Highly charged

Dr Wilfried Nörtershäuser provides an insight into a career spent traversing the fields of atomic, nuclear and particle physics

How did your academic career guide you to your current research endeavours in the field of laser spectroscopy?

I began employing collinear laser spectroscopy in my diploma work for the trace analysis of very rare isotopes in environmental samples, and during my doctoral thesis I developed a different laser-based technique for this purpose. This was in Mainz, Germany, where I was part of a working group that used techniques developed for atomic physics to study subjects in nuclear and particle physics. Here, I learned how fruitful it can be to cross the borders between disciplines. Since the techniques we developed for ultratrace analysis could also be used to study exotic isotopes (which are produced at accelerators in minute quantities), I joined a project aiming to measure, for the first time, nuclear charge radii of short-lived isotopes of the lightest elements. Later, I became the spokesperson and leading investigator of this project. It is a thrilling experience when you see a new technique that you have been developing for a couple of years successfully working and unveiling something that nobody knew before.

When I returned to Mainz to establish my own research group called ‘Laser spectroscopy on highly-charged ions and exotic radioactive nuclides’ (LaserSpHERe), I continued working in this field but also joined a collaboration conducting tests of time dilation in special relativity and took up another one of Mainz’s historic research endeavours, the test of quantum electrodynamics. We use laser light to measure the spectrum of various elements, isotopes and charge states with very high precision in order to study fundamental aspects of forces and symmetries in nature.

What have your investigations so far unveiled about the structure of atomic nuclei?

We have, for example, studied the nuclear size of very light elements, most recently the chain of beryllium (Be) isotopes. These light nuclei are not as compact and homogeneous as one might imagine. Instead they are strongly clustered, meaning the protons and neutrons inside the nucleus arrange into small groups, moving around the common centre of mass. Since all protons in Be nuclei are bound within α-particles, we were able to extract information about the movement of these clusters inside the nucleus. It turned out that in Be, the 7th neutron is, on average, 8 fm away from the rest of the nucleus, which is almost unbelievably far. The fact that this neutron is still bound to the nucleus can only be understood by the quantum mechanical nature of the interaction.

Another observation that surprised us was the fact that adding another neutron and forming 8Be considerably reduces its spatial neutron distribution but also gives rise to an increase of the charge radius. It turned out that this is due to the correlation of the two additional neutrons arising from the fact that they are not located in the orbits that classical nuclear physics expects.

The LaserSpHERe group has performed several precision experiments – most of them together with colleagues from other universities and research institutes. What have been the main advantages of this collaborative approach?

It is always beneficial to gather people with expertise on different aspects of the experiment. Experiments at accelerator facilities are demanding and require careful preparation and strong support during execution – you only have a few days to carry out your experiment, so during this time you have to run it around the clock and immediately repair or replace anything that fails. Hence, it is wise to distribute the load on several shoulders.

Can you describe your work and the goals driving your investigations?

Light absorbed and emitted by electrons in the atomic shell is our main source of information about atomic structure, and as such has driven the development of quantum mechanics and quantum electrodynamics. We use laser light to measure the spectrum of various elements, isotopes and charge states with very high precision in order to study fundamental aspects of forces and symmetries in nature.

How do you ensure the successful impact of your work on interested stakeholders and the general public?

LaserSpHERe regularly publishes its work in high-profile journals and participates in relevant conferences, and we also try to inform the public about interesting new results by launching press releases. Moreover, we are happy to be invited to present our new ideas at the Workshop on the Generation, Measurement and Application of High-Voltage Direct Current organised by Germany’s National Metrology Institute.
Lasers unlimited

Based at the Technical University of Darmstadt, Germany, the LaserSpHERe working group is collaborating with other research teams and facilities across the world to stretch the limits of what laser spectroscopy can achieve.

AT THE TECHNICAL University of Darmstadt, Germany, a working group known as ‘Laser spectroscopy on highly-charged ions and exotic radioactive nuclides’ (LaserSpHERe) is growing from strength to strength. Led by Dr Wilfried Nörtershäuser, the team’s aims are twofold: firstly, to test the fundamental symmetries and interactions of highly charged ions, and secondly, to better understand the structure of exotic radioactive nuclides.

AN ION’S MERRY-GO-ROUND

All of the experiments relating to LaserSpHERe’s first task are performed at the GSI Helmholtz Centre for Heavy Ion Research in Darmstadt. Here, the team utilises laser spectroscopy to investigate highly charged ions, which are created by accelerating heavy ions up to 70 per cent of the speed of light and then sending them through a thin foil so that they lose almost all of their electrons. The remaining electrons experience the immensely strong static electric and magnetic fields of the heavy nucleus. The ions are then stored in the experimental storage ring (ESR), where they circulate in closed orbits for up to one hour. “The ESR has a circumference of about 108 m, hence the ions revolve about 2 million times a second – travelling as far as the distance between the Earth and the Moon within two seconds,” expands Nörtershäuser.

