PS PUBLIC SERVICE REVIEW
science & technology 07

Helga Nowotny
Developing a knowledge and innovation ecosystem

Martin Rees
How our search for far away planets is accelerating

Matthias Kleiner
Towards the creation of a European Grant Union

Sir David Attenborough
Making access to the natural world easier

Climate: nature vs. mankind

How measurements provide the basis to understand climate variability

A quantum of excellence

…at Vienna University of Technology…

Quantum mechanics, the key of our understanding of nature, laid the foundation of 20th Century physics. Even the most fundamental aspects of matter cannot be understood without quantum theory. For instance, the classical theories of Maxwell's electrodynamics and Einstein's special and general relativity cannot even explain the existence of atoms. Without doubt quantum science will be at the focus of the developments of the technologies of the 21st Century. Thus, it should be no surprise that the study of quantum phenomena and the development of quantum technologies belong to the main research topics at the Faculty of Physics at Vienna University of Technology (TU Vienna). It is worth noting that at TU Vienna the only nuclear reactor in Austria is in operation (Fig. 1).

Probably the biggest milestone dates back to the pioneering matter-wave experiments of H Rauch and his group in the 70s who for the first time succeeded in splitting a beam of neutrons into two coherent sub-beams propagating along trajectories which were separated by a macroscopic distance of several centimetres (Fig. 2) and to detect the resulting interference pattern after their subsequent recombination. Many fundamental quantum science experiments have since then been performed with neutron interferometry, which have meanwhile become standard examples in nearly every textbook of modern physics. The first direct verification of the 4π-symmetry of fermion wave functions were mentioned as an outstanding, and at that time, spectacular example of these matter-wave interference experiments.

Fig. 1: Cherenkov light of the 250kW TRIGA research reactor of the Vienna University of Technology

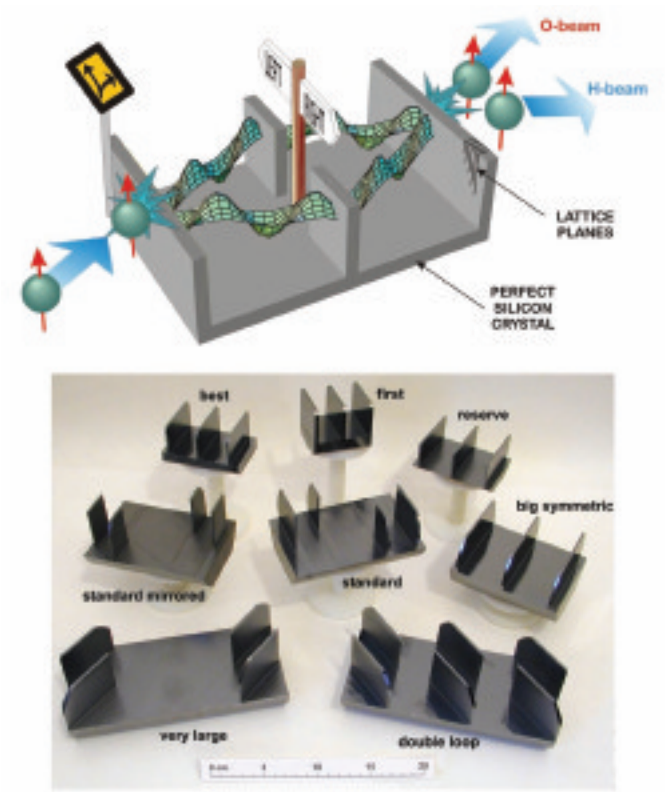

Fig. 2: (Top) Schematic sketch of a monolithic perfect crystal neutron interferometer. (Bottom) A collection of various types of interferometer crystals

Without claiming completeness and disregarding the other likewise important fields of research at the Faculty of Physics due to limited space, we present a selection of typical examples of quantum physical research performed at the four institutes that currently comprise the faculty.

