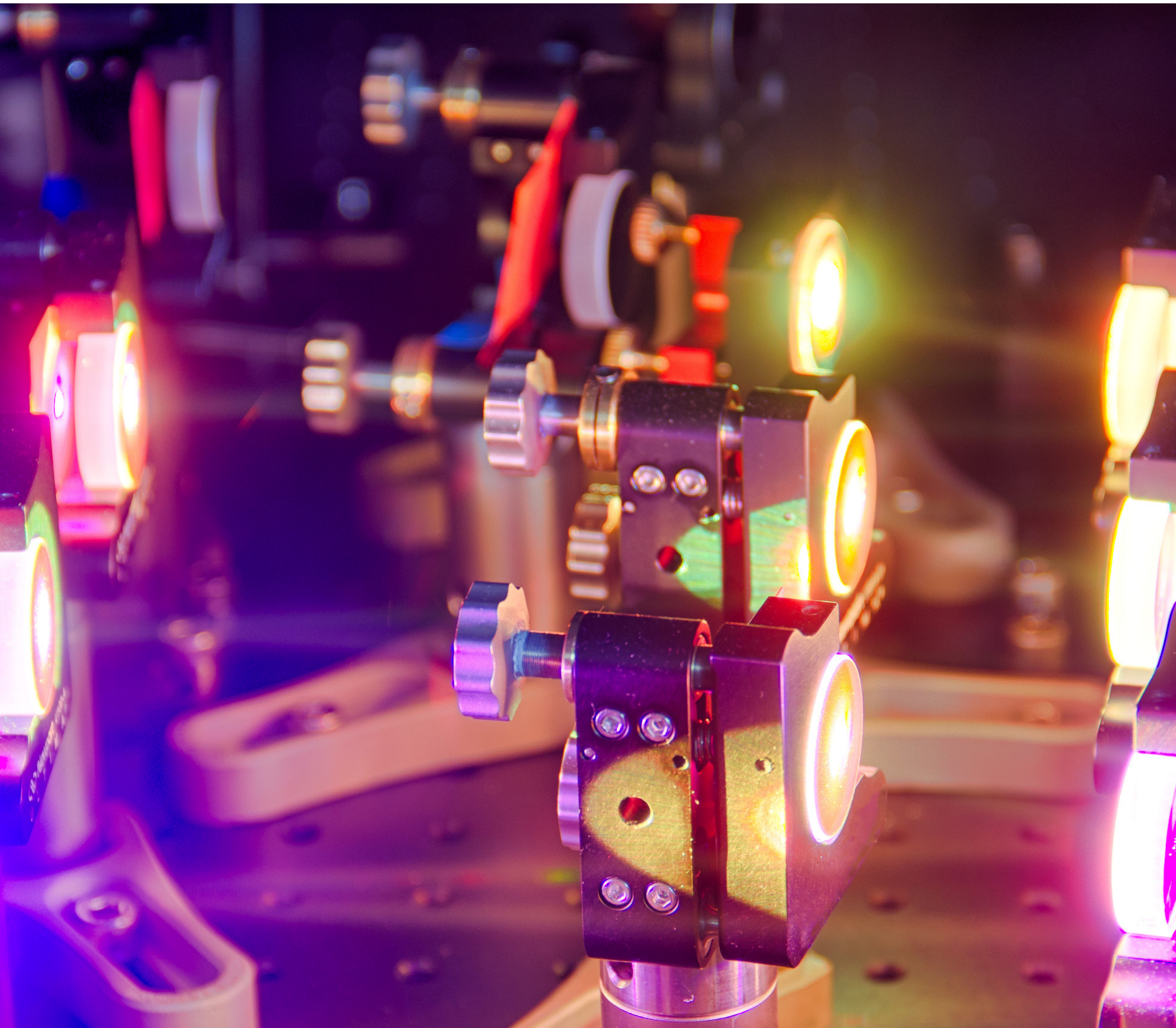
MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK
HEIDELBERG

Progress Report
2017-2019



Cover: Laser light impinging on chirped mirrors in a home-built optical setup in the new MPIK laser labs. These laser pulses are then used for optical upconversion to extreme-ultraviolet frequencies to study attosecond responses of bound electrons in atoms and molecules and their modification in intense fields.

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Imprint

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Foreword

This report for the period of 2017-2019 is meant to give a broad general overview over the main research areas at MPIK, technological infrastructure, and some recent selected science highlights. The chapters are organized by scientific topics and fields of research rather than individual divisions, who cooperate in many areas to achieve common goals and visions.

Physics at MPIK evolves around exploring the extremes:
- from highest-precision measurements to acceleration mechanisms of cosmic particles,
- from lowest-background radiation measurements to extreme radiation intensities,
- from fastest motions of quantum matter to tests of drifts of fundamental constants,
- from cold molecular reactions in space to astrophysical processes in stars and supernovae,
- from dark matter to bright light.

The years of 2017-2019 marked the startup of two new research groups at the MPIK: Since the beginning of 2017, Florian Goertz is heading his group on New Physics, Electroweak Symmetry Breaking, and Flavor. In Spring 2019, Brian Reville kicked off his group on Astrophysical Plasma Theory. The groups thus complement the spectrum of science at MPIK spanned by the divisions of
- Klaus Blaum (Stored and Cooled Ions)
- Jim Hinton (Non-thermal astrophysics)
  succeeding Werner Hofmann (retired/emeritus since June 2019)
- Christoph H. Keitel (Theoretical Quantum Dynamics and Quantum Electrodynamics)
- Manfred Lindner (Particle and Astroparticle Physics)
- Thomas Pfeifer (Quantum Dynamics&Control)

MPIK now also shines in new light: The quantum-dynamics laser labs were inaugurated in May 2017, with first lasing in February 2018, close to 60 years into the institute's foundation anniversary. This anniversary also provided an opportunity to show the public around the institute during an open-house day on 16 September 2018. Lots of hands-on activities, exhibits and posters provided insights into what nature teaches us from the (sub-)nanoscale of elementary particles, the motion of atoms and molecules to the macroscales of the universe, where the existence of dark matter and nearly non-existence of antimatter create puzzles of astronomical dimensions.

Led by MPIK Scientists, several scientific breakthroughs have been accomplished in the last three years, which are highlighted on the following pages. These successes are enabled by the close cooperation of division scientists with the excellent infrastructure, consisting of mechanics and electronics workshops, different service groups as well as by the administration. Thanks thus go to all members of the Institute, in particular our junior and senior scientists, partners at and students from Heidelberg University and outside research institutions for their dedicated and engaged work and contributions. 2019 marked also the retirement of Werner Hofmann, who lifted the MPIK internationally visible into the gamma-ray sky with H.E.S.S. and the preparation of the CTA project. We are also grateful for his essential contributions to setting the stage and transforming the entire institute from its pure nuclear past into its broad and fruitful present and future at the dynamical core of fundamental physics.

