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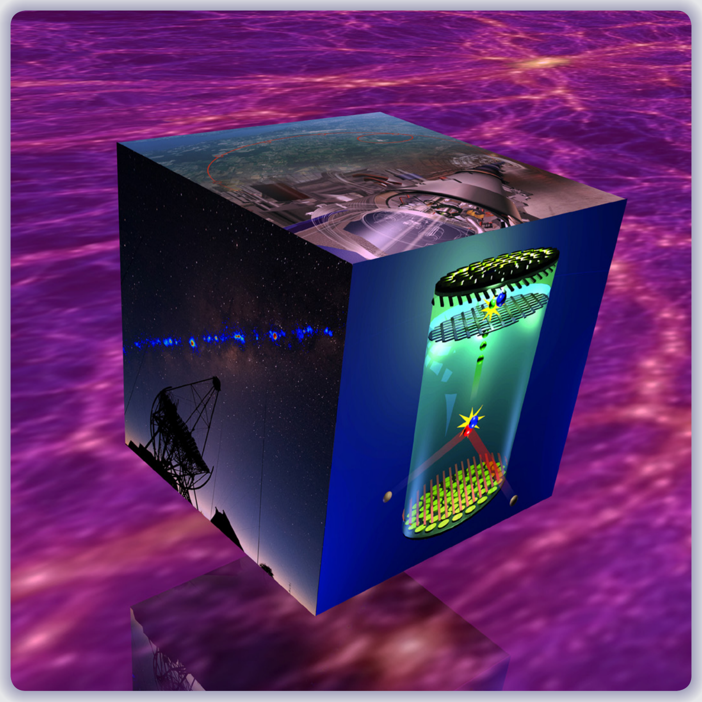
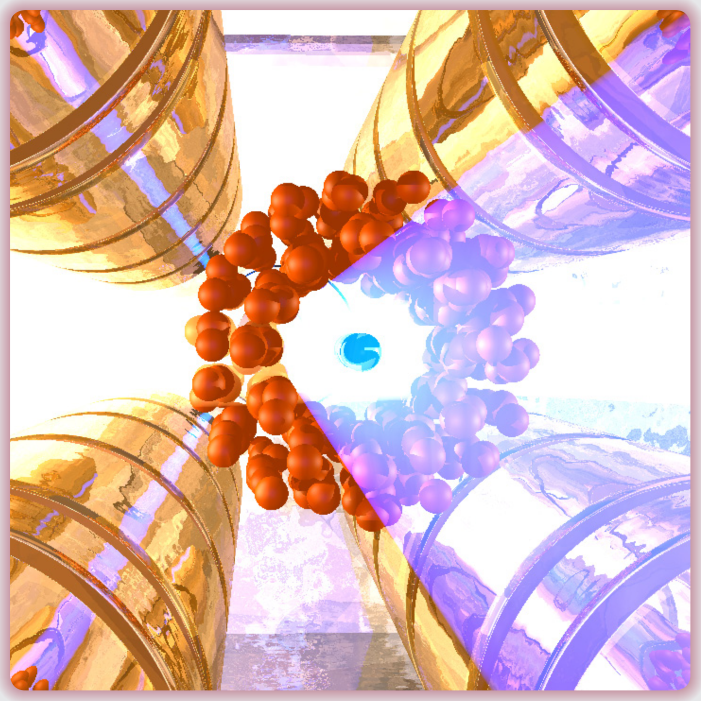
The Institute and its Fields of Research

ASTROPARTICLE PHYSICS

QUANTUM DYNAMICS





Astroparticle Physics:
Complementary strategies for searching dark matter:
direct, indirect and collider.
Background: millenium simulation (MPI for Astrophysics)

Quantum Dynamics:
Ion trap CryPTEx:
highly charged ions are cooled and embedded at defined positions in a laser-cooled ion crystal.

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The Institute and its Fields of Research

Astroparticle Physics	**The High-Energy Universe** **Invisible Particles** **The Search for New Physics**
Quantum Dynamics	**Highest Precision** **Observing Fastest Motions** **Exploring the Extremes**
Infrastructure	**Scientific and Technical Service**

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Overview

The Max Planck Institute for Nuclear Physics (MPIK) is a research establishment of the Max Planck Society (MPG) for the Advancement of Science, which is committed to basic research in all fields of science.

The MPIK was founded in 1958 under the leadership of Wolfgang Gentner. Its precursor was the Institute for Physics, a part of the MPI for Medical Research, led by Walther Bothe from 1934 to 1957. Since 1966 the MPIK has been led by a board of directors. The initial scientific goals were basic research in nuclear physics and application of nuclear-physics methods to questions concerning the physics and chemistry of the cosmos.

Today, activities are concentrated in the two interdisciplinary research fields **Astroparticle Physics (the crossroads of particle physics and astrophysics)** and **Quantum Dynamics (dynamics of atoms and molecules)**.

Scientists at the MPIK collaborate with other research groups from all over the world. They are involved in a large number of international collaborations, partly in a leading role. Particularly close connections exist to some large-scale facilities such as GSI Helmholtzzentrum and FAIR (Darmstadt), DESY (Hamburg), CERN (Geneva), INFN-LNGS (Assergi L'Aquila) and LCLS (Stanford).

Klaus Blaum *Christoph H. Keitel* *Manfred Lindner* *Thomas Pfeifer* *Jim Hinton*

In the local region, the Institute cooperates closely with Heidelberg University, where the directors and further members of the Institute hold teaching positions. To foster young scientists, three International Max Planck Research Schools (IMPRS) have been established together with other institutes.

The Institute's support units contribute considerably to the successful scientific work: precision mechanics and electronics shops both with affiliated apprentices' training shops, engineering design office, information technology, radiation protection, safety and environment, library, public relations and media, as well as administration and technical building services.

In addition to the scientific divisions, at the Institute there are several independent research groups led by young physicists, as well as senior Max Planck Fellows. Scientifically, they are affiliated to one of the divisions and thus broaden its research focus.

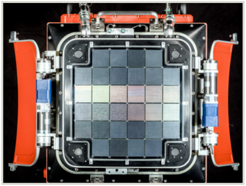
The Scientific Divisions

Prof. Dr. K. Blaum – stored and cooled ions

The division focuses on precision experiments with stored and cooled ions as well as on the investigation of fundamental processes of molecular ions. For this purpose, short-lived radionuclides, highly-charged ions or simple molecular ions are trapped in Penning traps and storage rings under conditions similar to those in space. This is complemented by the development of novel storage, cooling and detection techniques for future experiments.

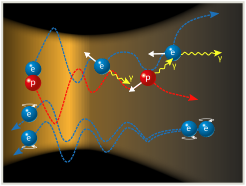
Prof. Dr. Jim Hinton – non-thermal astrophysics

Research in the division covers two main areas. High-energy astrophysics, employing both Cherenkov telescopes for atmospheric Cherenkov radiation and dense particle detector arrays, explores the sources and acceleration processes of high-energy particles in the Universe. Particle physics experiments on heavy-quark production and decays and the search for the neutrinoless double-beta decay probe the standard model of particle physics.



Honorarprof. Dr. C.H. Keitel – theoretical quantum dynamics and quantum electrodynamics

The efforts of the division focus towards a detailed understanding of the quantum mechanical interplay of all constituents of atomic, ionic and nuclear systems with laser and X-ray fields considering also relativistic and QED effects. The theoretical work equally aims at optimizing various applications such as high-precision tests, nuclear quantum control, particle acceleration, or creation of new particles.

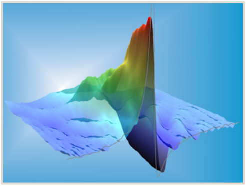


Prof. Dr. Dr. h.c. M. Lindner – particle and astroparticle physics

The division works on current topics in particle and astroparticle physics with a considerable overlap between experiment and theory. The focus of the experimental activities is on projects in the fields of neutrino physics and the search for dark matter. The broader theoretical activities include phenomenological interpretations of experimental data and purely theoretical questions in a broad context of particle and astroparticle physics.

Prof. Dr. T. Pfeifer – quantum dynamics and control

Scientifically, the division focuses on the fundamental quantum dynamics of small systems (atoms, molecules, ions, nuclei) and their interaction and control by strong fields. Precise spectroscopic (“listening”) and imaging (“watching”) experimental methods serve as tools to find answers to fundamental questions about the nature of motion on very short and very long time scales.



THE HIGH-ENERGY UNIVERSE

Gamma-ray sources along the Milky Way discovered by the H.E.S.S. Cherenkov telescope array in Namibia.

What are the cosmic sources of high-energy gamma rays?
How and where are cosmic particles accelerated?
What impact do relativistic particles have on astrophysical systems?

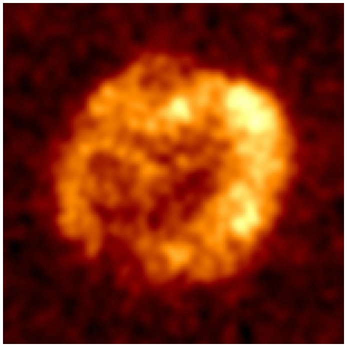
Cosmic Accelerators – Astronomy at the Highest Energies

High-energy astrophysics at MPIK is characterized by a close cooperation between experimentalists and more theoretically oriented astrophysicists. They study non-thermal phenomena in the Universe using the High Energy Stereoscopic System H.E.S.S. in Namibia and the High Altitude Water Cherenkov Detector HAWC in Mexico to detect very-high-energy (VHE) gamma rays from the cosmos, in order to understand the acceleration of particles to extreme energies in cosmic sources and the role that these particles play in astrophysical systems.

Particles in the VHE range cannot be produced as thermal radiation, as is the electromagnetic radiation in most other wavelength regimes; only in the Big Bang were high enough temperatures reached for a very short time. VHE gamma radiation is produced when strongly accelerated charged particles interact with the interstellar gas or photon fields. In contrast to the charged particles, known as cosmic rays, the gamma rays travel in a straight line from the source to the observer, allowing the imaging of sources and the study of the astrophysical processes at work.

Charged particles can obtain very high energies in many astrophysical sources, for example in the giant shock waves generated in supernova explosions or in the plasma jets emerging from the immediate vicinity of the massive black holes at the centres of active galaxies. Considerable effort at the Institute is going into the modelling and theoretical description of processes within the different cosmic accelerators, as well as into VHE observations.

Recent highlights from H.E.S.S. include the detection of gamma-ray bursts and the first resolved emission from the jets of active galaxies in the gamma-ray band. In 2018 a whole issue of the journal Astronomy & Astrophysics was dedicated to H.E.S.S. observations within our own galaxy, where more than 80 VHE gamma-ray sources have been discovered. These objects include many supernova remnants and pulsar wind nebulae, several discovered in follow-up observations at other wavelengths, following the H.E.S.S. detections. The centre of the Milky Way is of particular interest and with H.E.S.S. VHE emission has been

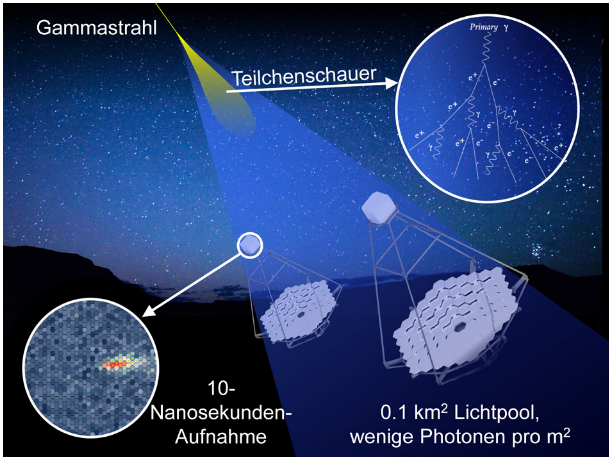


The supernova remnant-RX J1713-3946 in very-high-energy gamma-ray light..

established from very close to the supermassive black hole at the heart of our galaxy, and also from gas clouds in the central region, bombarded by cosmic rays with up to petaelectronvolt (1 PeV = 10^{15} eV) energies and glowing in gamma rays.