At the Institute of Applied Physics (IAP) cutting-edge basic research in the area of atomic physics at surfaces is performed. The interaction of slow highly charged ions with solid surfaces leads to the formation of so-called 'hollow atoms'. The hollow atom, an exotic creation during atomic collisions, is a short-lived multiply excited neutral atom which carries the larger part of its Z electrons in high N levels while some inner shells remain transiently empty (Fig. 3). This extreme population

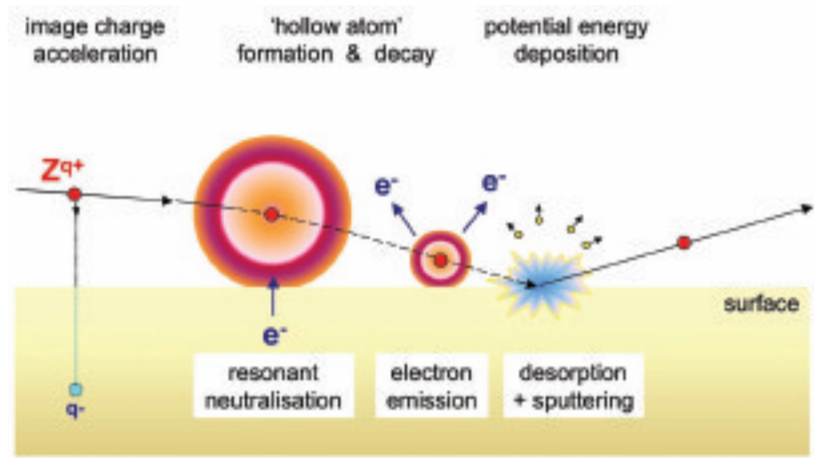

Fig. 3: Formation of 'hollow atoms' upon the interaction of slow highly charged particles with solid surfaces

inversion can last for, typically, 100 femtoseconds during the approach of a slow, highly charged ion towards the surface. Despite its short lifetime, the formation and decay of hollow atoms is studied through the ejected electrons and characteristic soft X-rays, and the trajectories, energy loss and final charge state distribution of surface-scattered projectiles.

In addition, upon surface contact a considerable potential energy is deposited in a very small surface volume, causing a strong electronic excitation of the latter, which subsequently leads to sputtering of target atoms and nano-sized modifications (hillocks, craters, etc.) of the surface (Fig. 4). Thorough investigation of the effects involved allowed the establishment of a method for melting materials on a nano-scale. This in turn might trigger various technical possibilities for semiconductor and nano-technological applications, since not only a phase transition from solid to liquid, but also a transition from crystalline to amorphous, or even from non-magnetic to magnetic by highly charged ion impact on solid surfaces is thinkable.

At the Institute for Solid State Physics (IFP), quantum physics is of central importance as well since every description of matter is based on quantum mechanics. Luckily, most phenomena such as the operation of lasers or radioactivity can be understood by considering the quantum mechanical properties of single particles alone. Surprisingly, this also holds for many cases in solid state physics, even though in solid matter myriads of quantum mechanical particles interact with each other, and in 1956 the Russian physicist Lev Landau explained why. He showed that in many cases, all these particles collectively form quasiparticles that behave as if they were independent of each other.

Thus, many important physical phenomena of the 20th Century, such as semiconductor physics and quantum tunnelling that is used in flash memory devices, can be understood by a relatively simple Fermi liquid theory of single, quantum mechanical quasiparticles. In some cases, however, this Fermi liquid theory breaks down, and phenomena such as the unconventional structure of the unconventional superconductor $CePt_3Si$ occur. The missing centre of inversion symmetry leads to a splitting of the electronic bands and thus to an unconventional superconducting state that has both spin singlet and spin triplet components, superconductivity, quantum criticality, Bose-Einstein condensation, fractional quantum Hall effect and superfluidity can only be explained by a true many-body theory of strongly correlated matter, exponentially more daunting than single particle quantum mechanics.