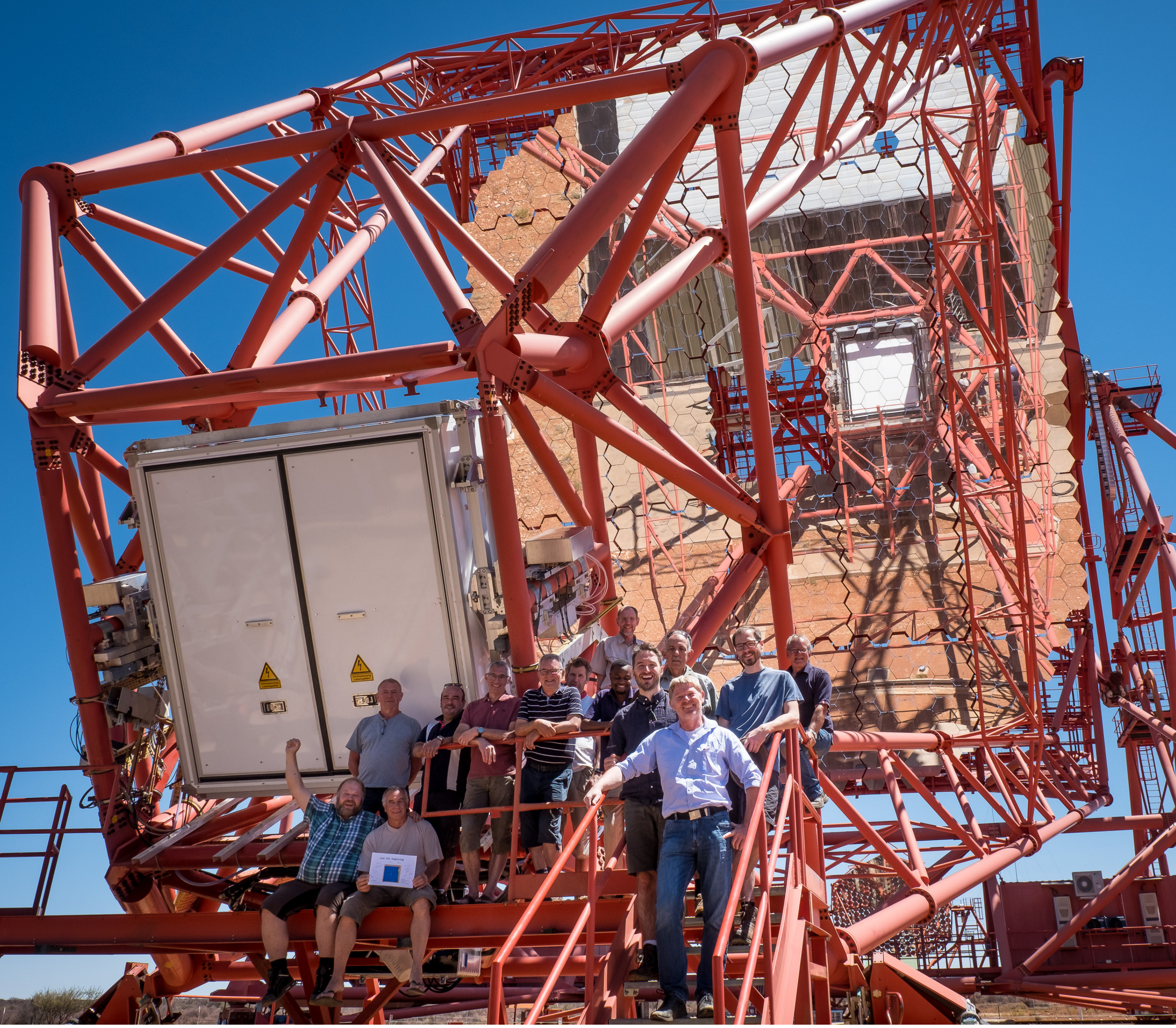
The following chapters of the report address the areas of "1 Astroparticle Physics", "2 Quantum Dynamics", and "3 Infrastructure". Lists of personnel, publications, theses, invited talks, teaching activities, organised conferences, and institutional collaborations are provided online.

Thomas Pfeifer
Managing Director

Contents

1

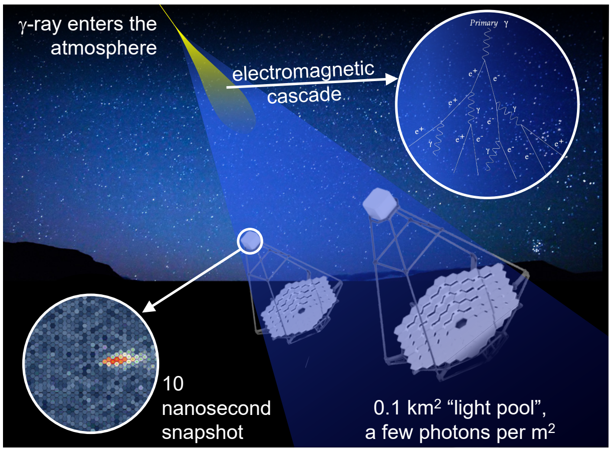
ASTRO-PARTICLE PHYSICS



1.1 The Non-Thermal Universe

In autumn 2019, the large H.E.S.S. telescope was equipped with a new high-performance camera, which shortly after installation captured its first image of the Crab nebula.

Cherenkov Telescopes and Water Cherenkov Detectors

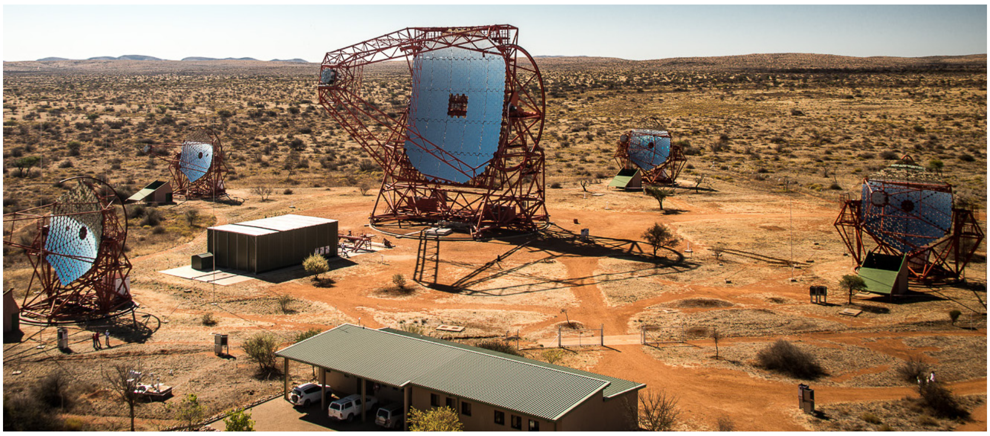


Observing gamma rays with Cherenkov telescopes.

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. (the High Energy Stereoscopic System) consists of five telescopes, four of them each with 107 m^2 mirror area deployed in a square of side length 120 m. A camera composed of 960 photomultiplier sensors is placed at the focus of each mirror. H.E.S.S. was the first instrument that was able to produce true images of astrophysical gamma-ray sources. In the centre of the array, a fifth, huge telescope with 614 m^2 mirror area and a camera with 2048 pixels has been operational since 2012, enhancing the sensitivity of the system and extending observations to lower energies.