HAWC observations complement those of H.E.S.S., providing sensitivity to larger-scale emission and up to higher energies. HAWC recently revealed very extended halos of high-energy electrons around two nearby pulsars and emission from the jets of the enigmatic Galactic micro-quasar known as SS 433.

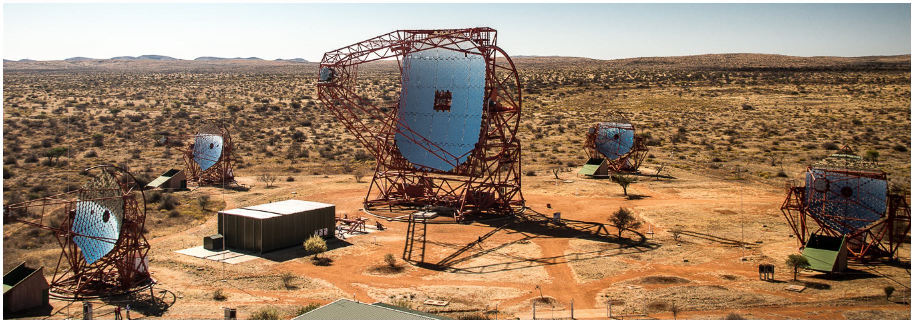
Cherenkov Telescopes and Water Cherenkov Detectors



Observing gamma rays with Cherenkov telescopes.

High-energy gamma rays from space – a trillion times more energetic than visible light – do not reach the Earth's surface. Nevertheless, they can be detected at ground-level via the particle cascades (known as air showers) that they generate in the Earth's atmosphere. One detection method makes use of the faint, bluish, and extremely short flashes of light (Cherenkov light) which the air showers produce. On dark nights these flashes can be detected using very large reflecting telescopes equipped with very fast and highly specialised cameras. To determine accurately the direction of the incoming gamma ray, the shower is observed stereoscopically by several of these telescopes.

H.E.S.S. consists of five telescopes, four of them are identically constructed, each with 107 m² mirror area and deployed in a square of side length 120 m. A camera composed of light sensors is placed at the focus of each mirror. In the centre of the array, a fifth, huge telescope with 614 m² mirror area equipped with and a camera of novel technology, enhances the sensitivity of the system and extends observations to lower energies. H.E.S.S. was the first instrument that was able to produce true images of astrophysical gamma-ray sources.



The H.E.S.S. Cherenkov telescope system in Namibia.

Preparations are underway for a next generation observatory with dramatically improved performance. The Cherenkov Telescope Array (CTA) will consist of two arrays, in Chile and the Canary Island of La Palma, with around 100 telescopes of three different sizes. CTA will bring much better resolution, higher sensitivity, a much wider energy range, and a collection area of many square kilometres at the highest energies. The MPIK instrumentation effort is in developing state-of-the-art cameras for small and medium-sized telescopes.

At high-altitude sites, the shower particles can be observed directly – and around the clock – using water-filled detectors, where they also produce Cherenkov light. The main detector of the HAWC observatory consists of a dense array of 300 tanks at an altitude of 4100 m. The tanks are filled with high-purity water and equipped with light sensors. They are surrounded by a sparse array of 350 smaller "outrigger" tanks, which significantly improve the characterisation of particle showers hitting the boundary area of the main array. The MPIK is playing a major role in the development of a next-generation gamma-ray observatory with large field-of-view, placed in the southern hemisphere, the Southern Wide-field Gamma-ray Observatory (SWGO). SWGO will make use of the same detection principle as HAWC, but cover a larger area and record a wider range of gamma-ray energies.

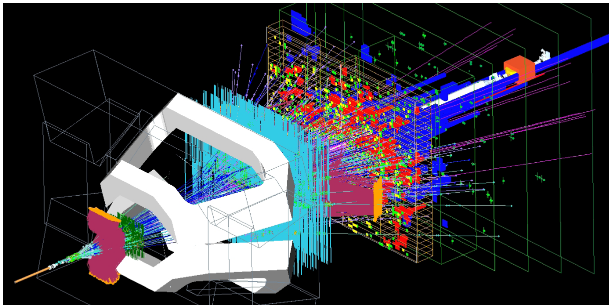
An "outrigger" tank in front of the main detector array of HAWC in Mexico.

The Early Universe – Elementary Particles at the Highest Energies

In high-energy collisions between elementary particles, a fraction of the kinetic energy is transformed into short-lived particles normally not found in nature, but that existed in the extremely hot and dense state of the Universe immediately after the Big Bang. Such particle collisions allow one to study the fundamental interactions between the elementary constituents of our world and to learn about the physics at the beginning of the Universe.

A group at MPIK is a member of the LHCb collaboration, which operates one of the four large experiments at the CERN Large Hadron Collider (LHC). In proton-proton collisions, the experiment does precision measurements of the properties of the strong, electromagnetic and weak interactions, and probes in proton-nucleus collisions the effects of the nuclear environment. Nucleus-nucleus collisions, finally, give access to collective phenomena in extended systems consisting of free quarks and gluons, so-called quark-gluon plasmas.

These measurements shed light on the properties of the Universe when it was less than a nanosecond old. At the same time, they contribute to the understanding of the interactions of high-energy cosmic rays with the atmosphere, which is needed for the interpretation of the data collected by the Cherenkov detectors.



Visualisation of a particle shower in the LHCb detector emerging from a proton-lead collision in the LHC.

INVISIBLE PARTICLES

The XENON experiment in the Gran Sasso underground laboratory in Italy.

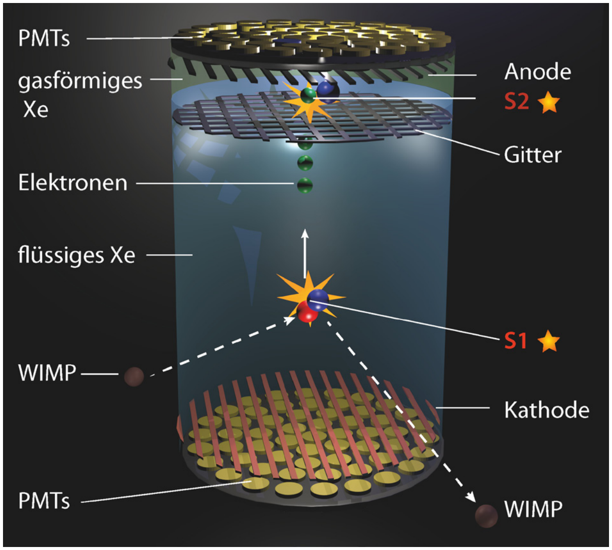
What is the nature of dark matter and how can it be detected?
Are neutrinos their own antiparticles?
What is their mass and how do they transform from one type into another?

Dark Matter – Structure-Forming Agent in the Universe

Astronomical observations such as galactic rotation curves, gravitational lensing at galaxy clusters or the cosmic microwave background suggest, that the Universe consists to about 27% of dark matter (DM), while the fraction of ordinary visible matter is only about 5%. The remainder is the mysterious dark energy which is made responsible for the acceleration observed in the expansion of the Universe.

From a theoretical point of view, weakly interacting massive particles, called WIMPs, are promising candidates for dark matter, since they should have formed in the early Universe in the required amount and since they are proposed in – anyway required – extensions of the Standard Model of particle physics. But MPIK researchers also study other solutions motivated by other theoretical aspects. Examples are “axions”, “sterile neutrinos” or particles only interacting gravitationally. Furthermore, combined analyses and interpretation of different experiments and embedding candidates into consistent theoretical models aim at a global picture and at resolving controversial results.

A division at the MPIK is involved in the direct search for WIMPs with the XENON experiments in the Gran Sasso underground laboratory in Italy which use ultrapure liquid xenon as the detector medium. The detectors are able to measure in a correlated manner the combination of scintillation light and ionization emerging from the expected rare interactions of WIMPs with xenon atoms. XENON1T reached the highest sensitivity of such experiments deeply probing into the expected parameter regions where WIMPs and other dark matter candidates are expected, but hasn’t so far seen a signal. This high sensitivity made it possible to

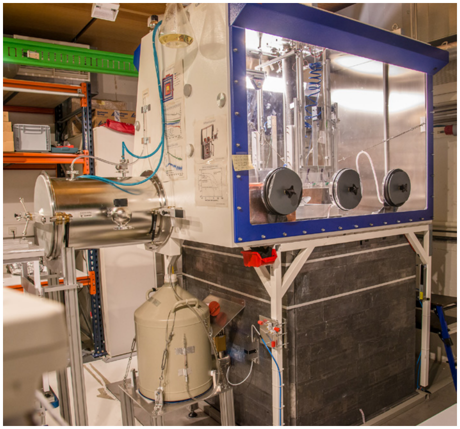


Operating mode of the XENON detectors. PMTs means photomultiplier tubes (light sensors), S1 and S2 are the prompt light signal and the delayed charge signal.

measure, by the way, a half-life of unimaginably long 1.8×10^{22} years for the double electron capture in ^{124}Xe. An upgrade to a larger detector, XENONnT, with a three-fold active xenon mass and using the same infrastructure is nearing completion and will lead to a ten-fold sensitivity increase.

In addition, the H.E.S.S. telescopes look for high-energy gamma rays, produced by the annihilation of dark-matter particles in the DM halo of the Milky Way.

Low Level Techniques



The GIOVE germanium spectrometer in the MPIK's underground laboratory.

Highly precise low-level techniques are essential for experiments looking for very rare events, where identification and reduction of the background plays a key role. At the MPIK, there is a long tradition and a lot of expertise in that field. The Institute's low-level underground laboratory provides shielding against cosmic rays and thus offers very good conditions for detector development for low-background experiments. Highly sensitive gamma-ray spectrometers and very pure miniature proportional counters serve to check the radiopurity of materials and are the heart of assay techniques for very low concentrations of radioisotopes.

Among the most notorious contaminants are the natural radioisotopes ^{222}Rn and ^{85}Kr, for which various world-leading screening, measuring and reduction techniques are employed. The "Auto-Ema" system extracts fully automatically the radon outgassing from solid materials allowing for its sensitive measurement and the selection of suitable detector materials. Rare-gas mass spectroscopy was pushed to ppq sensitivity which allows, for example, to control ^{85}Kr in Xe to the level of 10^{-23}. Novel surface coating technologies are developed in order to push the backgrounds to unprecedented levels and to be most sensitive to dark matter.

Neutrinos – Particles with Striking Properties

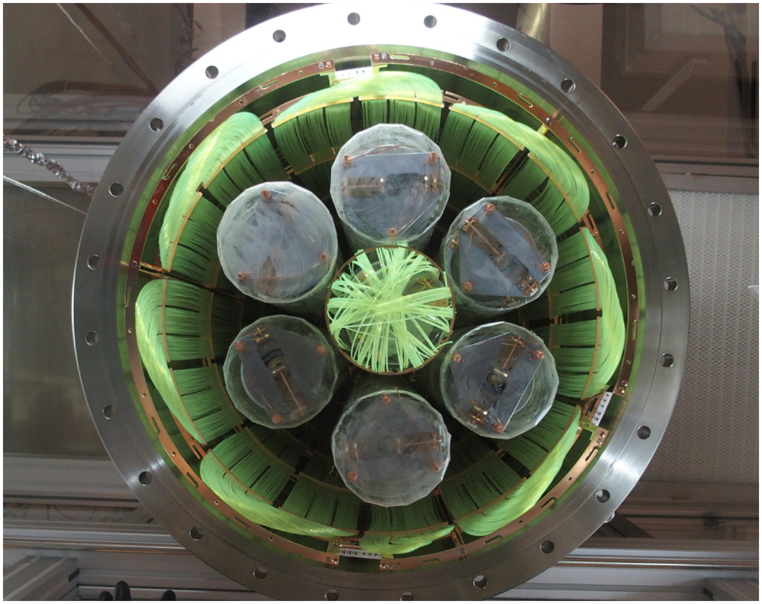
Neutrinos are electrically neutral elementary particles of tiny mass which occur as three different types, so-called flavours. Besides photons, they are the most abundant particles in the Universe, but we don't notice them as they interact only rarely with matter and penetrate it nearly without hindrance. Thus, highly sensitive detectors with excellent shielding against background signals are required to detect them.

