mirror resonator chamber is evacuated. With this frequency comb, we will measure XUV lines very accurately. For this, we plan to guide its light into the new superconducting CryPTEx-II trap (Cryogenic Paul Trap Experiment II). Here, we cool the highly charged ions, first sympathetically by the cold ion crystal, and then by special laser techniques to reach the quantum-mechanical ground state of motion, extremely close to absolute zero.

Emission of Highly Charged Ions – Spectroscopy of Plasmas

The highly charged ions can be purposely excited by collisions, lasers or electron impact. Electrons in the ion then jump from lower to higher "orbits", or states. Their spontaneous jump back to the initial state then causes light to be emitted. This radiation has very well-defined wavelengths, characteristic for each ion type, which can appear from the optical and ultraviolet ranges all the way to hard x-rays. Highly sensitive detectors collect and analyse the emitted photons. In the solar corona, a plasma at a temperature above one million degrees extends several solar radii above the surface. Iron ions in various charge states present there emit extreme ultraviolet radiation, which reveals the local temperatures. Some long-lived excited states are affected by collisions and the density of the plasma. In an EBIT, these plasma parameters can be adjusted as desired, and their respective spectral features and lifetimes precisely measured. The results are compared with the theory in order to investigate the contribution of QED effects of growing complexity in strong fields.

Free-electron lasers and synchrotron storage rings deliver x-ray light with high intensity. To use this light, we bring our instruments there. An important example in this context: Two prominent x-ray emission lines of 16-fold charged iron exhibit an intensity ratio both in the laboratory and in space that contradicts the respective most precise calculations. Due to this, the determination of temperatures and densities in astrophysics becomes uncertain. While our thorough, highly precise measurements and calculations using top-level methods rule out all hitherto proposed explanations for this discrepancy and thus exacerbate the contradiction, our new accurate experimental results may be used in the meantime to empirically correct the astrophysical models.

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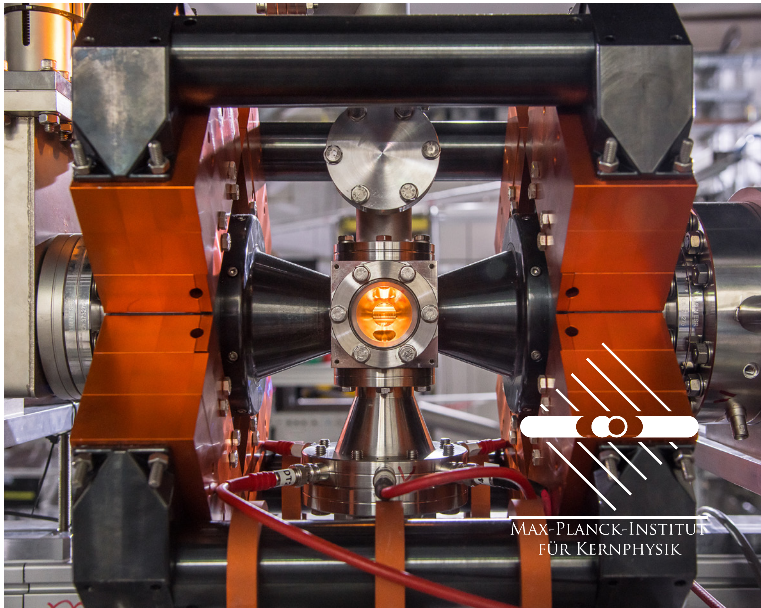
Highly Charged Ions

at 100 Million Degrees or Close to Absolute Zero



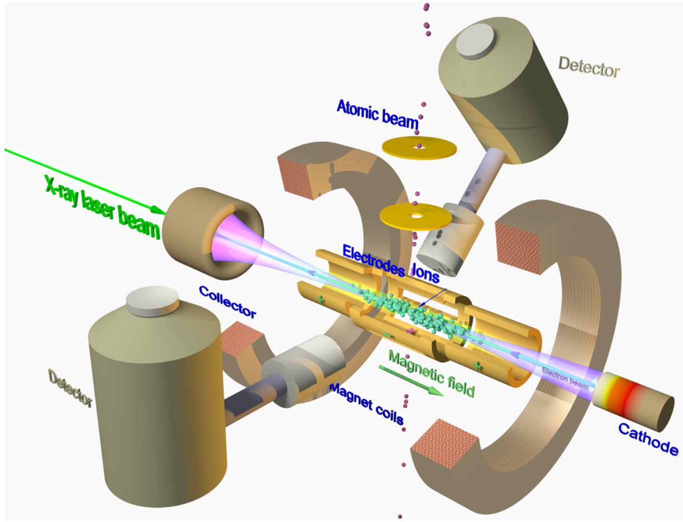
Highly Charged Ions at 100 Million Degrees or Close to Absolute Zero

Both in the interior of stars and their surroundings temperatures of several million degrees prevail. Also matter spiralling down into black holes or matter attracted by neutron stars from a companion normal star reaches such high temperatures. In these extreme conditions, atoms lose their electrons through collisions forming a mixture of positive ions and free electrons, a hot plasma. Light emitted by the ions then reveals key information about their properties. Such stellar furnaces can be reproduced and controlled in the MPIK laboratories with compact instruments: Electron beam ion traps (EBITs) produce and trap highly charged ions. Our experiments accurately test effects from Einstein's theory of relativity and quantum electrodynamics (QED), and look for possible weaknesses of fundamental theories of physics. Cooled highly charged ions could become the basis of the most precise clocks, and – together with novel frequency combs – could serve as pacemaker at still inaccessible frequencies up to the x-ray regime. For this purpose, we probe the quantum-mechanical development of electronic energy levels with their ultrashort laser pulses.