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 two of the different telescope types. In 2019 the camera technologies developed at MPIK for CTA were used to upgrade the central telescope of H.E.S.S.



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

The CTA SST camera

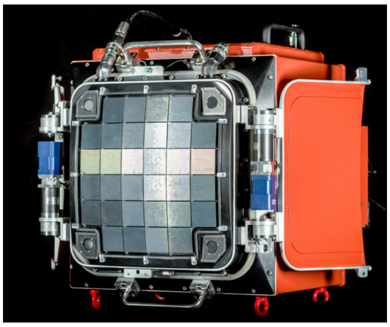
The Cherenkov Telescope Array (CTA) will host up to 70 Small-Sized Telescopes (SSTs) at the CTA Southern Hemisphere site at Paranal in Chile. The SSTs are distributed over several square kilometres and provide sensitivity in an energy range between a few TeV and 300 TeV. Several international groups have developed options for the SST design. One such proposal involves a dual-mirror optical design with a primary mirror of 4 m in diameter, a secondary mirror 2 m in diameter and a compact camera of roughly 0.5 m in diameter.

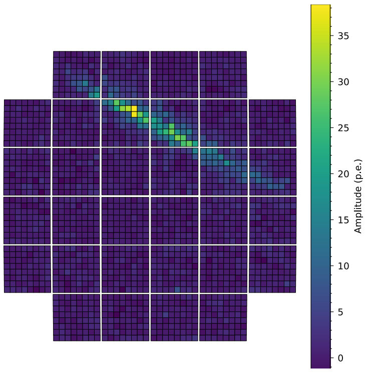
MPIK has led the development of a camera for use in such an optical system. The Compact High-Energy Camera (CHEC) features a modular design and provides full waveform information for all 2048 pixels with a sampling rate of one giga-sample per second. The CHEC collaboration includes institutes from Australia, Germany, Japan, the Netherlands, and the UK. MPIK is coordinating the project and leading the effort into full-camera assembly, integration, and verification. A prototype camera, CHEC-S has been developed, built, and commissioned. CHEC-S was installed on a prototype SST structure at the INAF observatory site in Serra La Nave on Mt Etna (Sicily) in spring 2019. The camera was commissioned and on-sky gamma-ray observations taken. The third figure shows an event lasting a few tens of nanoseconds captured in the camera. Following commissioning, CHEC-S underwent review within CTA and has recently been selected from three candidates as the basis for the final SST Camera. A final design phase will proceed to optimise the camera design for the production phase of CTA.

References:

[1] J. Zorn et al., NIMA 904, 44-63, (2018), DOI: 10.1016/j.nima.2018.06.078

[2] R. White et al., 35th International Cosmic Ray Conference, ICRC2017, arXiv:1709.05799





One of the 'outrigger' tanks in front of the main detector array of HAWC in Mexico.

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 HAWC (the High Altitude Water Cherenkov gamma-ray 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 survey observatory in the southern hemisphere, the Southern Wide field-of-view Gamma-ray Observatory (SWGO). SWGO will make use of the same detection principle as HAWC, but cover a larger area and a wider range of gamma-ray energies.

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, and investigate the acceleration of particles to extreme energies in cosmic sources and the role that these particles play in astrophysical systems.

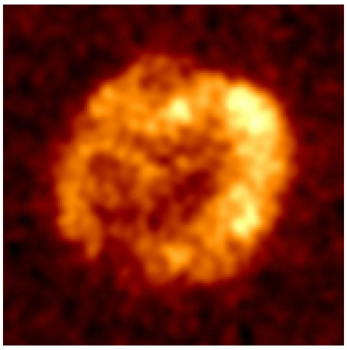
Particles in the VHE range cannot be produced as thermal radiation, as is the electromagnetic radiation in most other wavelength regimes; only in the Big Bang were high enough temperatures reached for a very short time. VHE gamma radiation is produced when strongly accelerated charged particles interact 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 VHE 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 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 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.

The recent upgrades of H.E.S.S. and HAWC and the future instruments CTA and SWGO will allow us to push forward our understanding of the energetic Universe, and of the role that cosmic rays play in all astrophysical systems – up to the scale of galaxies and beyond.



The supernova remnant RX J1713-3946 as seen by the H.E.S.S. telescopes.

Gamma-ray burst afterglow emission detected in very-high-energy gamma-rays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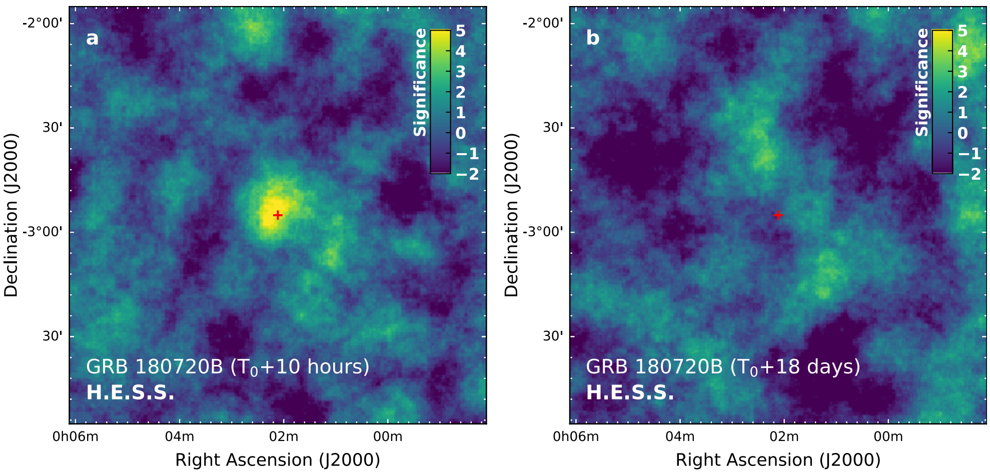
Gamma-ray bursts (GRBs) are the most dramatic explosive phenomena in the Universe, yet until 2019 no convincing ground-based detection of gamma-ray emission from GRBs had ever been made. Now three GRBs have been detected from the ground – at very high energies – two of them with the H.E.S.S. telescope system. GRBs begin with very luminous and highly variable emission that after some time (typically a few seconds) begins to decrease monotonically. The measurement of emission at VHE with H.E.S.S. from GRB 180720B was not just the earliest measurement from the ground, but remarkable as the emission was detected 10 hours after the beginning of the burst (T_0, see panel a). This discovery was made with the central 28 m telescope of the H.E.S.S. array. The red cross indicates the position of the GRB measured by contemporaneous optical observations. At the same location, significant gamma-ray emission detected by H.E.S.S. can be seen. In panel b the same region of the sky is shown as observed 18 days later. At such late times, the very-high-energy emission has faded to a level that it is no longer detectable. Measurements with H.E.S.S. of another bright GRB, 190829A, starting 4 hours after the burst, confirm the presence of particle acceleration to very high energies very late in GRBs.

