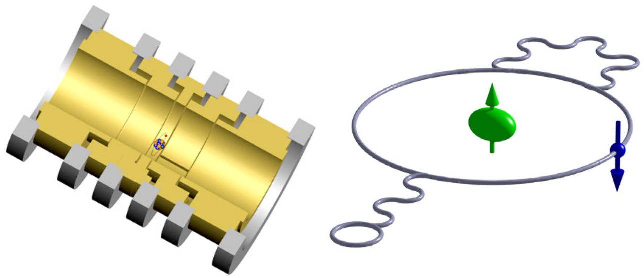

Left: A highly charged ion with only one electron stored in a cylindrical Penning trap. Right: Schematical illustration of the quantum electrodynamical effects of an electron (blue), orbiting around a nucleus (green) and interacting with a strong external magnetic field.

The *g*-factor experiment ALPHATRAP at the MPIK performs such measurements, in which the electron is bound in highly charged ions and thus experiences extremely strong electromagnetic fields in the vicinity of the nucleus. To date, measurements on highly charged silicon ions represent the most precise test of quantum electrodynamics in strong fields of bound states. Conversely, the comparison of measured data and theoretical results allows, for example, to determine with high precision the electron mass or the fine-structure constant α, since these enter the calculation as parameters. This way, our group successfully achieved the presently most accurate determination of the electron mass. In the future, ALPHATRAP will make it possible to perform these tests of QED also in the strongest fields using very heavy, highly charged ions and to contribute to a precise determination of fundamental constants of the standard model.

Another *g*-factor experiment in the future will aim to precisely measure the magnetic moment of a single helium-3 nucleus and the hyperfine structure in singly charged helium-3. These measurements will allow to establish hyperpolarized helium-3 as a standard in magnetometry, and thus to contribute substantially to the determination of the magnetic moment of the muon. In addition, the measurements of the hyperfine structure will provide a precise test of QED in a system depending on nuclear spin, and complementary to measurements on muonic systems enable the determination of nuclear structure effects.

The MPIK contributes to further *g*-factor experiments to precisely measure the magnetic moments of the proton and the antiproton as a test of CPT symmetry (University of Mainz, CERN: BASE).

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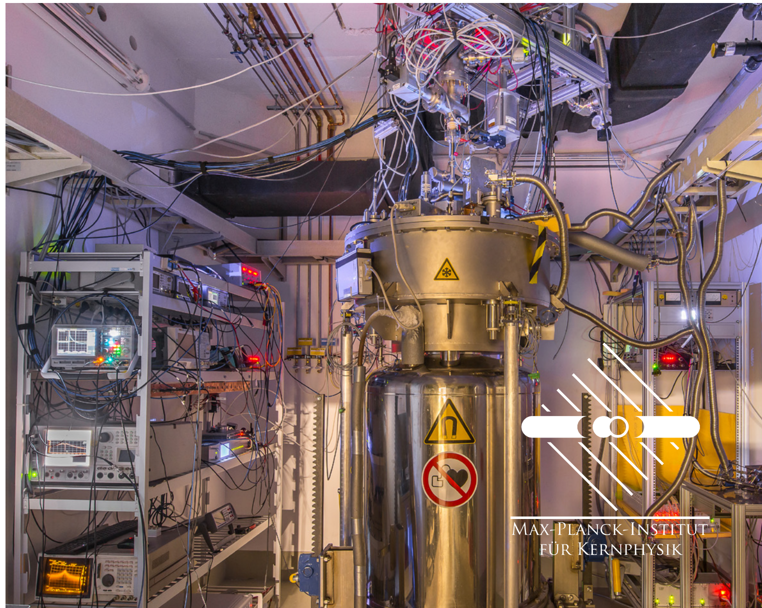
Penning Traps

Precision Measurements on Single Ions

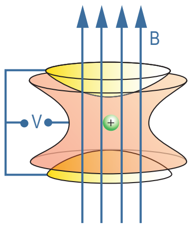


Penning Traps

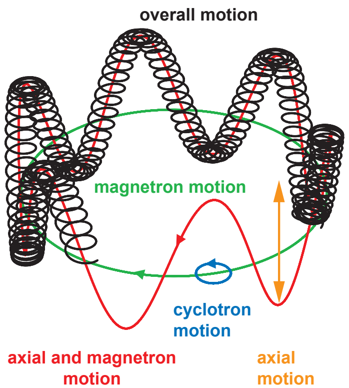
Precision Measurements on Single Ions

In order to approach answers to many questions in fundamental physics, the basic building blocks of nature must be investigated very accurately. Therefore, it is necessary to isolate and store single particles. With respect to charged atoms (ions), the so-called Penning trap has proven to be an ideal tool for this purpose.

