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Research with beams of highly charged ions

Ultra-high vacuum technology enables generating the highest charge states.

In our environment, we encounter mainly weakly charged ions, for example, in the flame of a candle or in a lightning. But there are also naturally occurring highly charged ions, i. e., ions with many electrons missing in the atomic shell. They correspond to exotic states like in the solar corona or in supernova events.

The study of highly charged ions in the laboratory plays an important role for astrophysics or for the study of processes in fusion plasmas. Basic research on the interaction of highly charged ions with solid surfaces offers interesting perspectives, for example for future quantum computer systems.

To date, spectroscopic measurements of atomic radii are only available for hydrogen-like systems with a single electron, as theory only describes these systems accurately. However, the required wavelengths belong to the ultraviolet region making them difficult to access with current laser systems. 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, explains: “Currently, there are promising efforts to achieve the required accuracy also for helium-like systems with two electrons. Their wavelengths are easier to access with laser systems, and thus the radii of atomic nuclei from helium to nitrogen can be determined more precisely in the future.” 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.

To generate highly charged ions

The electron-beam ion-source (EBIS, **Fig. 1**) used in Darmstadt is one of several methods to generate highly charged ions directly. In addition, low-charged ions can be converted into highly charged ions using high-energy accelerators and gas or foil stripper targets.

The energy required for the ionization stems from the radiation with lasers. All other technologies are based on electron collisions. In high-energy accelerators, the singly charged ions hit 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 provides sufficient energy to leave the atomic shell.

Electron-beam ion-sources produce the highest charge states (**Fig. 2**), making them the optimal choice for COALA in Darmstadt. The technology offers ideal conditions as long as the vacuum technology provides sufficient conditions.

Operating principle

In an electron-beam ion-source of the Dresden-EBIS-A type, as used at TU Darmstadt, a highly emitting cathode is heated to about 2200 K in vacuum. The resulting beam of free electrons is 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 A/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 a electron-beam ion-trap (EBIT).

As long as the energy of the electron beam exceeds the binding energy, further shell electrons are removed by continuous electron impact ionization, increasing the charge state of the ions until all shell electrons are removed and only the bare nucleus remains.

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.

The ionization process is hindered by recombination. In this process, free electrons are captured from ions and the charge state is reduced until the ion is completely neutralized and becomes an atom. Recombination depends on the number of neutral atoms and thus scales directly with vacuum pressure. In the production of highest charge states up to completely ionized atoms, the recombination with neutral particles is unwanted.

Fig. 1 Such an ion source is used in Darmstadt at COALA.

The working pressure must provide a mean free-path length between two gas atoms which exceeds the interaction cross-section of the electron impact ionization. In contrast, the capture of electrons from the electron stream of the EBIS itself is rather unlikely, as the kinetic energy of the electron beam is too high for the electrons to be captured.

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 corresponding to their mass ratio. Therefore, heavier elements push lighter elements out of the ionization zone of the drift tubes and reduce their residence time. However, a long residence time is a prerequisite for achieving the highest possible charge states and increasing the probability of interactions for electron collisions. At the same time, an analysis of the generated ions and their charge states enables a qualitative analysis of the residual gas. Thus, an EBIS always represents an excellent mass spectrometer as well.

Technical challenges

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

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 (**Fig. 3**). 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 10^{-10} and $5 \cdot 10^{-9}$ mbar.

The ion source is baked out over several days at temperatures around 120 °C in order to achieve the basic vacuum of $\approx 10^{-10}$ 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 to 70 °C and would lose their magnetic properties. Therefore, special magnet systems are used which do not lose their permanent

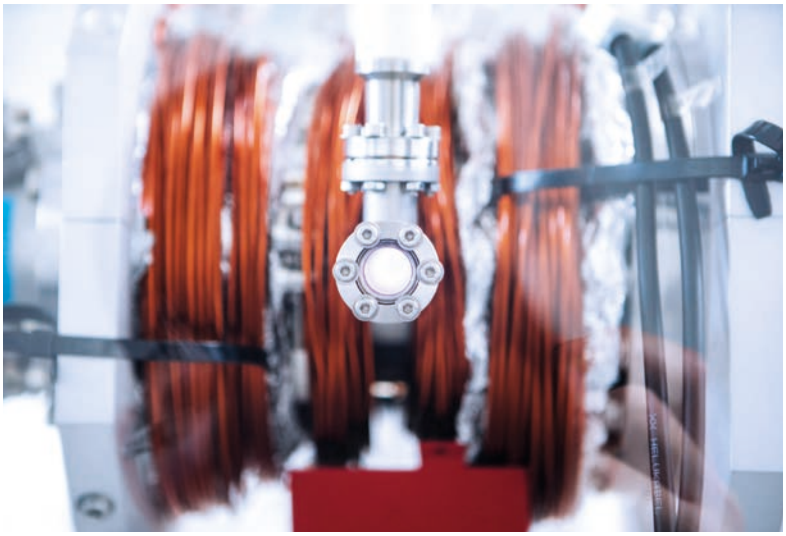

Fig. 2 Electron beam ion sources are direct sources of highly charged ions.

magnetic properties around 120 °C. Thus, a time-consuming disassembly of the magnets before bake-out is omitted. The magnetic field strength reaches about 1.1 T at the surface of the magnets and generates a focusing magnetic field with a strength of about 650 mT in the beam axis of the ion source.

Application in Darmstadt

The highly ordered electron flow (plasma) generated in this way is beneficial for beam quality and was one of the reasons for using the EBIS source at COALA. Another advantage arose during research work on an accelerator ring: "We need a specific electron configuration of carbon^{4+} (C^{4+}) for our experiments. We didn't doubt to produce C^{4+} with the EBIS, but needed to know about the configuration. Our test measurements proved that EBIS was the best source," explains Philip Imgram of LaserSpHERe.

The development and expansion of COALA was driven by the need to become less dependent on large accelerator facilities. Beam times at large laboratories are very limited, so Winfried Nörtershäuser's group wanted to build their own facility. In the meantime, COALA has become a facility 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 remain permanently connected to the system: major conversions are no longer needed between experiments.

The installation of the EBIS-A source took place in September 2021. One month later the first resonance was measured; after another fortnight the proof-of-principle was achieved. The first task was to determine the size of ^{12}C, which is normally measured by electron scattering and spectroscopy of muon atoms. In electron scattering, electrons hit a target. Their distribution afterwards yields information about the size of the nucleus. But these experiments are limited in precision and do not work well for quickly decaying radioactive isotopes. "At COALA, we use laser spectroscopy to infer nuclear size. To do so, we need to excite an electron to another level and measure the energy difference very precisely, because the nuclear size contributes in a small but measurable amount to this value", Philip Imgram explains. To compare the results of the experiments with theory, the experiments must be performed on atomic systems with a maximum of two electrons.

Looking to the future

The researchers decided to study ^{12}C as a proof of concept because its nuclear size is known quite accurately from other experiments. If the results are in agreement the new method actually works. The next step will be to apply the experiment to ^{13}C, which is not as precisely known. If the method proves successful, the team hopes to install the EBIS source on a large accelerator ring to study radioactive isotopes.

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Fig. 3 The EBIS system in Darmstadt uses turbopumps from Pfeiffer Vacuum.