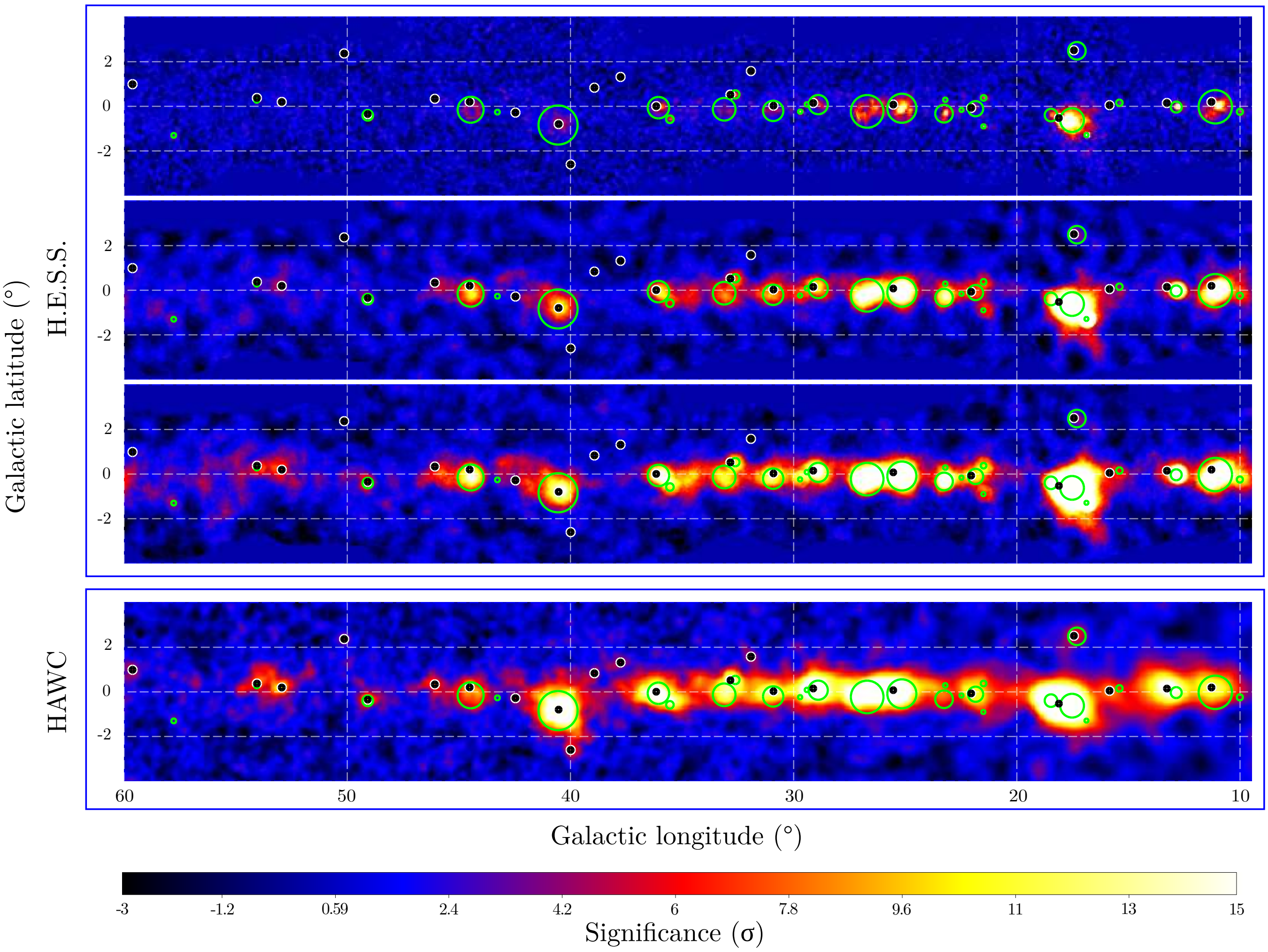
Reference:
H.E.S.S. Collaboration (H. Abdalla et al.), Nature 575, 464–467 (2019), DOI: 10.1038/s41586-019-1743-9



Galactic plane surveys with H.E.S.S. and HAWC

The H.E.S.S. Galactic Plane Survey (HGPS) was a 10 year long observation program where the H.E.S.S. telescopes in Namibia systematically scanned the band of the Milky Way for very high energetic (VHE) gamma-ray emission. The analysis of the data, led by MPIK, resulted in the first homogeneous catalogue of Galactic VHE gamma-ray sources and a set of sky images, both published in 2018 [1]. In total 78 sources were discovered of which 31 could be firmly identified and associated with already known supernova remnants, pulsar wind nebulae, binary objects, and stellar clusters. Most of the remaining unidentified sources had possible associations with already known objects, but a firm identification can only be established, when the results from the HGPS are combined and compared with data from other instruments.

On the other side of the Atlantic ocean, the HAWC gamma-ray observatory located in Mexico has been continuously monitoring the northern sky for more than 4 years and produced a sky map of the VHE gamma-ray emission. Part of it overlaps with the galactic plane scanned by H.E.S.S.. A recent comparison of updated HGPS data and data from the HAWC observatory is shown in the figure [2]. It illustrates the part of the Galactic plane at longitudes between 60° and 10°, where both instruments have reasonable sensitivity. The green circles are the 68% containment of the H.E.S.S. sources and the black dots are the location of the sources detected by HAWC. To be able to compare the data obtained by the two completely different instruments, the HGPS data had to be processed as similarly as possible to the HAWC data. The procedure is illustrated in the panels of the figure top to bottom: first an energy threshold of ~1 TeV was selected in both datasets as a compromise between sufficient statistics, good quality reconstruction, and reasonable angular resolution. Secondly, the resolution of the H.E.S.S. data was downgraded to the angular resolution of HAWC of ~0.4°. Finally, a special background subtraction method, named “field-of-view background method” was applied to the H.E.S.S. data. The lowermost panel shows the image measured by HAWC. After the special processing of the HGPS data, the agreement between both instruments becomes obvious: most of the structures can be found in both maps. The remaining small differences can be explained by a lack of sensitivity of one instrument compared to the other to detect a specific source for example. Despite their intrinsic differences, both instruments have shown to be very complementary and give a very consistent image of the Galactic plane in VHE gamma rays.



