Research with Beams of Highly Charged Ions

Generation of highest charge states with ultra-high vacuum technology

In our environment, we encounter mainly low-charged ions, for example in the flame of a candle or in thunderstorm lightning. But there are also naturally occurring highly charged ions, i.e. ions with a high number of missing electrons in the atomic shell. We experience these, for example, in exotic states such as the solar corona or in supernova events.

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For this reason, the study of highly charged ions in the laboratory plays a major role for astrophysics. However, highly charged ions produced in the laboratory are also extremely important in other fields. Spectroscopy of highly charged ions is used to study processes in fusion plasmas. Basic research on the interaction of highly charged ions with solid surfaces provides interesting perspectives, for example, for future quantum computer systems.

"To date, spectroscopic measurement of atomic radii has been performed only on hydrogen-like systems with a single electron, because only for these is the theory sufficiently accurate. Experimentally, however, these simple atomic systems have the disadvantage that the wavelengths to be used lie far in the ultraviolet range of the optical spectrum and are thus difficult to access with current laser systems," explains Prof. Dr. Wilfried Nörtershäuser, head of the LaserSpHERe **(Laser Spectroscopy of Highly Charged** Ions and **Exotic Radioactive** Nuclides) research group at the Institute of Nuclear Physics at TU Darmstadt. "Currently, however, there are promising efforts to achieve the required accuracy also for more complex, helium-like systems with two electrons. Their wavelengths are much more accessible with laser systems, and thus the radii of atomic nuclei from helium to nitrogen can be determined much more precisely in the future than is currently possible. By installing the ion beam facility with the EBIS-A ion source, the COALA apparatus offers the ideal conditions for this." Prof. Dr. Nörtershäuser and his team conduct precision experiments at the frontier of atomic, nuclear and particle physics using the **Collinear Apparatus** for **Laser Spectroscopy** and **Applied** Sciences (COALA). Its research focuses on laser spectroscopy of highly charged ions and exotic short-lived isotopes, with the goal of precisely determining the charge radii of atomic nuclei.

Laser spectroscopy of highly charged ions and exotic short-lived isotopes is the main research focus of Prof. Dr. Nörtershäuser's group.

Figure 1: EBIS ion source

Technologies for the generation of highly charged ions

The **Electron Beam Ion Source** (EBIS) used in Darmstadt is only one of several technologies for the generation of highly charged ions. Like lasers and **electron cyclotron resonance ion sources** (ECRIS), EBIS is considered a direct source of highly charged ions. In addition, low-charged ions can be converted into highly charged ions using high-energy accelerators and gas or foil stripper targets.

The energy transfer required for ionization is realized by radiation in laser ion sources. All other technologies have in common that the driving process for ionization is based on electron collisions. In high-energy accelerators, the singly charged ions are fired at quasi-resting electron impact partners at high energies. In electron cyclotron resonance and electron beam ion sources, the process is reversed. The initially gaseous neutral molecules or atoms are at rest. For electron beam ionization, the electrons are accelerated and collide with the shell electrons of the atoms. The transfer of kinetic energy from the fast electrons to the shell electrons gives them sufficient energy to leave the bond of the atomic shell.

Of all the direct sources of highly charged ions, the highest charge states were produced with electron beam ion sources, making them the optimal choice for use at COALA in Darmstadt. The technology offers ideal conditions for achieving high charge states, as long as the vacuum technology used provides sufficient general conditions.

The highest charge states have so far been produced with electron beam ion sources

Operating principle of an electron beam ion source

In an electron beam ion source of the Dresden-EBIS-A type, as used at the TU Darmstadt, a highly emitting cathode is heated to about 2200 K in a vacuum. This generates a beam of free electrons which are accelerated from the electron gun towards the drift tube ensemble acting as an anode. During this process, the electron beam is compressed by a strong magnetic field, causing the electron current densities to reach values of several 10 amperes per cm^2. This high-density, high-speed electron beam encounters thermal gas atoms in the area of the drift tubes and collides with their shell electrons. The resulting ions are trapped by an electrostatic field in the area of the drift tubes, in what is known as the **E**lectron **B**eam **I**on **T**rap (EBIT).