Many of these effects appear only at very low temperatures or when the dimensions of the problem are reduced. The extensive low and ultra-low temperature infrastructure of the IFP and the competencies of the Center for Micro and Nanostructures (ZMNS) are thus prime assets. Currently, the main quantum scientific focus of the IFP is directed towards the investigation of quantum critical behaviour, heavy fermion behaviour, metal insulator transitions, unconventional superconductivity, and quantum tunnelling – most of them being strongly correlated electron systems.

The theoretical modelling of such materials is very demanding. The IFP has chosen a combined experimental and theoretical approach. The theoretical methods of choice are

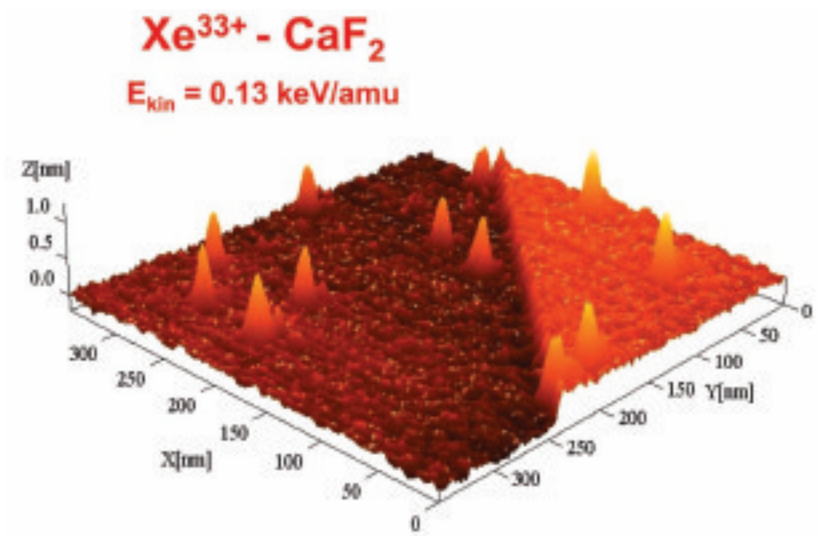

Fig. 4: Nano-sized modification of a CaF_2 surface upon bombardment with Xe^{33+} ions

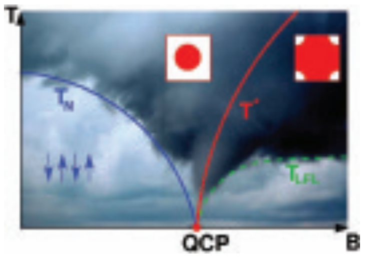

Fig. 5: Illustration of a phase diagram in the vicinity of a quantum critical point (QCP). As the magnetic field and temperature are varied, the system switches to different physical behaviours. Only at very low temperature it shows anti-ferromagnetic (below T_N) and Landau Fermi-liquid behaviour (below T_{LFL}). Inside the tornado, however, all physical properties show non-Fermi-liquid behaviour even down to the temperature of absolute zero. Across the scale T, the Fermi surface changes abruptly from small (left) to large (right) in some of the most interesting compounds*

both the dynamical mean field theory and extensions thereof, combined with density functional theory, and model calculations.

As a representative example, the crystallographic structure of $CePt_3Si$ is shown in Fig. 6. There the missing centre of inversion symmetry leads to a splitting of the electronic bands and thus to an unconventional superconducting state that has both spin singlet and spin triplet components. Here, in contrast to conventional superconductors, where the lattice-phonon interaction is essential, magnetic fluctuations are the glue for the formation of Cooper pairs.

The research programme of the Institute for Theoretical Physics is characterised by a remarkable diversity covering a broad spectrum of topics ranging from high-energy physics, quantum field theory and quantum gravity to atomic and condensed matter physics. Non-linear dynamics of complex systems is one of the overarching themes connecting many research topics ranging from the fundamental to the applied. Many of the research topics make use of and belong to the sub-discipline 'computational physics'. Two vastly different highlights may serve to illustrate the breadth of the research endeavour. One such highlight is the field of quantum gravity, recently recognised by the Start prize for young investigators awarded to Daniel Grumiller.