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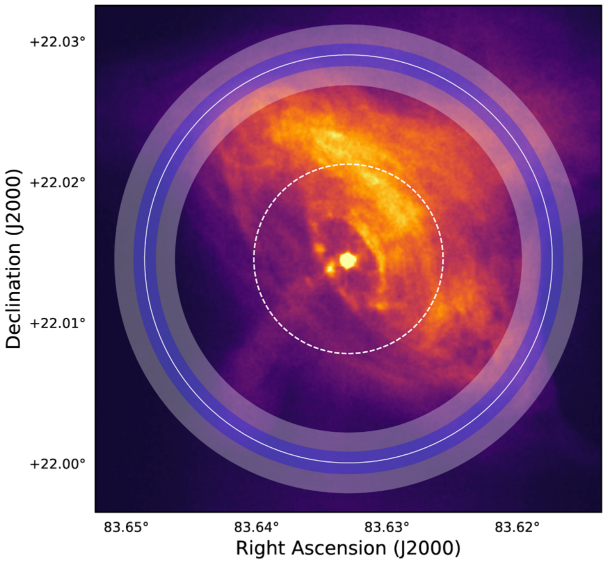
[1] H.E.S.S. Collaboration, A&A 612, A1 (2018), DOI: 10.1051/0004-6361/201732098

[2] A. Jardin-Blicq, V. Marandon, F. Brun, 36th International Cosmic Ray Conference, ICRC2019, arXiv:1908.06658v1

Crab size measurement

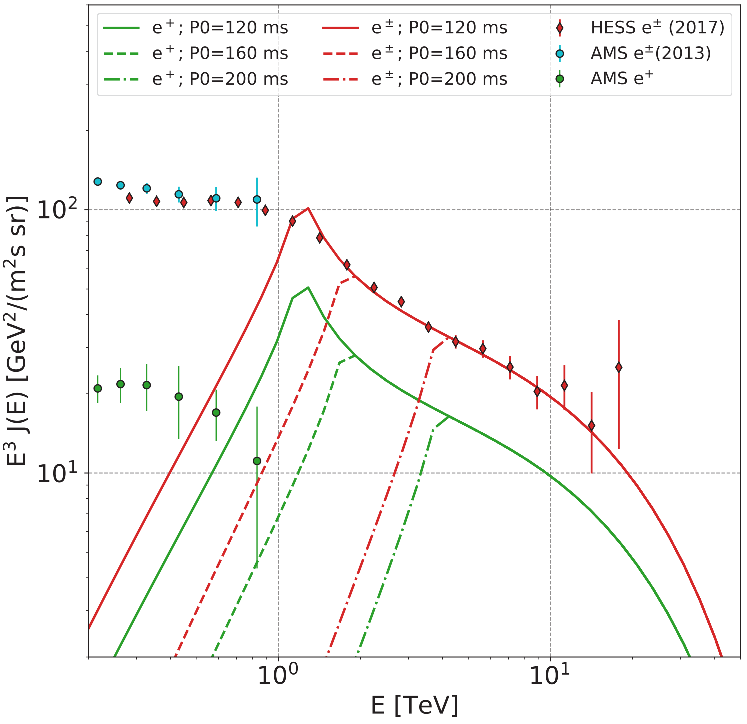
The Crab Nebula is a bright and well known object to astronomers at all wavebands, but as the first detected and brightest steady source it holds a special place for very-high-energy (VHE) gamma-ray astronomers. The nebula belongs to the source class known as pulsar wind nebulae (PWN), which are formed by a wind of electron-positron pairs streaming from the central pulsar. Upon colliding with the surrounding medium, a wind termination shock is created where electrons and positrons are accelerated to ultra-relativistic energies. These energetic particles go on to radiate their energy away by the synchrotron process and via inverse Compton scattering, which results in gamma rays in the VHE range (> 100 GeV). Since its first detection in 1986 this source has been deeply studied by VHE observatories and many of its properties are well understood, however measurement of the size of the emission region has until now proved impossible. This difficulty is due to the size of the Crab Nebula being smaller than the point spread function (PSF; the precision with which the direction of gamma-ray photons is measured) of VHE gamma-ray observatories. However, recently the H.E.S.S. collaboration have been able to control and understand the instrument PSF to the degree where this challenging measurement could be made, determining a size of 52 arcseconds (blue ring), significantly larger than the extension seen in X-rays (dashed circle and background image). As the first measurement of the size of the nebula in inverse Compton emission, this represents a significant step forward in understanding the distribution of ultra-relativistic particles and magnetic fields in the nebula, and hence in our understanding of this whole class of astrophysical particle accelerators.



Reference:
H.E.S.S. Collaboration (H. Abdalla et al.), Nature Astronomy (2019), DOI: 10.1038/s41550-019-0910-0

Cosmic ray electrons

A small fraction of the cosmic rays bombarding the Earth are electrons and positrons. Unlike the much more numerous protons, these particles lose their energy rather quickly. Recently, the electron spectrum has been measured with H.E.S.S. to extend up to around 10 TeV. At these energies electrons cool so fast that they must originate in very nearby sources. Using the new constraints from HAWC on the diffusion speed of cosmic particles, the properties were calculated that would be needed for a local source to match the H.E.S.S. measurements. A very plausible culprit is a pulsar inside the so-called 'Local Bubble', very close to the solar system, that has so far evaded detection. This object may reveal itself in the near future in a number of different ways: a sharp rise in the positron fraction at high energies, as a new very extended gamma-ray nebula, or a new radio pulsar detectable for the first time with SKA. The figure shows the electron flux at the Earth (multiplied by energy cubed for clarity) versus electron energy. Model curves are shown for electrons and positrons together (red) and just positrons (green), for different assumptions on the initial spin period of the pulsar.



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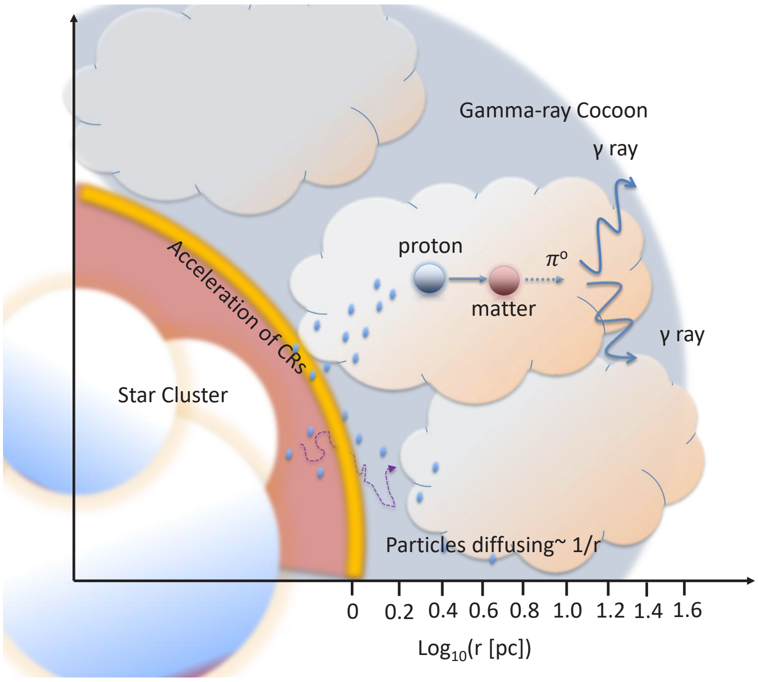
R. López-Coto, R.D. Parsons, J.A. Hinton, G. Giacinti, Phys. Rev. Lett. 121, 251106 (2018), DOI: 10.1103/PhysRevLett.121.251106

A new paradigm for Galactic Cosmic Rays?

