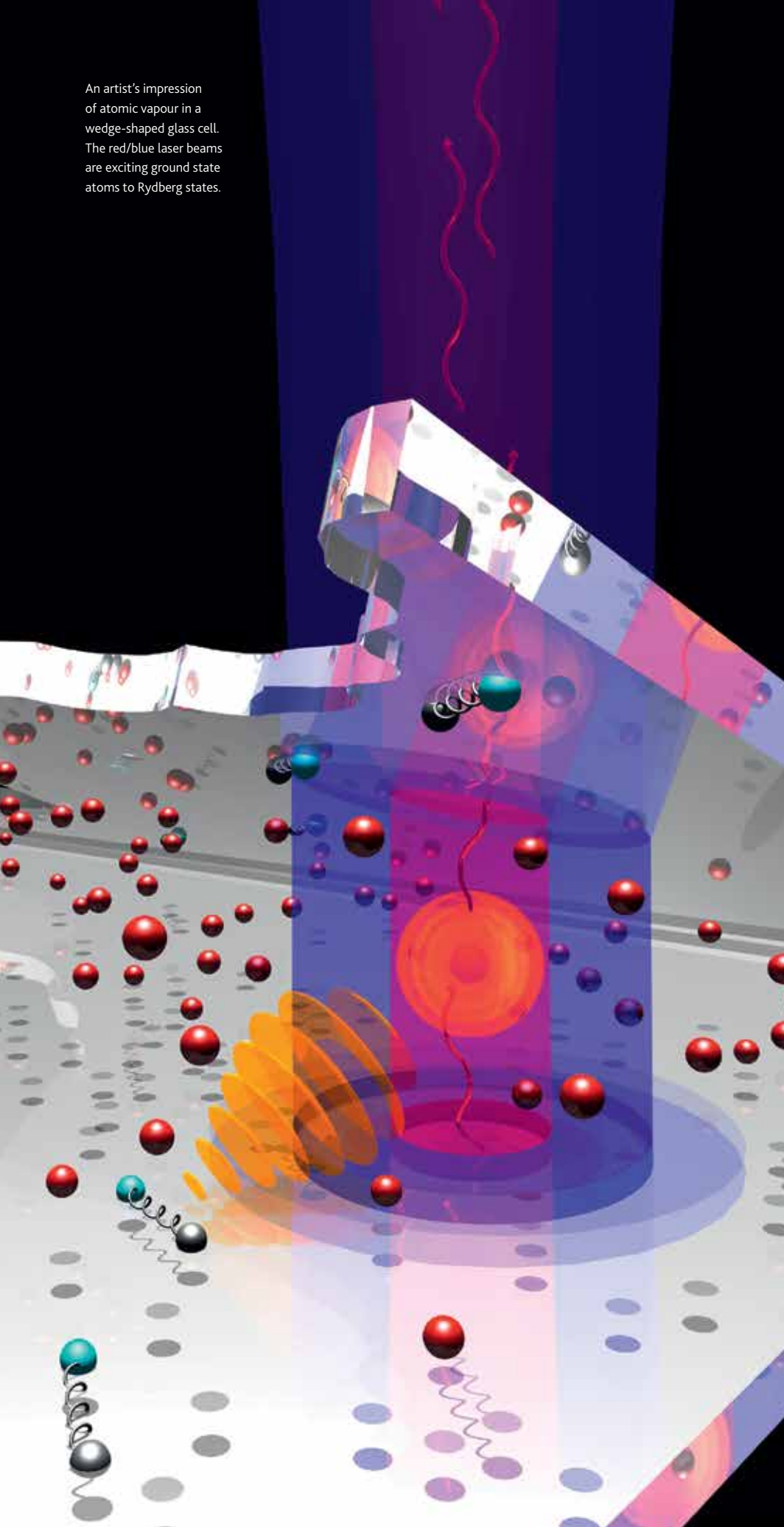
devices, but they present one drawback – the need to be kept at ultracold temperatures to remain effective. This is a serious practical limitation to the use of these and other atomic candidates in quantum technology. Pfau and his colleagues have recognised this limitation and are working to try and overcome it. They are now looking at mesoscopic ensembles of atoms which promise to remain functional at room temperature. To this end, the group is creating mesoscopic Rydberg ensembles – consisting of tiny glass cells containing rubidium atoms which are excited to the Rydberg state by lasers. These cells have great potential as they are a simplified version of the interconnecting nodes required for quantum devices: "We hope that this can be used to build quantum devices that do not need refrigeration," summarises Pfau.

The work being conducted at the 5th Institute of Physics is world-leading and requires a wide range of expertise and close collaboration with engineers. Supervised by Pfau and his colleagues Dr Sebastian Hofferbeth, Dr Robert Löw and Professor Hans Peter Büchler, undergraduate to graduate members of the team work cooperatively with expert engineers led by Professors Norbert Frühauf and Manfred Berth. Although these senior researchers lead various aspects of the research and Pfau the entire laboratory, they recognise the need for all voices to be heard regardless of experience: "We have a very informal atmosphere with flat hierarchies – we study the laws of nature and these laws do not respect any human hierarchy," points out Pfau.

In the not too distant future, research being conducted at the University of Stuttgart and other institutions all over the world will hopefully provide us with the knowledge to create quantum devices. Pfau is hopeful that their work on Rydberg atoms and molecules will contribute to these practical applications, but he does not think this is the most significant aim: "It is important that we keep on training more people in this field at the forefront of research as there is so much unexplored room at the bottom".



An artist's impression of atomic vapour in a wedge-shaped glass cell. The red/blue laser beams are exciting ground state atoms to Rydberg states.



INTELLIGENCE

QUANTUM PHYSICS OF INTERACTING RYDBERG ATOMS

OBJECTIVES

To push the limits of experimental quantum physics, ranging from fundamental questions about quantum phenomena to applications of quantum devices.

PARTNERS

Control of Quantum Correlations in Tailored Matter (CO.CO.MAT) SFB/TRR 21 – Stuttgart, Ulm, Tübingen

Center for Integrated Quantum Science and Technology (IQST)

Stuttgart Research Center of Photonics Engineering (SCoPE), University of Stuttgart

BMBF, Research Association Quantumcommunication

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PROFESSOR DR TILMAN PFAU completed his PhD in the group of Professor Jürgen Mlynek in Konstanz in 1994. He next took postdoc positions at ENS Paris, MIT Cambridge and Konstanz before founding the 5th Institute of Physics at the University of Stuttgart in 2000, where he also became Full Professor. Since then, he has become a guest professor at Helsinki University of Technology in Finland, Tsinghua University in Beijing, China, and the University of Toronto in Canada.



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