Unifying quantum theory with gravitation is one of the outstanding challenges in theoretical physics. Black holes may provide important clues and they are omnipresent in our universe. Stars that are similar to but slightly heavier than our sun collapse to a black hole during the end of their life-cycle. These stellar black holes are relatively easy to observe if they are orbited by a brightly shining partner star. On the theory side, black holes are a milestone on the road to quantum gravity, like the hydrogen atom was for the development of quantum mechanics.

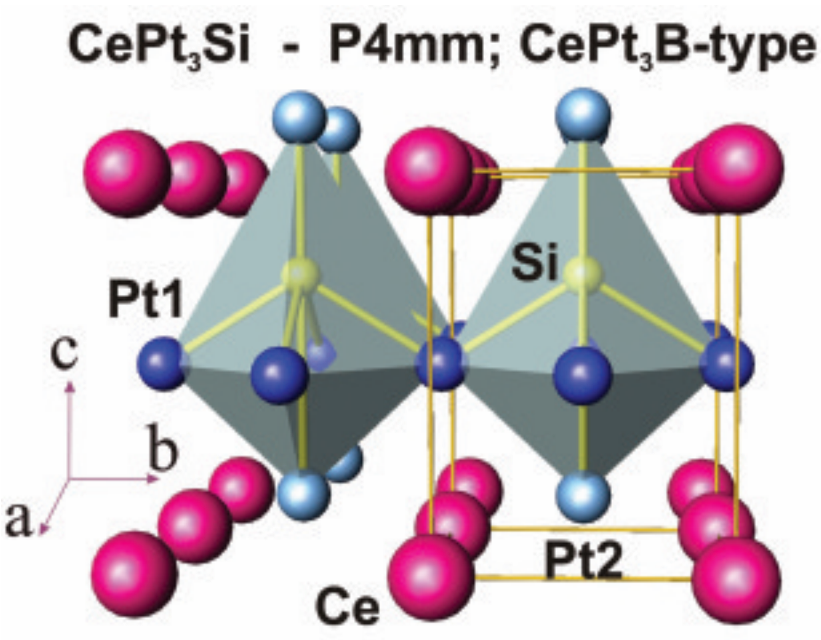

Fig. 6: Crystal structure of the unconventional superconductor $CePt_3Si$

Fig. 7: Central part of a ^3He-^4He dilution refrigerator at the IFP that cools samples down to about 10 milli-Kelvin prior to its combination with a nuclear demagnetisation stage with a base temperature in the micro-Kelvin range

An essential insight from this research field is the 'holographic principle'. It allows unexpected applications of black hole physics, eg. in heavy ion collisions or condensed matter physics. The theory group at TU Vienna is actively involved in these research areas. On the applied side, the institute coordinates an interdisciplinary special research programme on the development of novel laser light sources. Theory plays a key role in guiding both the development of novel ultra-short coherent light sources and their usage to probe quantum dynamics on the ultra-short timescale. Such novel pulses open up novel opportunities not only for probing but also for controlling and actively steering quantum dynamics on the atomic and molecular level and guiding chemical reactions. A prototypical example is the controlled break-up of a molecule by choosing an appropriate designed pulse with sub-femtosecond time structure. The molecular fragments (H and H^+) can be directed either to the right or to the left, as shown in Fig. 8.

Dedicated quantum science at the Atominstitut (ATI), which hosts the university research reactor, ranges from matter-wave interferometry of