There are many recent hints that the long-held standard paradigm of Galactic cosmic ray acceleration and propagation is in trouble. The paradigm holds that supernova remnants (SNRs) accelerate all of the locally measured protons and nuclei from GeV up to PeV energies. Newly measured features in the spectra of cosmic rays, and secondary particles produced in the interstellar medium, suggest that this picture is too simplistic and, furthermore, the measured gamma-ray emission of sources suggests two distinct classes of particle accelerators. The known gamma-ray SNRs exhibit rather soft spectra indicating acceleration up to at most 100 TeV. An emerging class of harder spectrum / higher energy sources appear to be associated with clusters of massive stars. The prominent massive stellar clusters Cygnus OB2, Westerlund 1, and the ultracompact stellar clusters located in the heart of the Galactic Centre, are all coincident with such-hard spectrum emission. Work is ongoing at MPIK to better understand these gamma-ray sources, and to improve our understanding of cosmic-ray transport in the galaxy. A new paradigm for the Galactic cosmic rays may be emerging.



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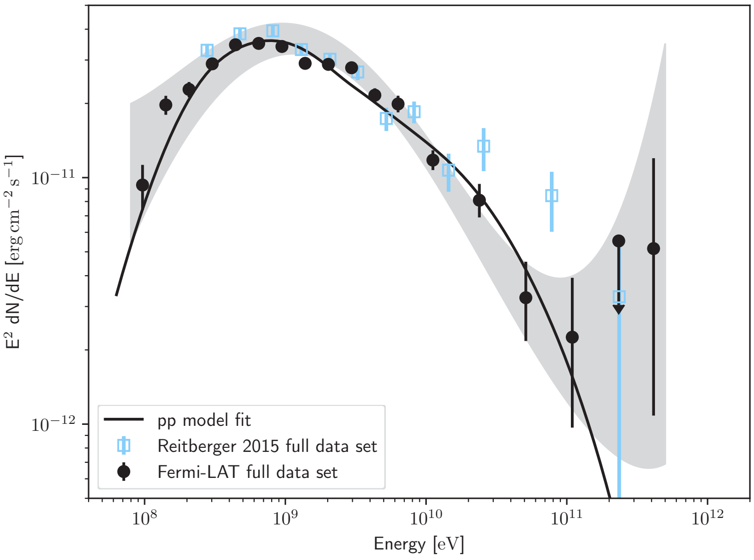
[1] F. Aharonian, R. Yang, E. de Oña Wilhelmi, Nature Astronomy 3, 561-567 (2019), DOI: 10.1038/s41550-019-0724-0
[2] R. Yang, F. Aharonian, Phys. Rev. D 100, 063020 (2019), DOI: 10.1103/PhysRevD.100.063020

Particle acceleration in the binary system Eta Carinae

The naked eye object Eta Carinae houses the most massive and luminous star in the local Milky Way Galaxy. Since the 1990s it is also known to contain a lower mass binary companion in a regular 5.5 year period with high eccentricity. At a distance of ~7 500 light-years, and with an orbit comparable to that of Uranus around the Sun, the binary system is not resolvable. We therefore must rely exclusively on indirect evidence to infer the properties of this fascinating system. With recent detections in both hard x-rays and gamma rays, a new window into Eta Carinae's inner workings has been opened. Using multi-wavelength data, we can test predictions regarding the nature of the stars, their surface properties and wind parameters. A new analysis of the Fermi-LAT satellite measured Gamma-ray data provides the most convincing evidence to date that the gamma-ray emission has its origins in pion decay from interactions between nuclei accelerated at the shocks in the wind collision region and the shocked material of the winds. Accounting correctly for the hard x-rays, which must be produced via Inverse Compton scattering of light from the stars, requires detailed modelling of the stellar luminosities and associated phase dependence of the emission zone, and tightly constrains/rules out many other existing models. The physical processes regulating the non-thermal particle acceleration at the shocks are remarkably similar to those frequently invoked to account for cosmic-ray acceleration in young supernovae, in particular with regards nonlinear magnetic field amplification by cosmic-ray currents. In combination with the predictable orbital periodic variability of shock conditions, the non-thermal emission from Eta Carinae provides a powerful laboratory for high-energy astrophysics.



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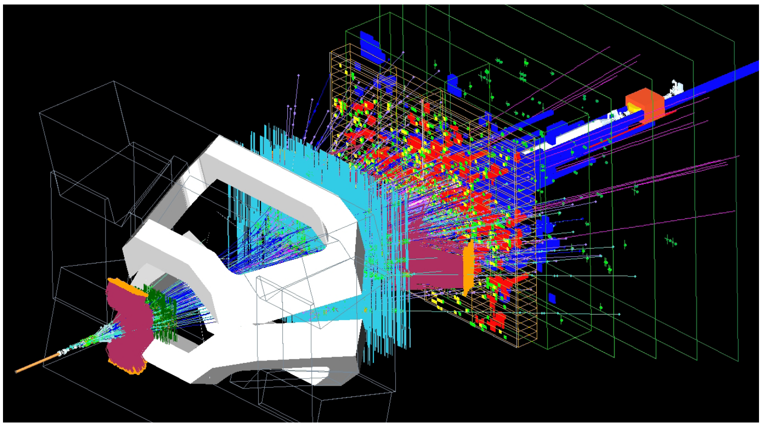
R. White, M. Breuhaus, R. Konno, S. Ohm, B. Reville, J.A. Hinton, to appear in A&A, arXiv:1911.01079 (2019)