When a neutron inside a nucleus beta decays to a proton and an electron, also an antineutrino is released and the element with the next higher atomic number forms. Some atomic nuclei, one of them the germanium isotope ^{76}Ge, are not subject to the single but instead the double-beta decay: two neutrons are decaying at the same time with emission of either two or possibly no neutrino. The GERDA experiment searched for the neutrinoless double-beta decay in pure germanium crystals highly enriched in ^{76}Ge. Neutrinoless double-beta decay, which is well motivated by theory, is an extremely rare event. Until now, no evidence for the decay was found – only that its half-life in ^{76}Ge must be at least $1{,}8 \times 10^{26}$ years. The successor project LEGEND200 is based on GERDA with a significantly higher ^{76}Ge mass which will improve the sensitivity considerably. A signal would prove that neutrinos are their own antiparticles, so-called Majorana particles, making it possible to deduce their mass.

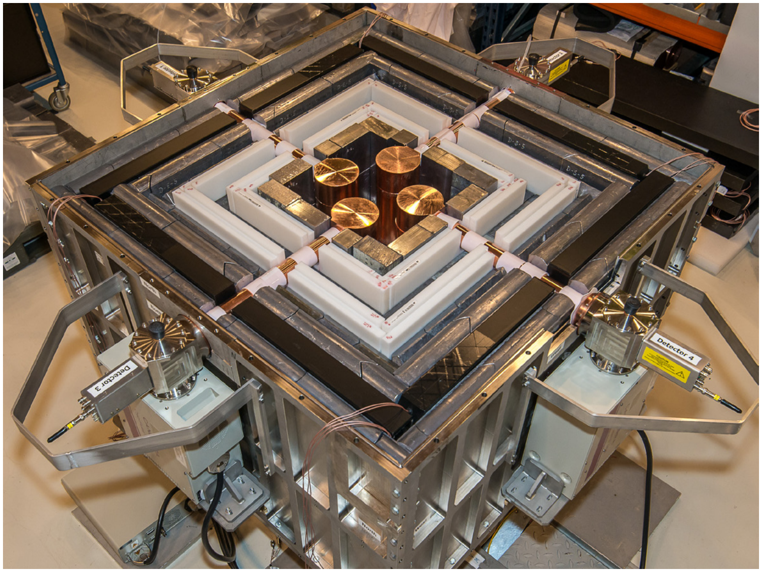
For the rest mass of neutrinos only limits and differences are known to date. Other experiments to determine the neutrino mass rely on the capture of an electron by a proton in a nucleus. Therefore, the knowledge of the exact mass difference between mother and daughter nucleus is necessary. A group at the MPIK is performing such precision measurements.

The three neutrino types (electronic, muonic and tauonic flavour) periodically change this property ("neutrino oscillations"). Therefore, with increasing distance from a nuclear reactor, which is a strong electron antineutrino source, the number of these neutrinos detected decreases. This way, besides other experiments, Double Chooz could verify that all oscillations take place and make precise measurements of their parameters. However, many experiments in the vicinity of nuclear power plants detect overall about 6% less neutrinos than expected. The STEREO detector tries to find out whether sterile, i.e. non-interacting, neutrinos might be responsible for this reactor neutrino anomaly. The segmented detector measures electron antineutrinos by means of a liquid gadolinium-containing scintillator. A changeover to sterile neutrinos would become visible in their energy spectra.

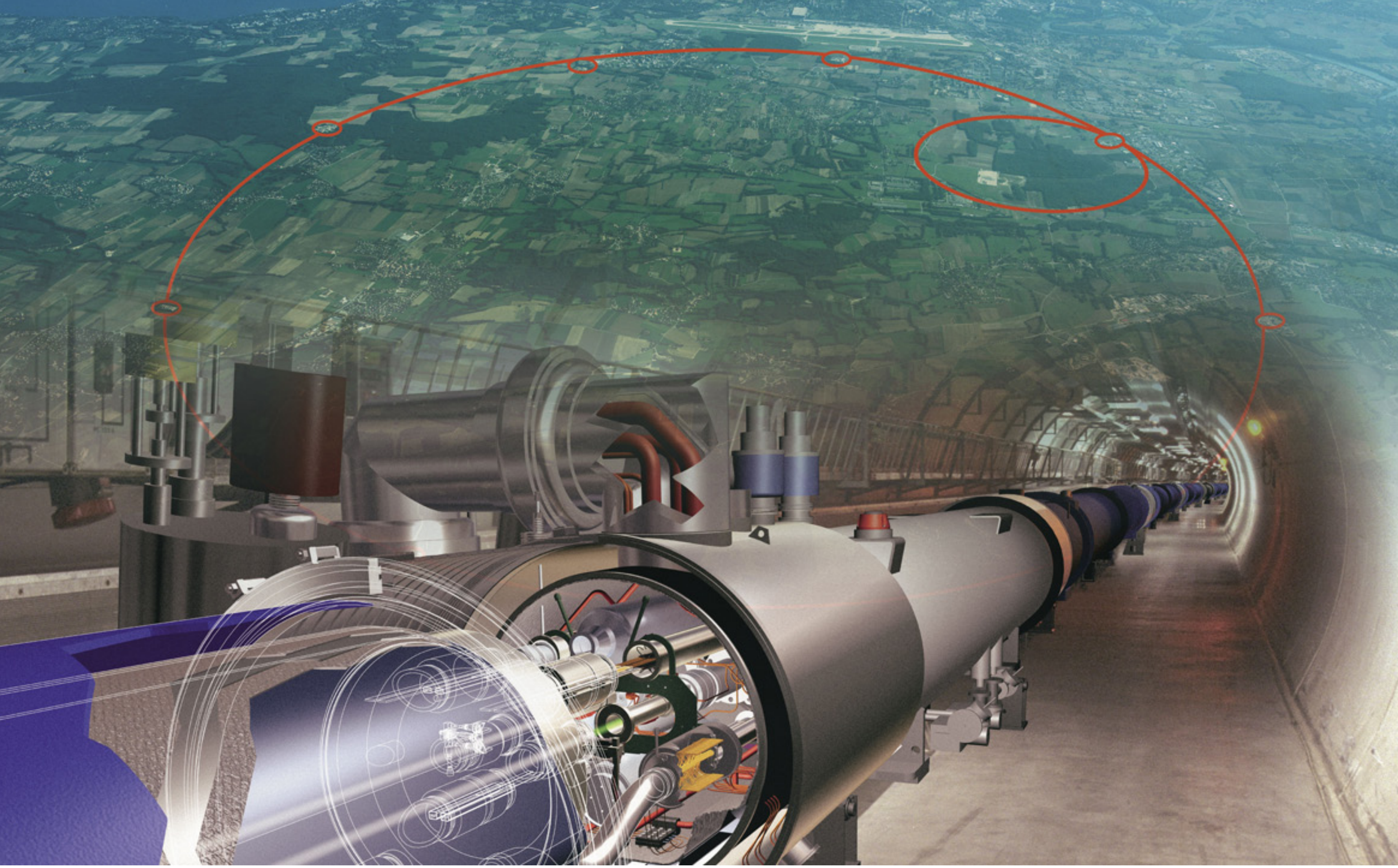
The CONUS experiment also uses reactor neutrinos to investigate the coherent neutrino-nucleus scattering – scattering of neutrinos at the nucleus as a whole. Highly pure germanium detectors with very low energy threshold measure the tiny energy transfer due to this scattering process, which, however, is significantly more probable than the interaction of neutrinos with electrons.



The germanium detectors of GERDA in their shielding.



Layers of lead and polyethylene shield the cooled germanium detectors of CONUS against radioactivity.



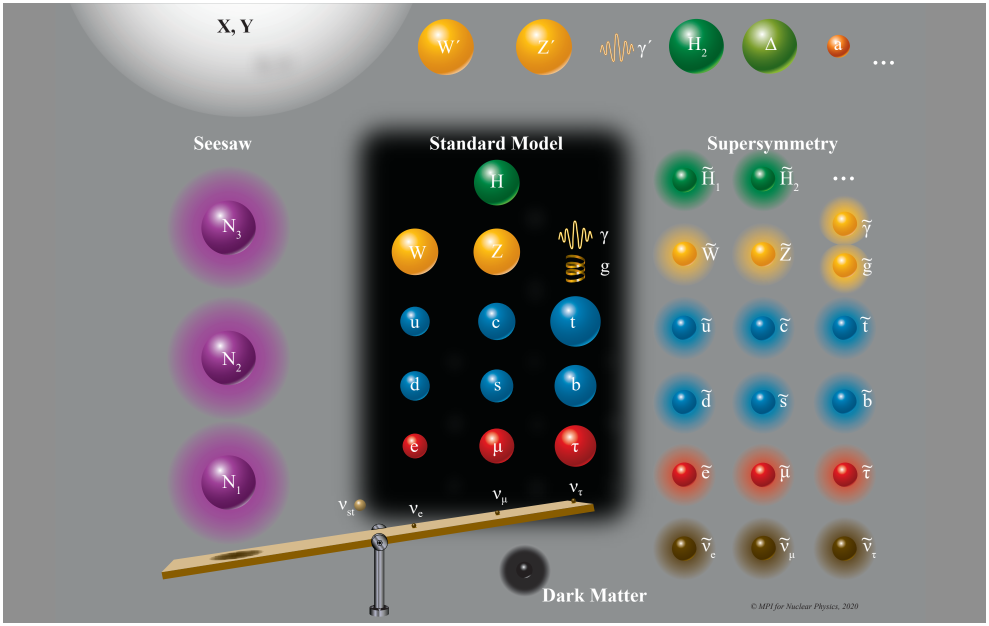
THE SEARCH FOR NEW PHYSICS

An upgrade of the Large Hadron Collider may detect physics beyond the Standard Model. (Image: CERN)

Which extensions are required for the Standard Model of elementary particle physics?
Why is there practically no antimatter in the Universe?
How can the fundamental forces of nature be unified?

The Origin of Mass – Physics Beyond the Standard Model

The Standard Model of elementary particle physics successfully describes all known elementary particles (and corresponding antiparticles): each 6 quarks and leptons. In addition, there are gauge bosons mediating the particle's interactions, and the Higgs boson. Its discovery on 2012 opened a number of fundamental questions that are addressed by theoreticians at the MPIK.



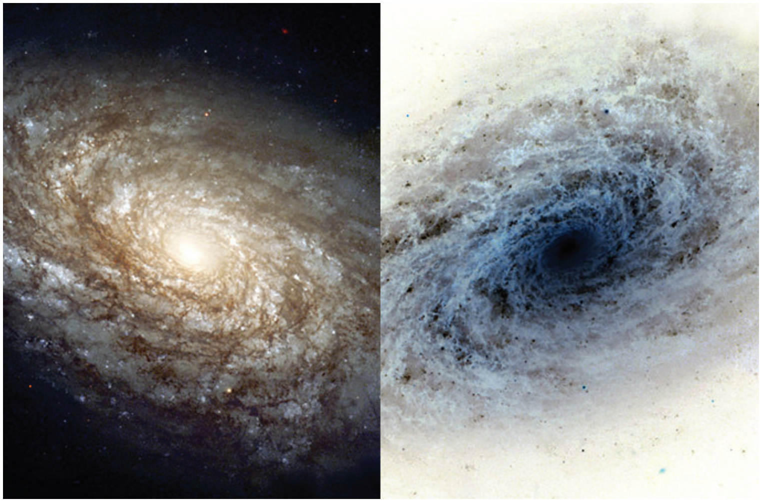
Elementary particles of the Standard Model (black background) and hypothetical particles.