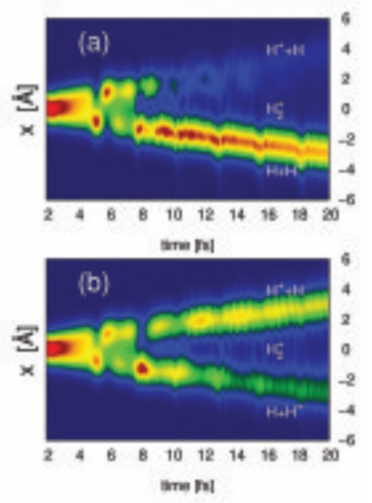

Fig. 8: Controlling the direction of molecular fragments by sub-femtosecond laser pulses

single neutrons and gravity induced quantum interference, to experiments probing many-body quantum physics, thereby building bridges between the different quantum worlds of photons, atoms and solid-state quantum devices within the 'quantum interconnect project', which is focused on the basic science of hybrid quantum systems. Since for quantum science to develop into a robust technology it will be necessary to pool the strengths of various quantum systems to overcome the weaknesses of single systems. For this to happen it is necessary to bridge the classical gaps between the different quantum domains by reliable and robust quantum interconnections.

Photons are ideal carriers of quantum information, but cannot be stored for a long time. Superpositions of hyperfine states in ultra cold atoms, or special engineered ensembles of nuclear spins, can faithfully be kept coherent for more than 100 seconds and are therefore an ideal candidate for a quantum memory, but fast operations or long-distance transfer of quantum states are difficult. Superconducting quantum circuits are extremely fast quantum processors, but lack a reliable quantum memory and a reliable long-distance quantum bus.

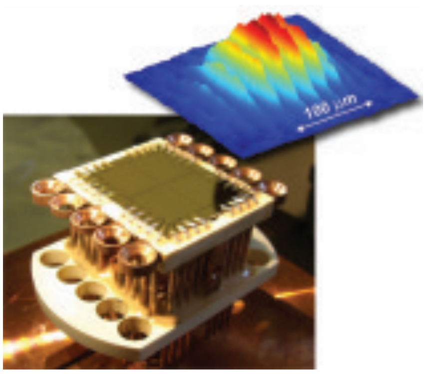

Fig. 9: The AtomChip technology allows the production and manipulation Bose-Einstein condensates. The enlarged 3D signature of a BEC is shown

One key technology to make quantum science experiments robust is miniaturisation and integration. The AtomChip is a key step in this direction. There the best of different worlds is combined in one integrated system: the exquisite quantum science of atomic physics and quantum optics with the vast technological possibilities of nanofabrication and micro optics. Atoms are trapped and manipulated by electric and magnetic fields generated by nanofabricated wire structures on the chip. Integrated micro optics and fibre optics connects the trapped atoms to light. An ambitious quantum metrology project aiming to realise an ultra-precise 'nuclear clock' was recently recognised as T Schumm was awarded the Start prize.

In the best tradition of the already mentioned pioneering matter-wave interference experiments, the Neutron Optics and Quantum Physics Group at ATI continues to study fundamental questions aiming to gain more insight into how a classical world emerges from the quantum structure of nature. A particularly remarkable highlight was the recently realised triple entanglement of spin, path and the energy degrees of freedom of polarised neutron beams to verify an inequality imposed by the so-called 'quantum contextuality', a wave-particle phenomenon completely counterintuitive to classical concepts. Likewise spectacular is the realisation of the so called 'quantum bouncing' of neutrons in the Earth's gravitational field in collaboration with the Institut Laue-Langevin (ILL) in Grenoble.

Gravity experiments might provide an answer for the 'big questions' about space, time, and a unification of all forces, where – as most physicists believe – space-time is not restricted to four dimensions. Hypothetical extra-dimensions, curled up to cylinders or tori with a small compactification radius should lead to deviations from Newton's gravitational law at very small distances. These ideas triggered gravity experiments of different kinds, which in the past 10 years have validated Newton's gravitational law down to about 20μm. Quantum interference experiments with ultracold neutrons (UCN) will enable the testing of the law of gravitation at smaller distances around 1-10nm, where gravity becomes 10,000 times larger than it is on the surface of the Earth. Such measurements with ultracold neutrons offer an incredibly high sensitivity to hypothetical non-Newtonian short-ranged interactions, which are about 21(!) orders of magnitude below the energy scale of electromagnetism. So, the way is paved for the search of new physics!

Faculty of Physics

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