The Early Universe – Elementary Particles at the Highest Energies

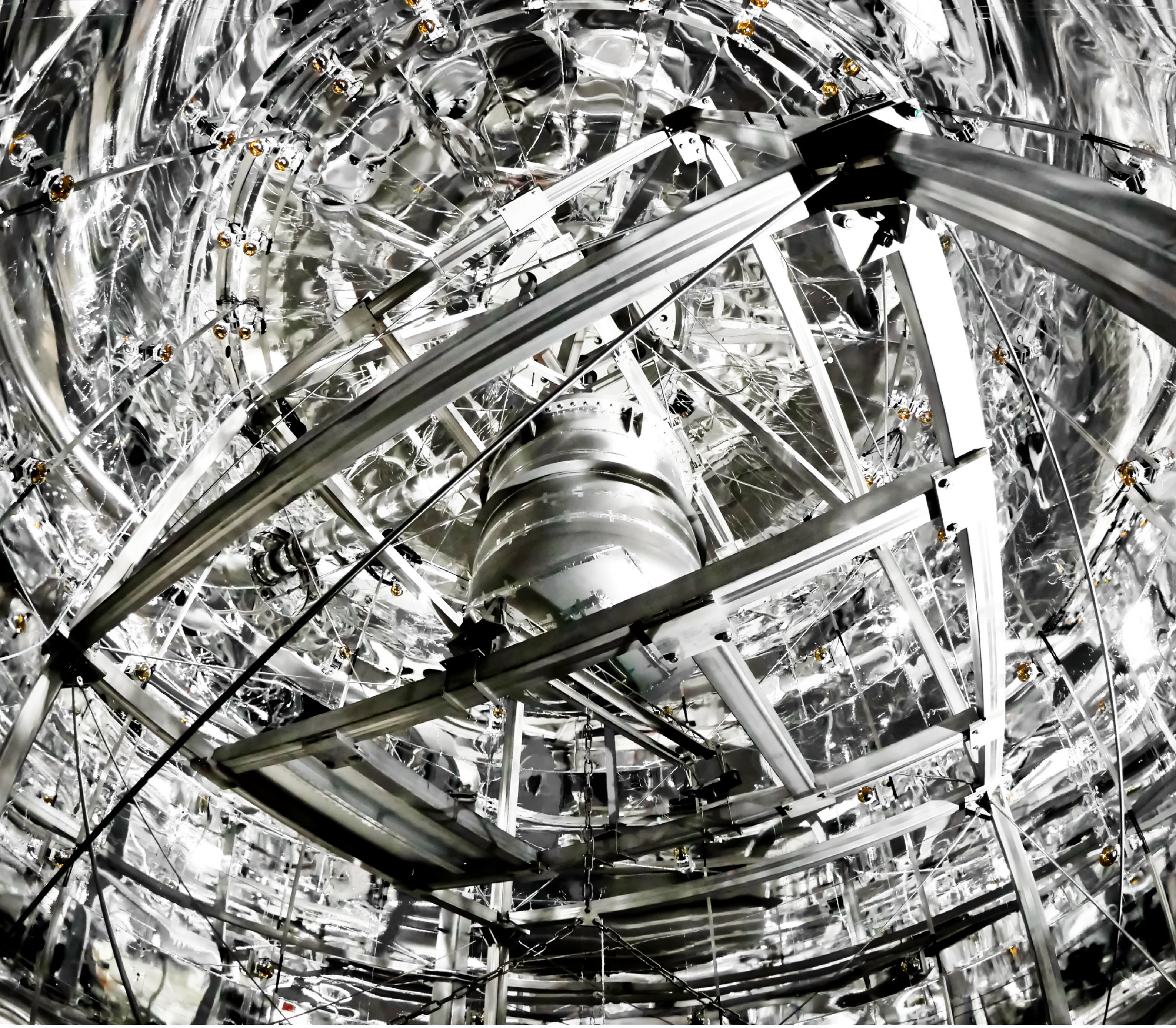
In high-energy collisions between elementary particles, a fraction of the kinetic energy is transformed into short-lived particles normally not found in nature, but that existed in the extremely hot and dense state of the Universe immediately after the Big Bang. Particle collisions at the high-energy frontier thus 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). With nucleon-nucleon centre-of-mass energies up to 13 thousand times the mass of a proton, it currently is the world's most powerful particle accelerator. In proton-proton collisions the experiment does precision measurements of the properties of the strong, electromagnetic and weak interactions, in proton-nucleus collisions the effects of the nuclear environment are probed. Nucleus-nucleus collisions, finally, give access to collective phenomena in extended systems consisting of free quarks and gluons, so-called quark-gluon plasmas.



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

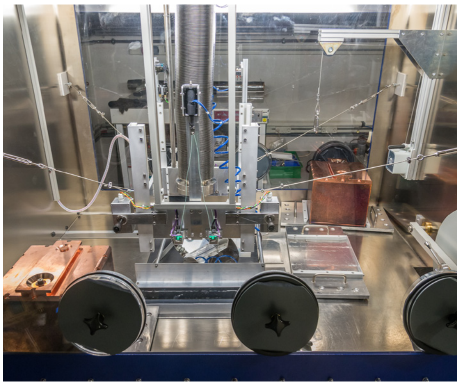
These measurements shed light on the properties of the Universe when it was less than a nanosecond old. At the same time they contribute to the understanding of the interactions of high-energy cosmic rays with the atmosphere, which is needed for the interpretation of the data collected by the Cherenkov detectors. The experimental particle physics group at MPIK is involved in studies of all types of collisions produced by the LHC. The focus is on the overlap between particle and astroparticle physics, where it uses its expertise from both fields to fully exploit the physics potential of the LHCb detector.



1.2 DARK MATTER AND NEUTRINOS

The XENON1T cryostat inside the water tank, which serves as an active veto discriminating against remaining cosmic radiation and radioactivity from the environment.

Low Level Techniques



View into the GIOVE germanium spectrometer in MPIK's low-level laboratory.

Very 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.

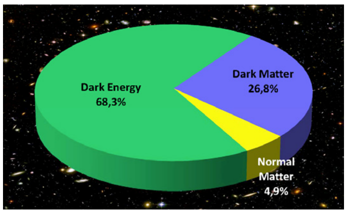
Among the most notorious contaminants are the radioisotopes ^{222}Rn and ^{85}Kr, for which various world-leading screening, measuring and reduction techniques are employed. The "Auto-Ema" system extracts fully automatically the radon outgassing from solid materials allowing for its sensitive measurement 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.

Dark Matter – Structure Forming Agent in the Universe

Based on cosmological observations such as galactic rotation curves, gravitational lensing at galaxy clusters or the cosmic microwave background, it was shown 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 responsible for the acceleration observed in the expansion of the Universe. From a theoretical point of view, weakly interacting massive particles, WIMPs, are promising candidates for dark matter, since they should have formed in the early Universe in the required amount and since they are motivated in required extensions of the Standard Model of particle physics. But the 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.

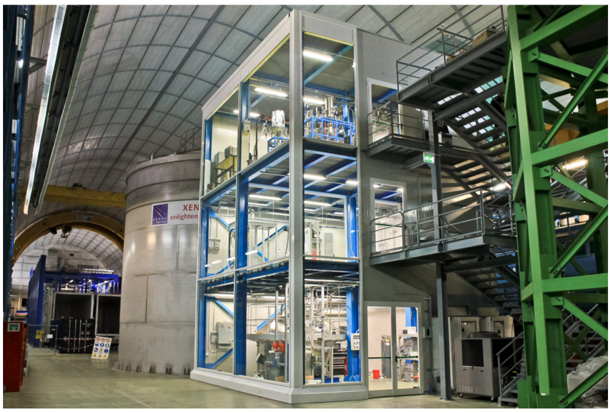
MPIK is involved in the direct search for WIMPs with the XENON experiments in the Gran Sasso underground laboratory in Italy which use ultrapure liquid xenon as the detector medium. The detector observes the combination of scintillation light and ionization emerging from the rare interactions of WIMPs with Xe atoms. XENON1T reached the highest sensitivity of such experiments deeply probing the expected parameter regions where WIMPs and other dark matter candidates are expected. The upgrade to XENONnT is nearing completion and will lead to a ten-fold sensitivity increase.