Both dark matter and the proof of non-zero neutrino masses as well as some further theoretical deficiencies require an extension of the Standard Model of elementary particle physics which seems to be valid only up to a certain energy, from which on so-called new physics comes into play. Theoreticians of the MPIK are studying supersymmetry and Grand Unified Theory as promising extensions of the Standard Model in connection to present and future particle physics experiments, and cosmology.

A lot of theoretical work is done at MPIK on the origin of neutrino masses and mixings via basic and phenomenological studies. The so-called seesaw mechanism is a way to explain the smallness of neutrino masses based on the presence of new heavy particles, which are in fact predicted by many theories beyond the Standard Model. Neutrino masses and dark matter may have a common origin. The overall aim is a deeper understanding of the fundamental laws of nature.

Matter and Antimatter – Search for the Crucial Difference

There is no indication that anywhere in the visible Universe considerable amounts of antimatter exist. Since particles and antiparticles must have been created in equal amounts in the Big Bang, there must be a fundamental difference between them. Else, they would have completely annihilated, leaving a Universe filled with pure radiation.

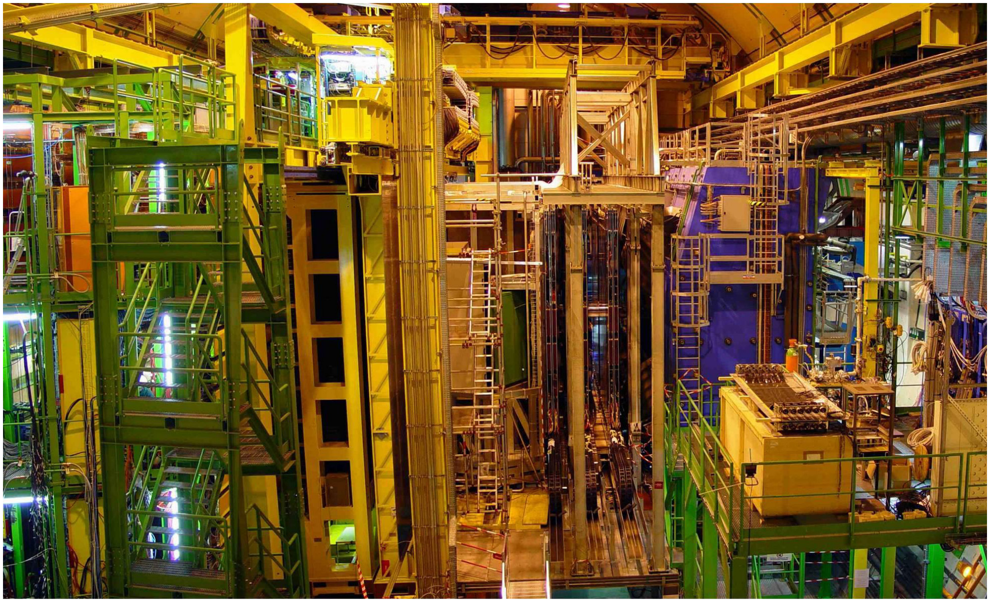


Despite intensive searches, astronomical observations have not provided any evidence of the existence of antigalaxies. Left photo: Hubble Space Telescope

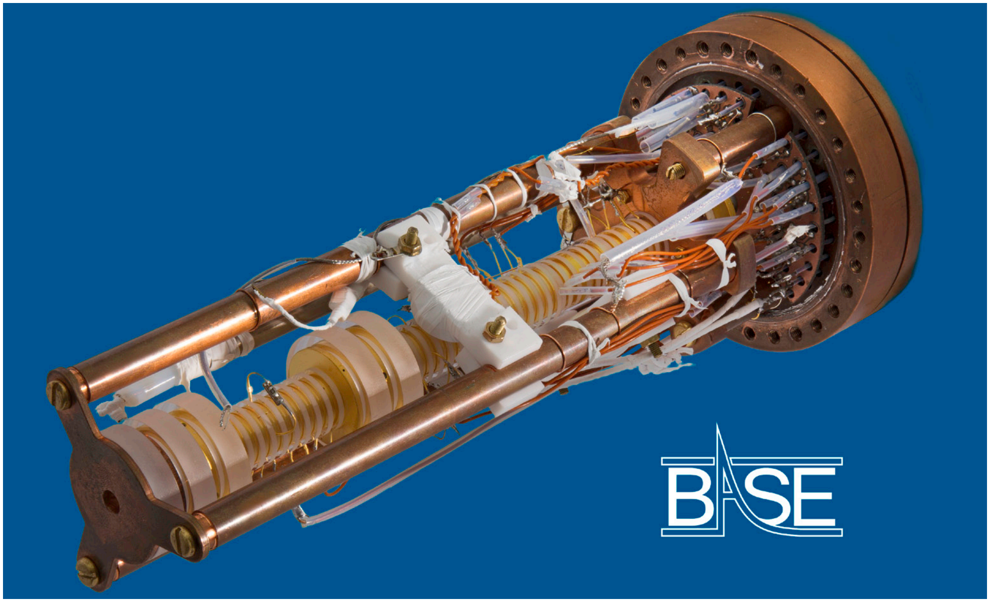
This symmetry violation must have occurred in the early Universe, but the Standard Model of elementary particle physics can’t explain the observed excess of matter over antimatter. A scenario for this, in which neutrinos play a crucial role, is the so-called leptogenesis which is explored by MPIK theoreticians. Here, the asymmetry of light particles subsequently induces the observed asymmetry of heavy particles.

The LHCb experiment at the Large Hadron Collider (LHC) of CERN in Geneva searches for matter/antimatter differences. Besides many other particles, in proton-proton collisions so-called B mesons are created, heavy particles consisting of each a light quark and a heavy antiquark; and reversely for their antiparticles. Measurements of their decays that lead to equal amounts of matter and antimatter showed that there are processes in which antimatter disappears faster than matter – however within the frame predicted by the Standard Model of elementary particle physics.

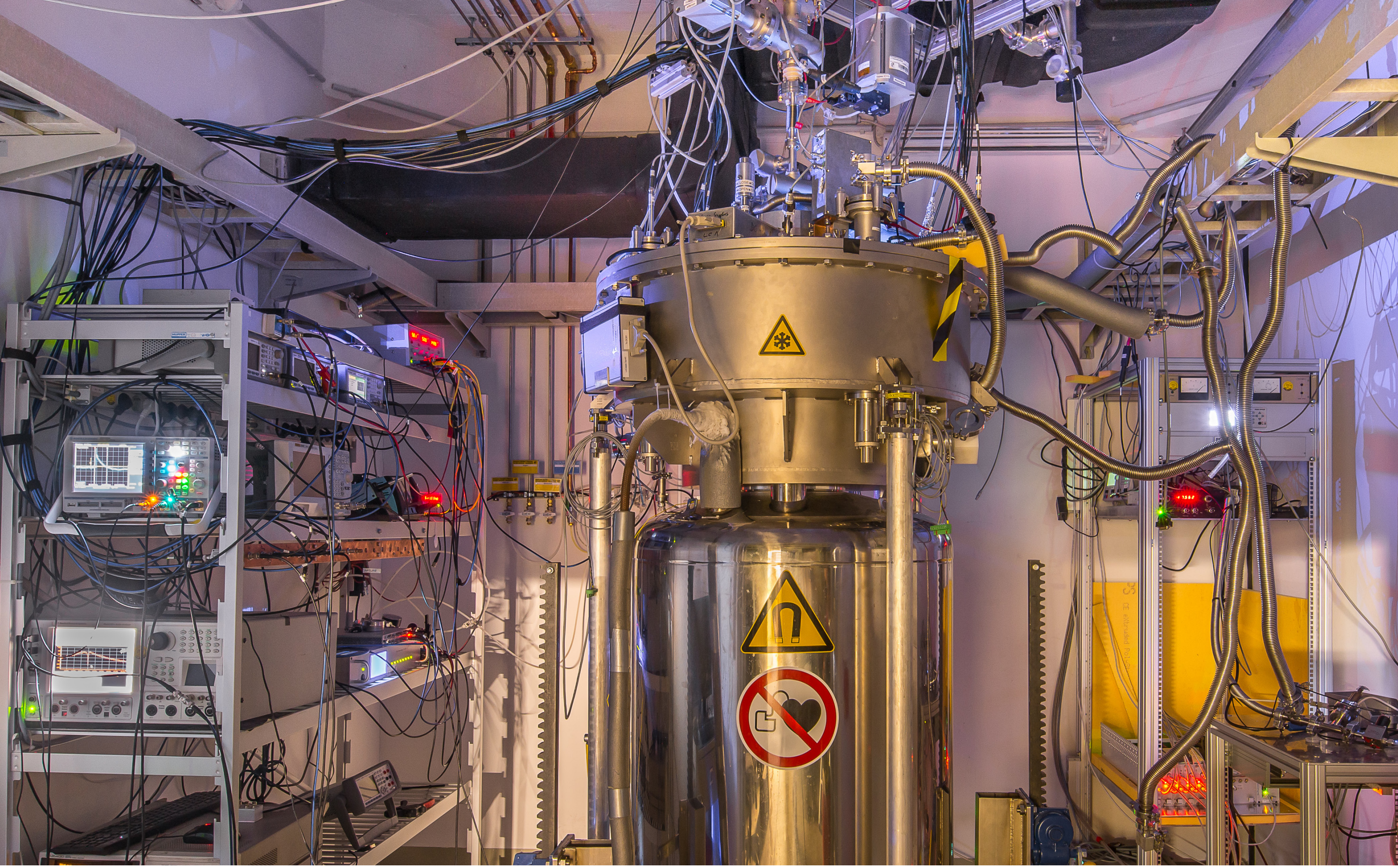
Measurements of the masses as well as of the magnetic moments of the antiproton and the proton in Penning traps didn’t yet reveal any differences despite the highest precision. But further advanced measurement techniques may resolve the puzzle.



The LHCb detektor with about 20 m in length and 10 m in hight has the dimensions of a one-family house.



The filigree Penning-trap system for measuring the magnetic moment of the antiproton has a lenght of about 15 cm.



Highst Precision

The ALPHATRAP laboratory.

What can we learn from the exact mass of nuclei?
What are the properties of highly charged ions?
Are natural constants really constant?

Nuclei – From the Building Blocks of Matter to the Formation of Elements

For basic research in physics, it is of great importance to know as exactly as possible the fundamental properties of atomic nuclei. Penning-trap mass spectrometry at MPIK allowed recently to perform world-record precise measurements of the atomic masses of the electron and proton, i. e., the simplest nucleus. The proton mass was found to be smaller than the previously accepted value. This helped to understand observed discrepancies in the masses of light nuclei.

Looking at heavier elements, the chemical composition of our Universe shows some surprising peculiarities: The Sun mainly consists of hydrogen and helium; iron is much more abundant on Earth compared to heavy elements like gold. Nucleosynthesis follows reaction paths involving fusion and capture processes, some of them yet mostly unexplained. Since nuclear fusion stops at iron, the most stable element, heavier elements are generated via proton or neutron capture under extreme conditions like in supernova explosions of stars or in hot environments like accretion discs around black holes or neutron stars.