At this stage, experiments using laser spectroscopy can be performed and allow the LaserSpHERe team and its partners to explore the potential limits of quantum electrodynamics and the special theory of relativity. The group has already successfully provided the first direct proof for a spectral line in highly charged bismuth ions – something that scientists in the field have been attempting for 14 years – and also confirmed the Doppler shift of light absorbed from fast ions at least up to an accuracy of two parts per billion, in accordance with the special theory of relativity.

It was during these experiments that the team made an unexpected finding: “While performing the experiment, we found that changing the laser light polarisation could make the resonance signal disappear,” Nörtershäuser enthuses. “At first we ignored the effect, but later we realised that the signal disappearance could be related to optical pumping – an effect that aligns the tiny magnets formed by most atoms and nuclei.” Generally, atomic magnetic poles can be orientated either through the application of strong external magnetic fields or through interaction with circularly polarised light. But it had been supposed that the latter was not possible within the context of a storage ring, as the rapidly changing magnetic fields along the ion’s orbit would destroy magnetic orientation faster than it could be created. LaserSpHERe’s finding, however, suggests otherwise: polarisation may be preserved for longer than expected. “This is very exciting, because polarised beams in the storage ring would allow entirely new types of experiments to be performed,” reveals Nörtershäuser. With this in mind, the team plans to investigate the phenomenon further in the future.

THE FLEETING LIFE OF A NUCLEUS

LaserSpHERe’s other objective is to determine nuclear ground state properties such as charge radius, magnetic dipole moments, quadrupole moments and spin. In order to explore the exotic regions of the nuclear chart, collinear laser spectroscopy is employed alongside a number of different detection techniques. “Studying these properties along a chain of isotopes...”

Central piece of the setup for the spectroscopy of $^{11}$Li...
INTELLIGENCE
LASER SPECTROSCOPY ON FAST BEAMS OF EXOTIC ISOTOPES

OBJECTIVE
To use the atomic spectrum to reveal details about the interaction of electrons with the nucleus and the electromagnetic fields surrounding the nucleus. Laser spectroscopy on highly charged ions is performed to test the theory of quantum electrodynamics in the strongest magnetic fields available in the laboratory while short-lived isotopes are studied to gain a deeper insight into nuclear structure.

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WILFRIED NÖRTERSHÄUSER studied physics in Mainz from 1990-95, where he also received his PhD in 1999. After a few years working as a postdoctoral researcher in the US, Tübingen and GSI Darmstadt, he received a Helmholtz Young Investigator Grant in 2005 and launched the LaserSpHERE group. In 2009, he became Junior Professor in Mainz, and in 2012 he was appointed Professor at Technical University of Darmstadt.

The LaserSpHERE group has joined forces with a number of international partners and august facilities to conduct these laser spectroscopy experiments. These include the COLLAPS setup at the On-Line Isotope Mass Separator (ISOLDE), an isotope production facility within the European Organization for Nuclear Research (CERN) and TRIUMF in Vancouver, Canada, where the LaserSpHERE team was able to determine for the first time the charge radius of the halo nucleus lithium-11 (11Li). In the near future, experiments are planned at the ATLAS experiment within CERN’s Large Hadron Collider and the CARIBU facility of Argonne National Laboratory, USA.

The cluster structure of 11Be and 12Be composed of two ‘alpha’-clusters and additional neutrons.

One challenge in this line of work is that the more exotic a system, the smaller the number of ions that can be delivered by the accelerator and the shorter their lifetime. Hence, laser spectroscopy on these systems is a race against time; the nuclei live only for a few milliseconds, barely the blink of an eye. Fast, accurate and increasingly sensitive detection techniques are therefore required to analyse them, which can create unique challenges. Gradually, however, LaserSpHERE is making headway; in 2009, for example, the team succeeded for the first time in measuring the size of a one-neutron halo using lasers, while in 2012 they were able to invalidate the shell model for beryllium isotopes. In each instance, the researchers had to find a way to solve the unique challenges faced. “One of the greatest difficulties I have encountered related to the low production rate of 11Li,” Nörtershäuser recalls. “While techniques capable of detecting such small numbers of atoms did exist, they either could not provide the required accuracy or were not able to cope with the very small lifetime.” Ultimately, the researchers overcame this by combining the sensitive technique of resonant laser ionisation with a spectroscopic approach that provided the required resolution.

RAISING THE VOLTAGE
With a series of impressive successes under its belt, the LaserSpHERE team is not content to rest on its laurels, but instead has a series of exciting developments for the future planned. The researchers have already begun work in establishing collinear laser spectroscopy as a tool to measure high voltages (ranging from 10,000-100,000 V) with high accuracy, with the aim of improving upon what has so far been demonstrated with this approach by at least two orders of magnitude. Nörtershäuser and his group have considered measuring the high voltage at the KATRIN experiment in Karlsruhe: “At present, they are able to measure the voltage at the electron spectrometer to an accuracy of one part per million. With our new approach, we will try to exceed this accuracy, but it will take some time and I am sure that we will have to overcome some unforeseen obstacles (as usual) before we reach this goal. Once we are successful, however, national metrology institutes might also be interested in this technique,” he concludes.