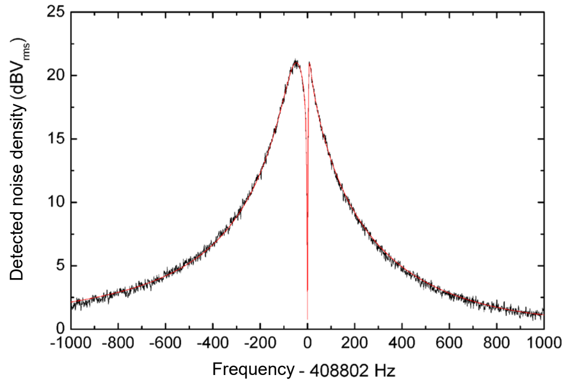
Principles of Penning Traps



The storage of single ions is possible due to their high sensitivity – because of their charge – to electric and magnetic fields. The first component of the Penning trap is a homogeneous magnetic field. The ion is forced on a circular orbit around the axis of the magnetic field by the Lorentz force. This two-dimensional harmonic motion is called cyclotron motion and has a frequency of $f_c = q \cdot B/(2\pi \cdot m)$, which is proportional to the external magnetic field strength B as well as to the charge-to-mass ratio q/m of the ion. However, the magnetic field does not confine ions along the field axis. This is achieved by an electrical quadrupole field superimposed on the magnetic field by means of suitably shaped trap electrodes. The combination of electric and magnetic fields thus leads to a three-dimensional confinement of the ion. The motion of the ion in the resulting total potential is now a complex orbit composed of three independent, harmonic eigenmotions.



Two in principle different methods are used to determine f_c: The first one is called “time-of-flight ion-cyclotron-resonance method” and enables the direct determination of the cyclotron frequency. To apply this method, an ion is resonantly excited around f_c and ejected from the trap. A single such measurement can be very fast, so this method is especially suited for short-lived nuclides. The alternative method comprises the measurement of the image current (~10^{-15} A) induced in the trap electrodes by the oscillating ion. This allows to determine the frequency non-destructively with one single ion for a repeated number of measurements over an extended period in time, thereby reducing the statistical uncertainty. Therefore, the image-current method is applied preferentially for stable nuclides.



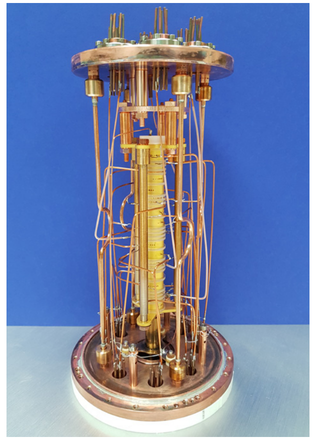
Signal of the axial frequency of a single stored and cooled ion in a Penning trap as a minimum in the noise spectrum of a superconducting oscillator circuit connected to the trap.

Nuclear Masses

Based on Einstein‘s principle $E = mc^2$, highly precise mass measurements provide important information about the binding energies in nuclei that are of interest in many fields of modern physics. For example, they enable tests of mass models or deliver input parameters for the description of nucleosynthesis in astrophysics.

As frequencies are among the best measurable quantities in physics, Penning traps are ideal tools to determine nuclear masses very precisely. Nowadays, short-lived radioactive nuclides are measured by the time-of-flight method with a relative precision of a few parts in 10^{-9}, but stable nuclides even down to 10^{-10}. Application of the image-current detection method allows relative precisions better than 10^{-11}.

The high-precision mass spectrometer PENTATRAP at the MPIK performs relative mass measurements on the accuracy level of 10^{-11} and below of long-lived, highly charged ions in the mid-heavy to heavy regime. Mass measurements at this level of precision can contribute to different fields of physics, such as tests of special relativity and bound-state quantum electrodynamics (QED), a next generation of atomic clocks, neutrino physics and dark matter research. A unique feature of PENTATRAP is the synchronous operation of five Penning traps allowing simultaneous measurements in several traps, which decreases systematic shifts. The application of the non-destructive image-current detection technique allows for frequency measurements over several hours to days, thereby reducing the statistical uncertainty. Highly charged ions for PENTATRAP are produced in two electron beam ion traps, one of which employs a laser ablation setup to provide ions from tiny, nanogramme-sized samples of rarely abundant isotopes. These are needed, for example, for planned contributions to the determination of the upper limit of the electron neutrino mass using the rare isotope 163Ho.



The PENTATRAP trap tower with electronics.

Further Penning trap mass spectrometer experiments have access to exotic nuclides at external accelerator facilities (GSI: SHIPTRAP, CERN: ISOLTRAP) or nuclear reactors (University of Mainz: TRIGA-Trap).

Magnetic Moments

Another basic property that can be measured with high precision using Penning traps, is the magnetic dipole moment of the ions, which is determined by the “g factor”. This is a dimensionless constant connecting the strength of the magnetic moment of a particle with its intrinsic angular momentum (spin). In the framework of quantum electrodynamics, the g factor can be calculated very accurately. Thus, precise measurements validate these calculations and, therefore, provide a test of the predictive power of the standard model. Experimentally, the spin direction in an external magnetic field can be determined via the Stern-Gerlach effect by precisely measuring a frequency of motion. Oscillating magnetic fields induce a transition between the two spin orientations. The g factor results from the associated resonance frequency.