Based on Einstein's principle of mass-energy equivalence, high-precision mass measurements are a power-

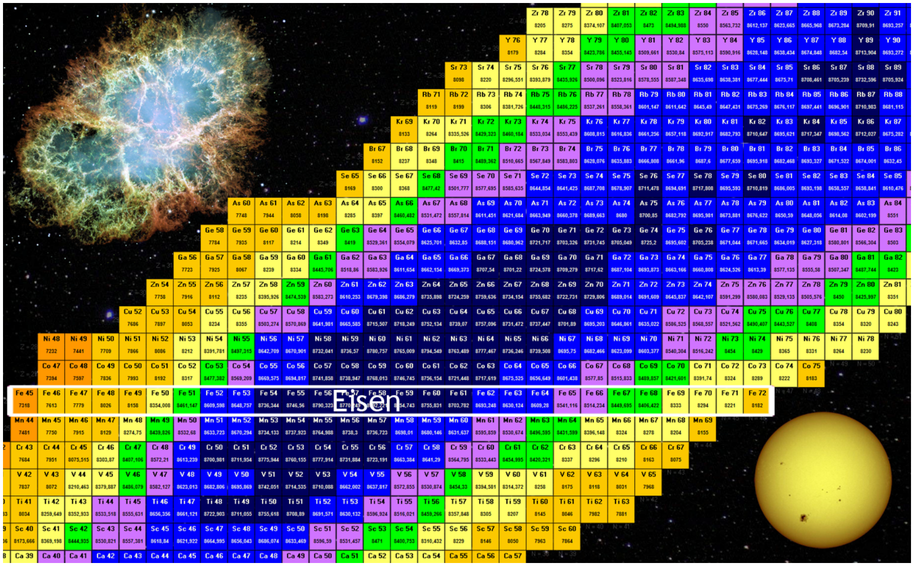


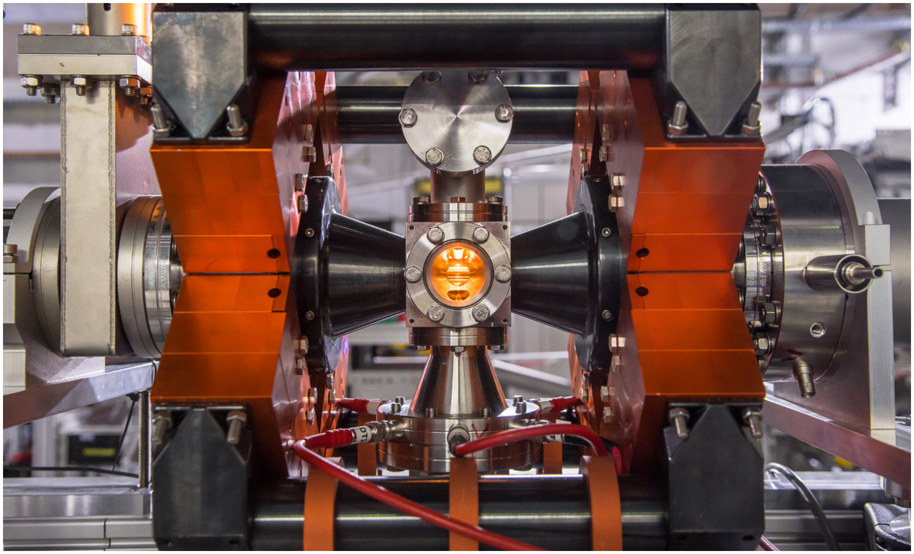
Chart of nuclides with the colour code showing the binding energy per nucleon: the most stable nuclides around iron are in dark blue.

ful tool to determine nuclear binding energies which are crucial for reaction pathways in nucleosynthesis. Mass measurements on these mostly short-lived exotic (e. g., neutron-rich) nuclei are used to explore the "terra incognita" on the chart of nuclides. This helps to figure out how many nuclides exist at all. In combination with theoretical models, the structure of nuclei even far from stability can be investigated.

Ion Traps

Ions can be stored in traps by the superposition of electric and magnetic fields in an extreme vacuum. Penning traps allow storage of a single ion that performs a characteristic oscillating motion in the trap. The ion's mass and further properties like magnetic moments of the bound electron in highly charged ions can be deduced from the motional frequencies if the charge state and the magnetic field strength are known, even in the case of exotic particles that live only for a few milliseconds. Penning-trap mass spectrometers are operated at MPIK and at external facilities like GSI and CERN, where exotic nuclei or antiprotons are available.

In an electron-beam ion trap (EBIT), highly charged ions (HCIs) are produced by impact of energetic electrons, then spatially confined, and electronically heated up to temperatures of millions of degrees. Thus, atomic matter under extreme conditions is prepared. A suite of accurate spectroscopic instrumentation attached to the EBITs collects precise data. Therefore, both stationary and mobile EBITs are available. One of the highlights of the latest EBIT developments at MPIK is the Tip-EBIT at

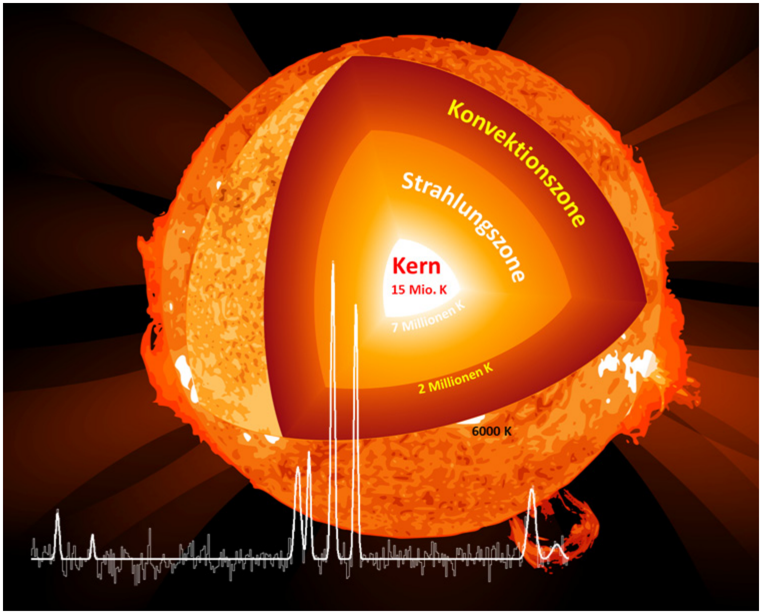


A newly developed miniature EBIT.

the experiment PENTATRAP which combines laser desorption and subsequent ionization. It thus extends the range of available HCIs to rare isotopes, which are synthesized in only sub-nanogram quantities. MPIK scientists in cooperation with the university of Aarhus have built a novel cryogenic ion trap (Cryogenic Paul Trap Experiment: CryPTEx), in which ion crystals can be produced by means of laser cooling, and subsequently highly charged ions cooled therein.

Highly Charged Ions – Matter under Extreme Conditions

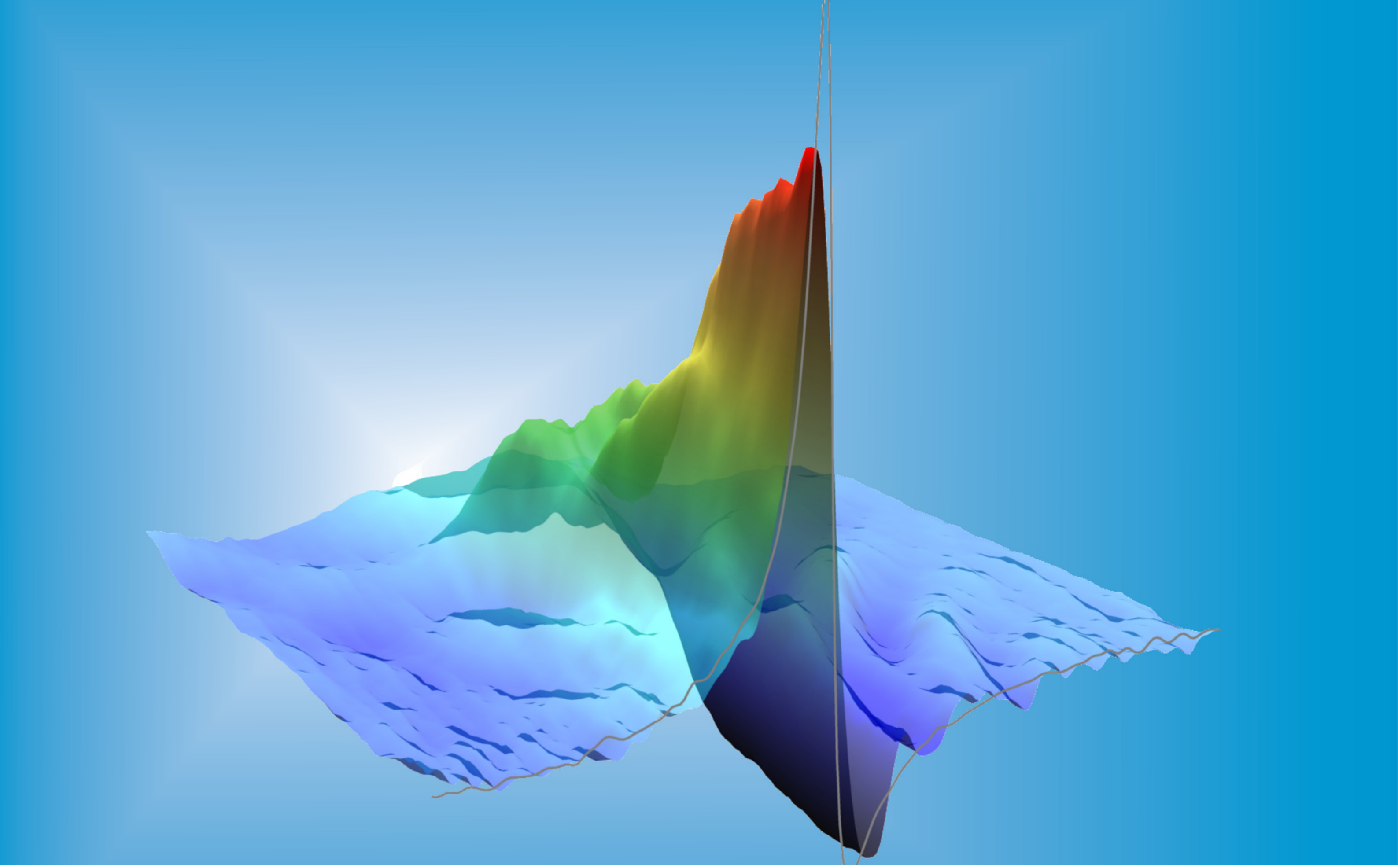
Highly charged ions (HCIs) are found in hot environments of more than one million degrees such as stellar atmospheres and cores, supernova remnants or accretion discs around neutron stars and black holes. In fact, most of the visible matter in the Universe is assumed to be highly ionized. Analysis of the observed light (visible, UV, or X-ray) from these ions needs support by theoretical structure calculations which are often not accurate enough to determine, e. g., the temperature of the hot environment. The controlled production of highly charged ions in an EBIT combined with high-precision spectroscopy provides direct experimental information. One example is the investigation of the X-ray absorption of highly charged iron ions at the synchrotron PETRA III (DESY) which provided important new insight into the radiation transport within stars.



Spectrum of iron ions which determine the radiation transport within the Sun.

The cryogenic ion trap CryPTEx provides efficient cooling of trapped HCIs for high-precision laser spectroscopy. In collaboration with the Physikalisch-Technische Bundesanstalt (PTB, Braunschweig), the MPIK contributes to the development of novel optical clocks using quantum logic spectroscopy and built a frequency comb for UV to far UV light for precision spectroscopy. The ultimate goal will be to test the time dependence of natural constants.

As one of the first results of the PENTATRAP experiment, for the first time very long-lived metastable electron configurations have recently been discovered in highly charged ions of heavy metals. This technique has the potential to become the method of choice for the search for metastable electron configurations suitable to HCI clocks. At the also new ALPHATRAP experiment, the magnetic properties (ground-state g-factors) of highly charged ions can be measured with fractional uncertainties at the 10^{-9} level. First results are in excellent agreement with state-of-the-art QED calculations.