As long as the energy of the electron beam exceeds the binding energy, further shell electrons are removed by continuous electron impact ionization, bringing the ion to an ever higher charge state. This can continue until all shell electrons are removed and only the bare nucleus remains.

Figure 2: Electron beam ion source

After passing through the drift tubes, the electrons are electrostatically directed by the repeller voltage to a cooled electron collector. The highly charged ions can leave the ion trap and are available for various applications.

Ultra-high vacuum as basic condition for high charge states

The ionization process is opposed by recombination. In this process, free electrons are captured by ions and the charge state is reduced. This process can continue until the ion is completely neutralized, i.e. back from the ion to the atom. Recombination depends on the supply of neutral atoms and thus scales directly with vacuum pressure. Especially in the production of highest charge states up to naked atomic nuclei, the process of recombination with neutral particles is detrimental.

Thus, the working pressure must be adjusted so that the mean free path length between two gas atoms is larger than the interaction cross section of electron impact ionization. In contrast, the capture of electrons from the electron stream of the EBIS itself is rather unlikely, since the electrons from the electron beam have too high a kinetic energy for capture into the atomic shell.

In addition to a good vacuum base pressure, the composition of the residual gas is also of interest. In collisions between ions of different species, such as argon and nitrogen, momentum transfer occurs in the ratio of their masses. This results in heavier elements pushing lighter elements out of the ionization zone of the drift tubes, which reduces the residence time of the ions. However, a long residence time is a prerequisite for achieving the highest possible charge states. This in turn increases the probability of interactions for electron collisions. At the same time, an analysis of the generated ions and their charge states also enables a qualitative analysis of the residual gas. Thus, an EBIS always represents an excellent mass spectrometer as well.

Technical challenge of the ultra-high vacuum

For the generation of high and highest charge states, a pressure of $1 \cdot 10^{-10}$ mbar is required. The pressure of the process gas (for example argon or xenon, also hydrogen or oxygen) is $5 \cdot 10^{-10}$ mbar to $5 \cdot 10^{-9}$ mbar. In this pressure range, the mean free path length is between10^4 and 10^5 m, so that the probability of interactions with other gas atoms decreases and recombination into lower charge states is suppressed.

The room-temperature EBIS system achieves its working pressure through a two-stage turbopump system consisting of a HiPace 400 and a HiCube 80

In the room-temperature EBIS systems developed by Dreebit GmbH, this working pressure is generated by a two-stage turbopump system consisting of a HiPace 400 and a HiCube 80 from Pfeiffer Vacuum. Due to the low gas load during operation of the ion source, the diaphragm pump in the HiCube 80 combination pumping station is sufficient.

The low gas flows for the process gas are generated with the UDV 146 gas metering valve. This allows automated gas flow control to set the working pressure between $1 \cdot 10^{-10}$ mbar and $5 \cdot 10^{-9}$ mbar.

The ion source is baked out over several days at temperatures around 120 °C to achieve the base vacuum in the range of $1 \cdot 10^{-10}$ mbar and a clean residual gas composition. This results in special requirements for the permanent magnets used. Typical neodymium-iron-boron (NdFeB) magnets have a Curie temperature of 60–70 °C and would lose their magnetic properties when the source is baked. Therefore, special magnet systems are used here, which can be baked out to 120 °C without losing their permanent magnetic properties. This eliminates the need for complicated and time-consuming disassembly of the magnets prior to bakeout. The magnetic field strength reaches values in the range of 1.1 T at the surface of the magnets and generates a focusing magnetic field with a strength of about 650 mT on the beam axis of the ion source. This makes it one of the strongest magnetic fields that can be generated with permanent magnets.

Application in Darmstadt

The highly ordered electron flow (plasma) generated in this way is a major advantage for beam quality and was one of the reasons for using the EBIS source at COALA. Another plus point was confirmed in advance during research work on an accelerator ring. Philip Imgram of LaserSpHERe explains, "We knew the EBIS source from research at a collaborative partner and knew what to expect. However, we were not sure if it was the right solution for our type of application." So in 2019, a temporary test setup was built at another institute's facility, which provided clarity. "We need a specific electron configuration of carbon^{4+} (C^{4+}) for our experiments. We didn't doubt that we could produce C^{4+} with the EBIS, but will the configuration come out that we

Figure 5: Facility at the TU-Darmstadt

can use for laser spectroscopy? We saw in the test measurements that it worked, and so it was clear that EBIS was the source we needed," Philip Imgram said in the interview.