Production of Highly Charged Ions in EBITs

Formerly, highly charged ions could only be produced by powerful particle accelerators. However, EBITs can now generate such ions through constant electron impact. An electron beam, focused to the width of a hair by a superconducting magnet with a field strength of up to 8 Tesla, produces highly charged ions and holds them floating in space. In this way, under vacuum conditions close to that of interstellar space, we make ions alike those present in the Universe at temperatures of many million degrees. These are then systematically investigated directly inside the EBIT, or are extracted for use in other experiments.

Our newest development, miniature EBITs, reach field strengths of 0.86 Tesla with permanent magnets (see the title picture). Their small size enables new applications, for example in precision experiments with lasers or at synchrotron x-ray sources.

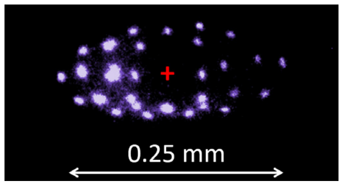


Electron impact or X-ray lasers excite the trapped ions. The resulting fluorescence is registered and analysed by various types of detectors and spectrometers.

Cold Highly Charged Ions – Towards the Most Precise Atomic Clocks

Highly charged ions hold their remaining electrons very tightly bound. Exciting them optically is very difficult due to quantum-mechanical rules; nonetheless, at MPIK we achieved this by means of lasers. Weak "forbidden" transitions in atomic ions are the cornerstone of the newest and most precise atomic clocks. We are developing such a clock using highly charged ions as a pacemaker. They are much less sensitive to external perturbations than any of the systems currently in use. Should the precision of atomic clocks increase further, then experiments that measure the temporal stability of natural constants would become feasible.

For this purpose, we have developed a technique to prepare ions from our EBITs at millikelvin temperatures by means of floating laser-cooled ensembles of ions (ion crystals) in a cryogenic Paul trap. Here, we cooperate closely with the Physikalisch-Technische Bundesanstalt at Braunschweig. Using a single frozen ion pair Ar^{13+}/Be^{+} and an ultrastable laser, and by applying the concept of quantum logic – where the spectroscopic signal searched for is transferred from the highly charged ion with two laser pulses to the beryllium ion – it was possible to determine the energies of spectral lines of the highly charged ion several million times more precisely than by traditional spectroscopic techniques.

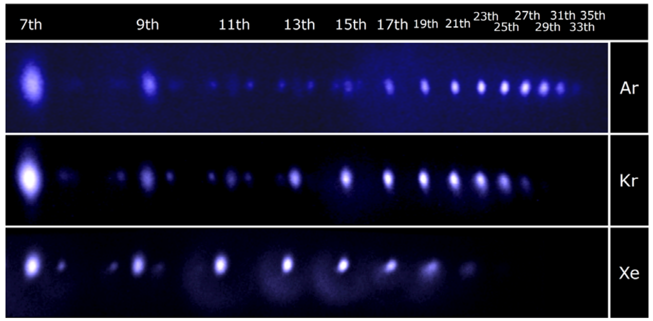


In the CryPTEx trap, a single, invisible Ar^{13+} ion (cross) is surrounded and cooled down below 100 mK by 29 crystallised Be^{+} ions fluorescing in the laser light.

Further, we could identify an optical clock transition in nine-fold positively charged praseodymium ions by high-precision relativistic atomic structure calculations, and exactly measure its wavelength. This line is extremely insensitive to external perturbations and, due to its unusual electronic structure, ideally tailored to test the temporal stability of natural constants.

The XUV Frequency Comb

Precision spectroscopy in the extreme ultraviolet (XUV) or even the x-ray region not only requires light sources with laser properties, but also highly charged ions, since only these remain sufficiently stable under such an irradiation. For this wavelength range, we have developed at MPIK a novel highly precise light source, an XUV frequency comb, which is based on the production of high harmonic frequencies of the laser light of an infrared frequency comb. At 100 million times per second repetition rate, its very short (150 femtoseconds), intense laser pulses are first amplified, then hundred-fold coherently superimposed in a mirror resonator, and thus further enhanced. There, the pulses are focused onto a noble-gas atomic beam, inducing a structure in the spectrum of each of the high harmonics, called an XUV frequency comb. Since air absorbs XUV radiation, the



Fluorescence images of different harmonic orders of argon, krypton und xenon in the XUV frequency comb.