OBSERVING FASTEST MOTIONS

The emergence of a spectral absorption line (Fano resonance).

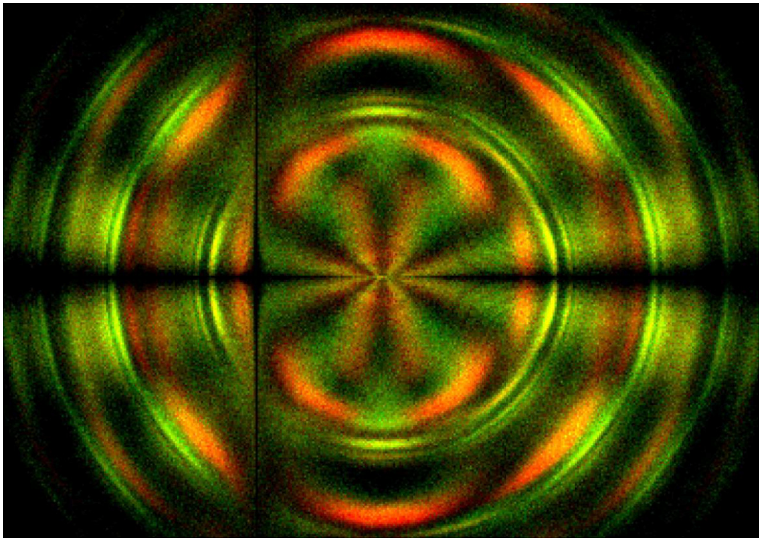
What is the role of time in quantum systems?
How can chemical reactions be steered by lasers?
How do molecules form in outer space?

Ultrashort Laser Pulses – the Microcosm in Extremely Slow Motion

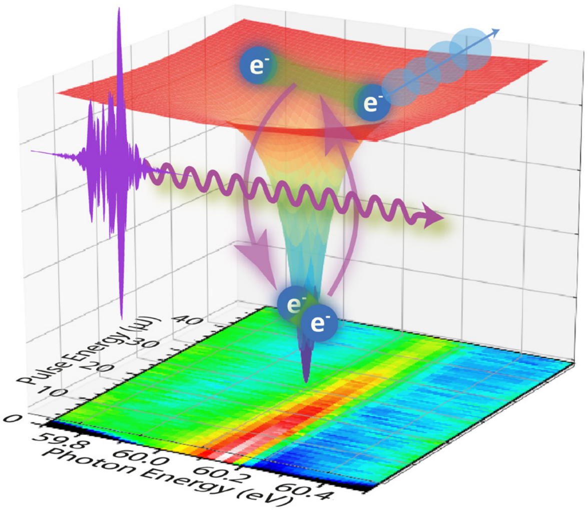
How does a quantum system evolve in time and is it possible to visualize or even control its motion? Today, this old dream of physicists from the early days of quantum mechanics has become a real and growing field of research. The time scales of processes elapsing in quantum systems are extremely short: During chemical reactions, the atoms are moving within 10 to 100 femtoseconds ($1\,\text{fs} = 10^{-15}\,\text{s}$), while the electrons which mediate the chemical bond are even faster: here, attoseconds ($1\,\text{as} = 10^{-18}\,\text{s}$) are the characteristic time scale.

A key tool for time-resolved experiments are ultrashort intense laser pulses which are used to steer the atomic or molecular dynamics with extremely high precision. An electron released from an atom by a strong laser field is driven back and forth and revisits its parent ion while probing its structure. The wave nature of the electron leads to interference effects like in a holographic image which can be analysed to resolve the time-dependent interaction with the residual electrons of the atom.

In most cases, a "pump-probe" scenario is applied, where the first "pump" laser pulse prepares the system in the desired way and starts the temporal evolution which is then probed by the second laser pulse. Intramolecular motions like vibration and rotation can thus be traced. Observing chemical reactions in real time at femtosecond resolution is a very promising research area. Using a combination with reaction microscopes, the possibility to observe of even the ultrashort time span needed for a rear-



Interferences in the photo-electron momentum distribution measured with a reaction microscope.



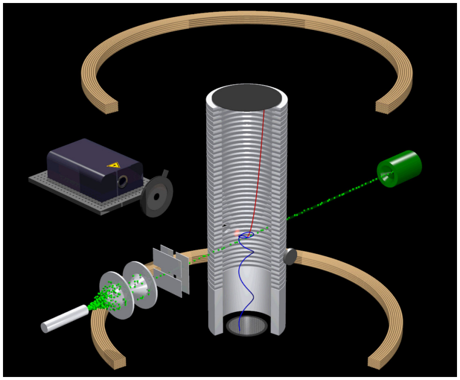
Schematic illustration for the powerful excitation of an electron pair (blue) in the helium atom by an intense ultrashort XUV laser pulse (violet).

rangement of atoms within a molecule has been successfully demonstrated.

To observe the motion of electrons, however, even shorter light pulses on the order of attoseconds are required. This can be achieved by the generation of high harmonics of an intense femtosecond laser. This way, the requested pulse durations of less than 100 attoseconds at wavelengths of some 10 nanometres can be reached nowadays. The helium atom represents a prototype for the correlated motion of electrons. Both its electrons can be excited by absorption of extreme-ultraviolet attosecond pulses. Another femtosecond laser pulse time-dependently probes the thus generated two-electron wave packet which can be reconstructed with the support of calculations that are based on known static wave functions. Laser pulses even allow to steer this electronic “couple dance”. In the future, a directed manipulation of the electron pairs in molecules may influence chemical reactions and enable hitherto impossible syntheses.

Spectroscopy – the measurement of the absorption and emission of light as it interacts with matter – is one of the most important tools of physics. Line spectra appear in the case of resonant interaction. Under certain conditions, they interfere with a continuous background and asymmetric line shapes (“Fano profiles”) emerge. This can be illustrated as the superposition of coupled oscillations. Using ultrashort laser pulses, it is possible to control the temporal evolution and thus the quantum interference – for example to achieve the transformation of a spectral absorption into an emission line and resolve the ultrafast formation of a Fano resonance on the femtosecond timescale.

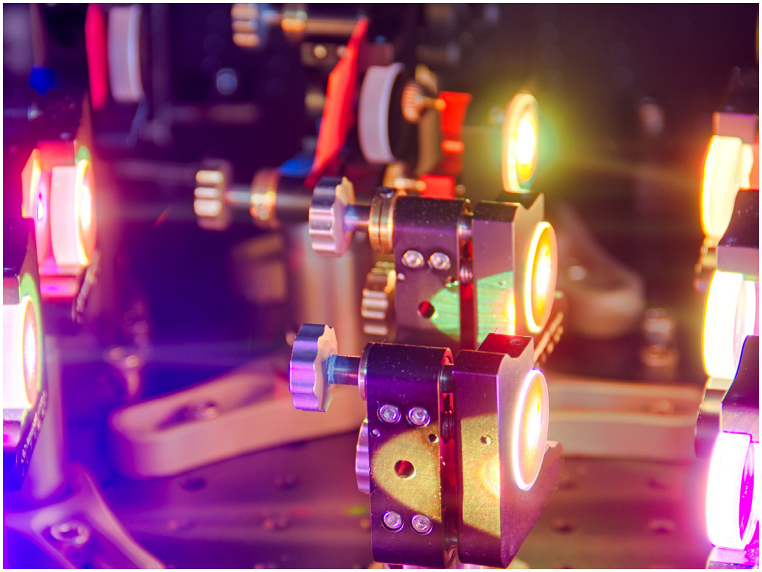
Reaction Microscopes and Laser Systems



Scheme of a reaction microscope.

Reaction microscopes – the “bubble chambers of atomic and molecular physics” – have been developed and are continuously improved at MPIK. Ultra-short intense laser pulses or particle beams induce a breakup of simple molecules. The fragment ions and electrons are caught by means of electric and magnetic fields and recorded by large-area time- and position-sensitive detectors. Their complete momentum vectors, and thus the geometry and dynamics of the molecules before their break-up, can be determined from the reconstructed trajectories of the fragments (“kinematically complete experiments”). Several reaction microscopes are deployed in-house and at the free-electron laser FLASH in Hamburg. For the cryogenic storage ring CSR, a specifically designed reaction microscope is presently under construction. It will be a key instrument for the worldwide unique possibilities for the investigation of slow and cold ions in the CSR.

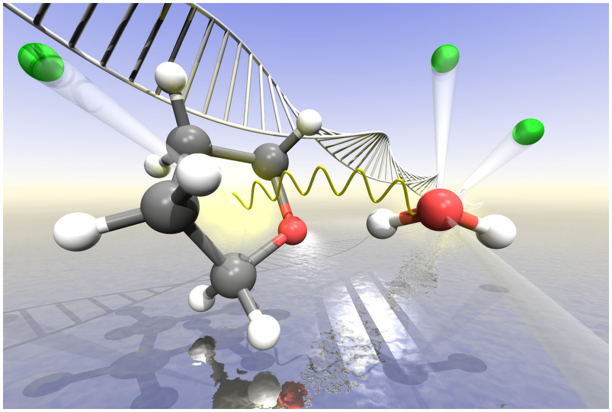
In the Institute's laser laboratories, phase-controlled laser pulses as short as 5 femtoseconds at intensities of up to about 10^{16} W/cm2 are routinely available for experiments. Even shorter pulses of some attoseconds duration are generated by nonlinear optical techniques. The resulting coherent high-harmonic radiation in the extreme UV range can then be combined with broadband infrared/visible pulses from the main Ti:Sapphire laser. Isolated as well as double and triple attosecond pulses are produced and used to probe gaseous atomic and molecular samples by interferometric methods. For pump-probe measurements, the time delay between two pulses can be precisely adjusted on attosecond time scales. Combined with spectroscopy or imaging detectors, this allows for direct and time-resolved observation of nuclear and electronic quantum motions in chemical reactions and also to control them.



„Chirped mirror" setup for generating ultrashort laser pulses.

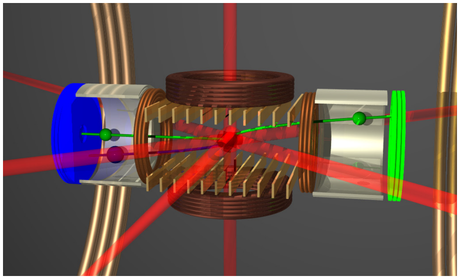
Colliding Atoms and Molecules – Billiard Game with Quantum Balls

Research on correlated quantum dynamics represents one of the great challenges in contemporary science. Researchers at the MPIK explore quantum dynamics on a fundamental level, starting from a limited number of few interacting particles in atoms and molecules, and extending to more complex finite quantum systems such as clusters or even biomolecules. Bombardment with charged particles (electrons, ions) is a key method for the study of these quantum systems. Novel multi-coincident imaging techniques developed at MPIK provide comprehensive information about few-body quantum dynamics and allow a test of theories for such reactions. Electron impact plays an important role in the environment, for example in the upper atmosphere and in interstellar space, as well as in technical plasmas and in radiation biology. During a collision, a molecule may break up into several fragments; this plays a crucial role in biological tissues, since, e. g., the DNA molecule can be altered chemically or even be destroyed.



Radiation damage to hydrated DNA via ultrafast energy transfer following electron impact.

Ultracold Dynamics – Investigating Exotic Quantum Gases



Scheme of the magneto-optical trap combined with a reaction microscope.