The development and expansion of COALA happened out of a need to become less dependent on large accelerator facilities. Beam times at large laboratories are very limited, so Prof. Dr. Nörtershäuser's group set the goal of building their own facility where they could test the new method for determining nuclear charge quantities without restrictions. In the meantime, COALA is the umbrella term for the facility in the basement of the Institute of Nuclear Physics, where various experiments such as high-voltage measurements or classical collinear laser spectroscopy are performed. With the installation of a new switchyard, several different sources can now remain permanently connected to the system and there is no longer any need for major conversions when the experiments are changed.

Experiments to determine the nuclear size

For Philip Imgram, after the installation of the EBIS-A source in September 2021, the final phase of his PhD thesis started, in which he is developing a new technique for the measurement of absolute nuclear charge radii together with the LaserSpHERe team. On October 28, 2021, the first resonance could be measured and after about two weeks there was proof that the experiment could work in principle. The first task was to determine the size of carbon^{12}, which is usually measured by electron scattering and spectroscopy of muonic atoms. In electron scattering, electrons are fired at a target and then the distribution of the electrons is observed. This allows conclusions to be drawn about the size of the nucleus. The problem with this is that these experiments are limited in precession and do not work well for radioactive isotopes because the nuclei decay very quickly due to their short lifetimes. "In our experiments at COALA, we want to use laser spectroscopy to infer the nuclear size. To do this, we need to bring an electron in our atom to a next level and measure this energy difference very precisely, because there is also a small but measurable amount of information in it that contains conclusions about the nuclear size," Imgram explains. To be able to confirm the results of the experiments with the theory, the experiments must be carried out on atomic systems with one nucleus and a maximum of two electrons.

In our experiments at COALA, we want to use laser spectroscopy to infer the nuclear size.

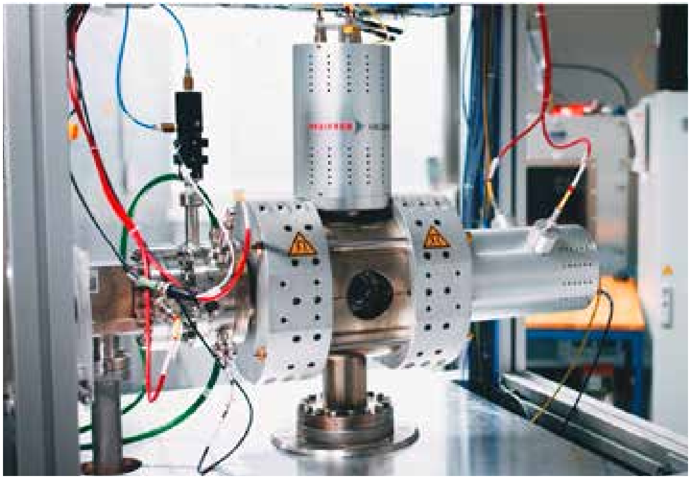

Figure 6: EBIS source in the facility at TU-Darmstadt

Looking to the future

Philip Imgram explains the further procedure: "For the theory part, we are dependent on the input of colleagues from theoretical physics, which sometimes takes a little time. But we're on a good track and hope to get the first real result of our target size out in a timely manner, which is the core size of carbon^{12}." The researchers chose to study carbon^{12} first because its core size is already known quite accurately from other experiments. So if the results from both measurements agree, there will be confirmation that the new method actually works. "Once we've figured that out, we want to apply the experiment to carbon^{13}, which is not as precisely known," Imgram explains. If the method proves effective here, the team hopes to install the EBIS source on a large accelerator ring in the future and study radioactive isotopes there. "But that's the very long-term plan; before that, we have to do a lot of testing here in Darmstadt at our COALA."

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