Very cold atomic gases with quantum properties are accessible by means of laser cooling. Lithium atoms behave as bosons or as fermions depending on the choice of their mutual interaction. In the bosonic regime weakly bound atom pairs form, the mutual distance of which is experimentally controllable. This exotic form of matter can be investigated with a reaction microscope. By ionization of all atoms in bound pairs or in few-particle systems and determination of all ion momenta, it is possible to deduce the initial spatial configuration of the particles. Here practically instantaneous ionization is done by an intense femtosecond-pulsed laser beam. Whether and how the quantum state of the gas influences its ionization dynamics is also of interest.

The Cryogenic Storage Ring

In the world-wide unique electrostatic cryogenic storage ring of the MIK, the CSR, beams of cold molecular ions of any size and highly charged ions can be investigated essentially without any influence of the environment. This is achieved by purely

The cryogenic storage ring CSR has a circumference of 35 m. The complete ion optics is inside the outer insulating vacuum chamber. The ions and, as the case may be the neutral atoms, are injected at the corner to the right front. The electron cooler is integrated into the rearward section, while the liquid-helium refrigerator system is to the left.

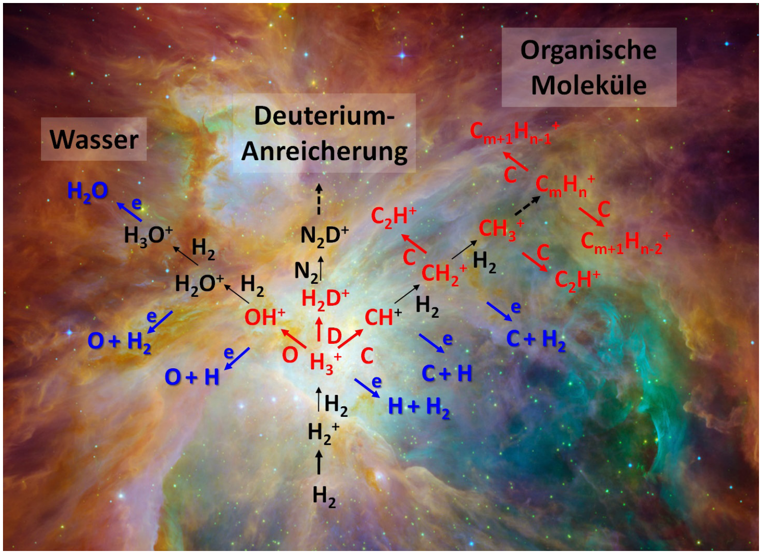
electrostatic ion optics, keeping the ring under extremely low pressure and at a temperature of a few degrees above absolute zero. The ions are produced in dedicated ion sources and injected into the ring by high voltages of up to 300 kV. In addition, a device for injecting beams of neutral atoms is attached to the CSR. An electron cooler improves the stored ion beam quality, and the electrons are available as reaction partners. Sensitive particle detectors in the corners of the ring count even neutral reaction products. For spectroscopic measurements, laser beams can be crossed with the stored ion beam. The innovative mechanical concept of the CSR was developed and realised in close cooperation with MPIK's engineering design office and precision mechanics shop.

Laboratory Astrophysics – the Chemistry of Space

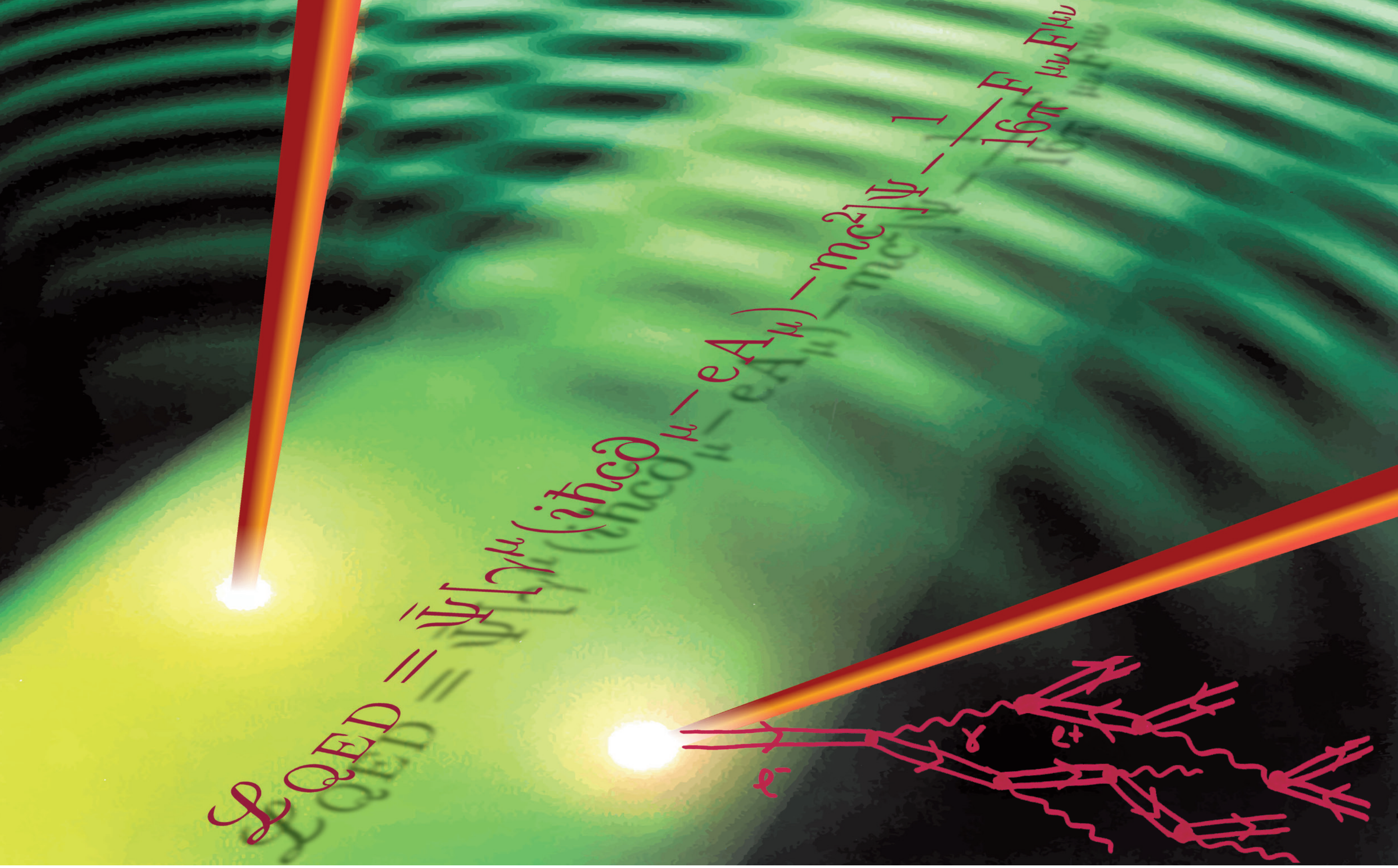
The chemistry of interstellar space is one of the most active fields of research in astronomy. Modern telescopes have discovered a variety of complex molecules in interstellar nebulae and protoplanetary disks, but the processes – often involving ions – that lead to the formation of large organic molecules under the extreme conditions of cold space still pose a riddle. It is also believed that the origin of life on Earth is closely linked to the formation of biologically relevant molecules in space. The search for interstellar water and prebiotic compounds is therefore the motivation for large international projects.

This gas-phase chemistry is driven by reactions involving ions and radicals which are created in collisions with photons and cold electrons. Here, the H3+ molecular ion plays a key role. The break-up of molecules after capture of an electron ("dissociative recombination") can be studied in detail in storage rings. In the cryogenic storage ring CSR conditions are reached that correspond to interstellar temperatures where the internal motion (vibration and also rotation) in molecular ions is in fact frozen.

The positive ions of interest range in size from small atoms and molecules up to larger organic compounds. Also, negatively charged molecular ions (anions) are of interest here as they represent an important source of slow electrons. Provided sufficient inner excitation (vibration), they can literally "evaporate" electrons. Moreover, collisions with neutral atoms are also of great importance for astrochemistry. A novel neutral-atom beam setup at the CSR has recently been commissioned. It combines ground-term atoms with cold molecular ions, and thus, for the first time, provides access to this largely unexplored class of processes under true interstellar conditions.



The network of cosmic chemistry in interstellar clouds.



EXPLORING THE EXTREMES

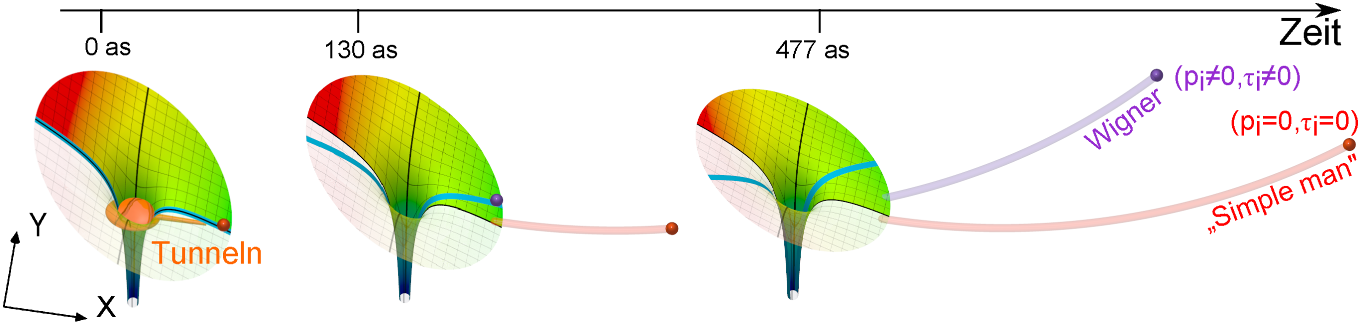
According to quantum electrodynamics the properties of matter and even of vacuum are altered by intense laser fields.

How does matter interact with intense laser light?
What are the effects of very strong fields on the vacuum?
Can extreme cosmic processes be simulated in the laboratory?

Matter in Strong Laser Fields – at the Frontiers of Feasibility

The investigation of the interaction of matter with laser pulses and x-ray beams by now has reached a level at which fundamental aspects such as the quantum nature of both light and matter, relativity and couplings among the involved particles have become key issues and substantial challenges alike. Theory helps to explore the effects of extremely strong fields, even though these partly will be reached experimentally only in the near future. This requires the search for solutions of the many-body time-dependent Schrödinger and Dirac equations. Furthermore, quantum electrodynamics, nuclear effects and pair creation are considered.

One typical topic of interest is the fully relativistic understanding of the quantum processes during tunnel ionization of an atom in a very strong field. A simple model of this process claims that the electron tunnels instantaneously through the laser-generated quantum barrier and appears at its exit with vanishing momentum. As a consequence, the complete momentum carried by the absorbed photons would be transferred to the ion.



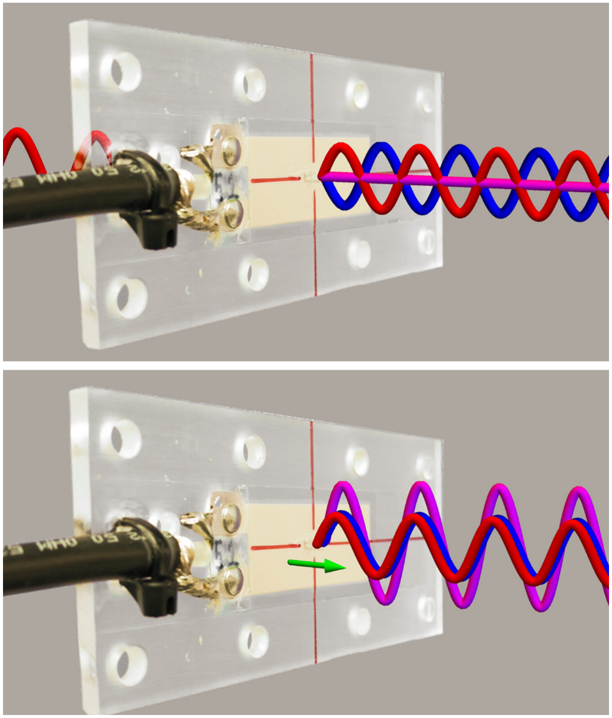
Tunnel effect in a circularly polarized laser field: The electron escapes from the atom through the potential barrier in the presence of the strong laser field. The "simple-man" (instantaneous) and Wigner (finite time) models predict different electron trajectories.

Meanwhile however, a complete quantum relativistic calculation has demonstrated that the above simple model needs to be corrected and that this momentum is shared by the electron and ion.

The question for the time span the electron needs for tunnelling is however controversial to date: Does this take time or is it instantaneous? Theoretical considerations based on a concept published by Nobel laureate Eugene Wigner in 1955 predict a finite tunnelling time. A recent joint theoretical and experimental study at MPIK using a refined model succeeded in translating the Wigner time into an observable quantity. An accurate analysis of electrons emerging from noble gases in ultrashort circularly polarized laser pulses gave evidence of a finite tunnelling time up to 180 attoseconds ($1\,\text{as} = 10^{-18}\,\text{s}$).

Extreme Light-Matter Interaction – Precisely Controlling and Probing Nuclear Transitions

Quantum optics with x-ray light emerged in the last years as a new field. Of particular interest are certain atomic nuclei that only interact with x-rays with an extremely well-defined photon energy, due to an effect discovered by Rudolf Mößbauer at the precursor institute of MPIK in 1958 (Nobel Prize 1961). Spectroscopy of such precise nuclear transitions forms the basis for numerous applications across the natural sciences. Establishing coherent and quantum control of these nuclei is crucial for future applications, but remains a big challenge due to the lack of intense x-ray sources with a small energy spread.



Control of x-ray light via mechanical motion of a resonant target. Before motion, the light scattered extinguishes the excitation. After motion, the waves enhance each other.

To tackle this problem, a joint theoretical and experimental study showed that the macroscopic motion of a sample can shuffle light intensity within the spectrum of given x-ray pulses such that it is enhanced at the desired energy. A recent follow-up work exploited such improved x-ray pulses to coherently control the quantum dynamics of matter. In parallel, the theory for a first application of the motion control was developed, which allows one to measure correlations between different observables of a quantum mechanical system without the usually unavoidable perturbing back action of the measurements on the system's dynamics.

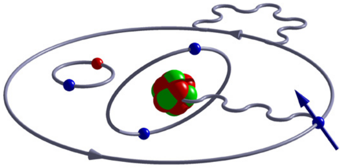
Extremely narrow nuclear transitions are also of interest for accurate measurements. A prime example is the nuclear clock based on ^{229}Th, which promises to improve the accuracy of the best atomic clocks available today. Recently, a team at the LMU Munich measured with increased precision the previously uncertain nuclear transition energy. The extraction of this energy from the experimental data required simulations performed at MPIK. Now lasers specifically designed to excite the nuclei can be constructed, fuelling fundamental research based on extremely precise time measurements.

Strong-Field Quantum Electrodynamics – Modifying the Vacuum

In the language of quantum electrodynamics (QED), the electromagnetic interaction is described as the exchange of so-called virtual photons between charged particles. A consequence of this theory is the fact that there is no empty space, i. e., the vacuum can be pictorially described as being filled with virtual particles. Though their existence is only allowed for a very short time – given by quantum uncertainty – the presence of virtual particles can be detected by high-precision experiments.

Of particular interest is the QED in extremely strong fields. Those fields will influence the charged virtual particles in the quantum vacuum such that the vacuum becomes polarized changing its optical properties. Theories deal also with the fundamental question of pair production, spin dynamics and radiation reaction. In the latter case a charged particle is accelerated in an electromagnetic field and emits electromagnetic radiation which in turn acts back on the particle's motion. Intense laser fields can help to test experimentally the underlying equations. Quantum aspects of radiation reaction in electron dynamics should show up in studies using already available laser systems. This is also of importance for many-particle ensembles like a laser-generated relativistic plasma.

Very strong fields also prevail in the vicinity of the nuclei of heavy elements. High-precision QED calculations of the inner structure of matter for especially highly charged ions are of particular relevance for our institute. The interplay of theory and experiment significantly contributes to the determination of fundamental properties such as the magnetic moment of the electron. On the one hand, comparison with precision experiments permits validation of QED predictions, while on the other hand theory helps to determine natural constants like the electron mass: its value became by an order of magnitude more accurate.

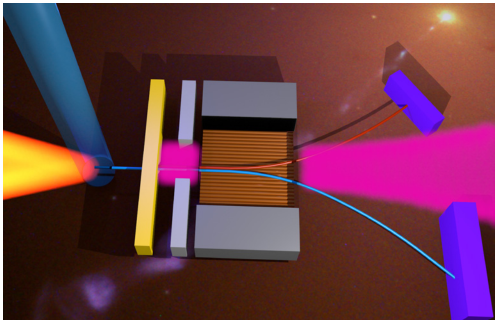


Scheme of the QED contributions to the electronic structure of highly charged ions: the electrons (blue balls) interact with each other and themselves via virtual photons (wave lines). In the field of the nucleus, also particle-antiparticle pairs (blue and red balls) may be virtually created.

Laser Astrophysics – Cosmic Accelerators in the Laboratory Scale

Highly intense laser pulses already enable the acceleration of particles to energies up to the order of gigaelectronvolts (1 GeV = 10^9 eV). In close collaboration with external experimental groups, MPIK researchers developed models for the production of ultrarelativistic lepton beams consisting of electrons and positrons in equal amounts via bremsstrahlung photons that convert to electron-positron pairs. Furthermore, more recent simulations demonstrated various concepts to generate polarized intense lepton and GeV gamma beams. They are based on spin-dependent high-energy photon emission when polarized intense laser beams collide head-on with unpolarized electron beams producing electrons and positrons with spin parallel and anti-parallel, respectively, to the laser's magnetic field direction.

The investigation of such highly energetic processes on laboratory scale is of considerable importance also for astrophysics: Cosmic gamma-ray bursts, for example, emerge from the extremely collimated ultrarelativistic leptonic jets which are emitted along the rotation axis of certain types of collapsing stars.



Laboratory production of ultrarelativistic electron-positron beams and gamma rays by laser-accelerated electrons hitting a metal target.

SCIENTIFIC AND TECHNICAL SERVICE

Aerial view of the Institute's campus from the south; in the background the city of Heidelberg.

Campus

The institute campus is situated in the forest 200 m above the city of Heidelberg. The main buildings are the Walther Bothe and the Wolfgang Gentner Laboratories with office and laboratory space. The library building with a lecture hall and a seminar room suitable for small conferences lies at the centre of the campus. Other significant buildings are the experimental hall complex, the electronic and mechanical workshop buildings, guest houses and several subsidiary buildings. In addition, there is a kindergarten on the premises. The neighbour to the south is the European Molecular Biology Laboratory (EMBL).

Scientific Information Services

The Institute's library presently holds about 26 200 monographs, book series, conference proceedings, theses prepared at the MPIK and about 6 200 journal volumes. Via the Max Planck Society, the library provides access to e-books, online dictionaries, databases and more than 40 000 e-journals. The MPIK actively participates in the Max Planck Society's open access activities via the Max Planck digital library. The publication management system PuRe offers the opportunity to publish papers and supplementary material and to prepare individual publication lists.

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View into the MPIK library.

Public Relations

It is a high priority of the MPIK that major research results are communicated well beyond the scientific community, to the public at large. The publication relations team writes press releases about selected results which are published via the Institute's homepage and internet services. Detailed information about the research at the Institute is kept up to date both online and as printed matter. Groups of visitors – from schools, universities or other interested people – are welcome for guided institute tours; for school students, we provide the "Saturday morning physics" courses.

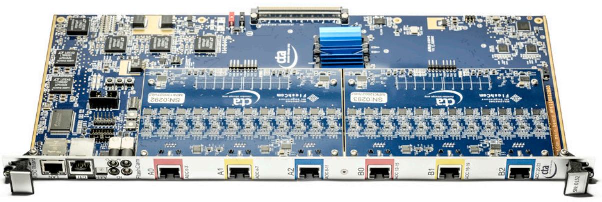
Information Technology

The server room in basement of the Bothe laboratory.

The central IT infrastructure provides computing power and storage space. A Linux cluster and several special-purpose servers with overall about 6500 processor cores are available for processing batch jobs. Data is stored on hard disks with a total capacity of over 13 Petabytes. For fast access, most of the data space is organized as a parallel file system. A central tape library is used as a backup system to assure data safety and as a long-term archive. All servers and file systems are attached with up to 100 Gigabit Ethernet connections to the network. The cluster mainly serves for data storage, data analysis and simulations in gamma-ray astronomy as well as for time-consuming calculations in theoretical quantum dynamics. Further, the IT group operates mail and web servers, supports users with desktop hardware and software, and maintains the technical infrastructure in the lecture hall and seminar rooms.

Electronics

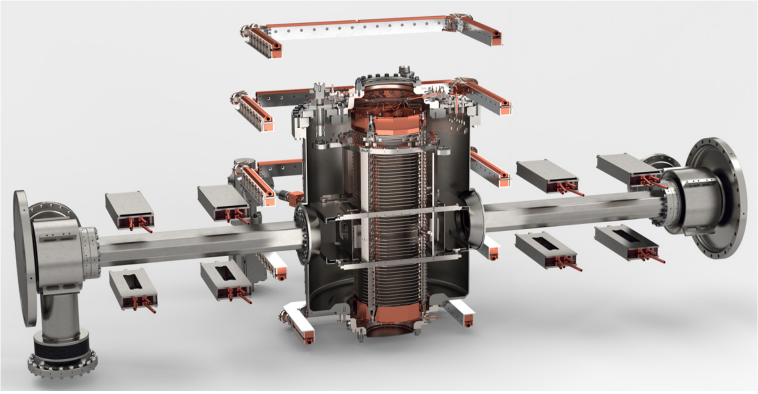
Electronics to control experiments and for data acquisition are developed and produced in the central electronics shop and the apprentices' shop, since in many cases the experimental requirements cannot be fulfilled by commercial devices. A new electronic circuit design is transferred to the layout of a board, which is then produced externally and tested before its integration into an experiment. The electronics group has specialist expertise in areas of critical importance to the institute, for example in the high voltage systems needed for ion traps, and the fast digitisation systems needed to capture the data from many experiments. Maintenance and repair of electronic devices is also performed.



Main board for FlashCam with FPGA and two plugged-on analogue-to-digital converter boards.

Engineering Design

Many of the components for scientific instruments that are built in the Institute’s precision mechanics shops are developed in the engineering design office based on a 3D-CAD system. It delivers three-dimensional views that can be rotated on the screen, technical drawings for the manufacturing process, data to directly control the CNC machines and lists of the required materials. The software package includes a numerical simulation tool to test the components beforehand.



Design drawing of the CSR reaction microscope.

Precision Mechanics

Both the central precision mechanics shop and the apprentices’ shop are equipped with modern CNC-controlled as well as conventional milling and turning machines. Further, a number of welding and soldering techniques are applied to produce vacuum components. Among the treated materials are steel, copper, titanium, tantalum, molybdenum as well as ceramics and plastics. The precision of the workpieces is checked with a high-resolution 3D measuring device. Several specialized mechanics shops are in charge of some large-scale experiments.

CNC 5-axis milling machine.

Technical Building Services

An ever-running technical building infrastructure as for example air conditioning of laboratories or uninterrupted power supply is a prerequisite for successful scientific work, in particular for experiments. The technical building services team is responsible for maintenance and repair of all installations in the buildings as well as of construction activities. Further tasks are the supervision of the care of the premises and coordination of the work of outside companies.

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