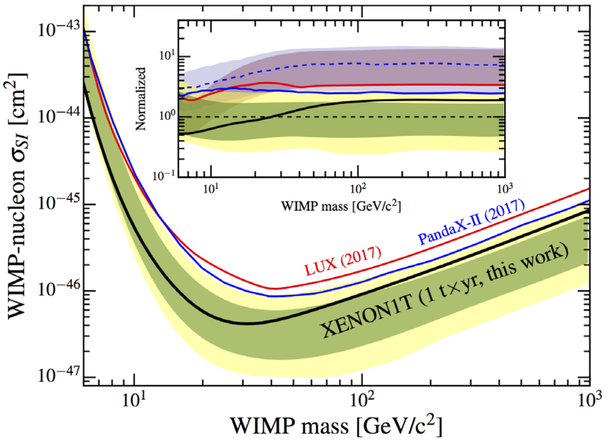
In addition, the H.E.S.S. telescopes look for high-energy gamma rays, produced by the annihilation of DM particles in the DM halo of the Milky Way. Despite the high sensitivity reached, none of the dark-matter detectors has so far seen a signal.



Composition of the Universe.

XENON1T probes dark matter with the world's best sensitivity





The direct detection of dark matter would constitute a great step in understanding the nature of this non-luminous component of our Universe. Data collected by the XENON1T detector with an unprecedented exposure of about 1 ton × year, agrees with the expected background and allows to place the most stringent exclusion limit on WIMP-induced spin-independent interactions for dark matter masses above a few GeV [1].

A key requirement to achieve the required sensitivity is a careful selection and control of the detector materials which determine the detector background. Gamma-ray spectroscopy, measurements of radon emanation with proportional counters and xenon purity control using rare-gas mass spectrometry are some of the tools that assure the lowest background levels ever measured. Such a low intrinsic activity allows the detector to search not only for dark matter interactions but also for other rare nuclear processes. The collaboration has been able to measure for the first time the double electron capture of ^{124}Xe. In this process, two electrons are absorbed in the nucleus simultaneously emitting two neutrinos. The signal in the liquid xenon originates from the relaxation of the electronic shell after the decay. The measurement in XENON1T has determined a lifetime of 1.8×10^{22} y for this process which is the longest half-life ever measured directly [2].

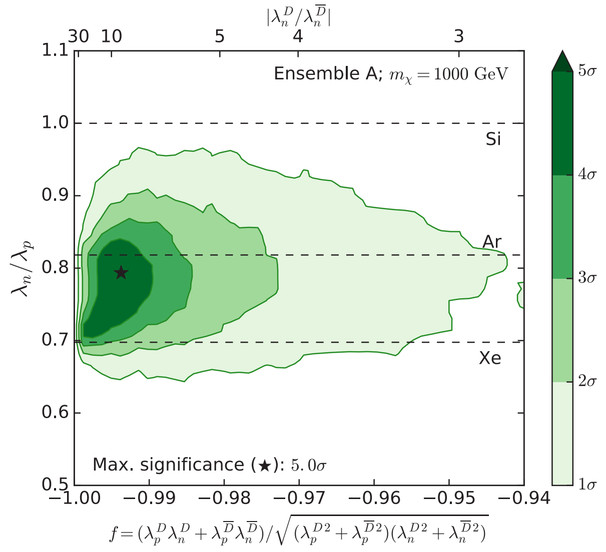
References:

[1] XENON Collaboration, Phys. Rev. Lett. 121 (2018) 111302, DOI: 10.1103/PhysRevLett.121.111302

[2] XENON Collaboration, Nature 568 (2019) 532, DOI: 10.1038/s41586-019-1124-4

Theory of dark matter

Improved direct detection limits on standard WIMP dark matter lead to increased interest in alternatives. A WIMP signal could, however, be around the corner in upcoming searches and combining direct searches with indirect and collider data one could learn about its properties (quantum numbers, spin, self-conjugate, etc.). Well-known simple models include the Higgs and the Z' portal, as well as dark photon models that require kinetic mixing. Many simple cases are essentially ruled out by a combination of different probes which allows to study which interactions, production mechanisms or non-standard masses are allowed.



Various aspects of dark matter models and phenomenology were studied. For instance, new interactions on the evolution of keV sterile neutrino dark matter in the early Universe can thermalize the sterile neutrinos and resolve the tensions with structure formation and X-ray observations. Due to its highly suppressed cross section (fermionic) dark matter interacting via pseudoscalar mediators was expected to be unobservable in direct detection experiments. However, the leading one-loop contribution to the effective dark matter-nucleon interaction dominates the scattering rate and was found to be in the vicinity of the neutrino floor. Direct detection signals from at least three different targets may be used to determine whether the dark matter particle is different from its antiparticle. We have determined the significance with which the self-conjugate nature can be rejected, and found cases with up to 5-sigma discrimination potential.

References:

[1] G. Arcadi et al., JCAP 1803, 042 (2018), DOI: 10.1088/1475-7516/2018/03/042

[2] G. Arcadi et al., Eur. Phys. J. C78, 203 (2018), DOI: 10.1140/epjc/s10052-018-5662-y

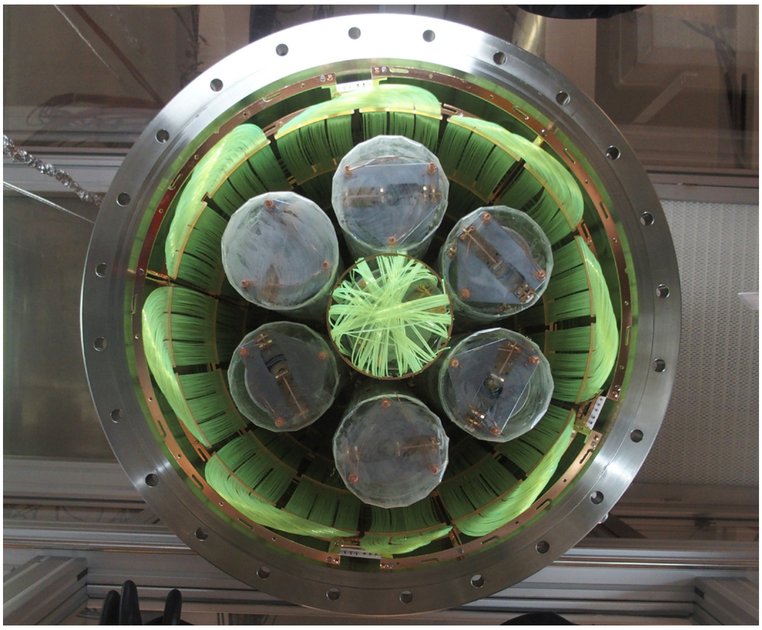
[3] B.J. Kavanagh et al., JHEP 1710, 059 (2017), DOI: 10.1007/JHEP10(2017)059

[4] R.S.L. Hansen, S. Vogl, Phys. Rev. Lett. 119, 251305 (2017), DOI: 10.1103/PhysRevLett.119.251305

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. Thus, sensitive detectors with excellent shielding against background signals are required to detect them.

A neutron inside a nucleus beta decays to a proton, an electron and an antineutrino leading to another element. 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 either two or possibly no neutrino. The GERDA experiment searches for the neutrinoless double-beta decay in pure germanium crystals enriched with ^{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 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.



The germanium detectors of GERDA in their shielding.

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.

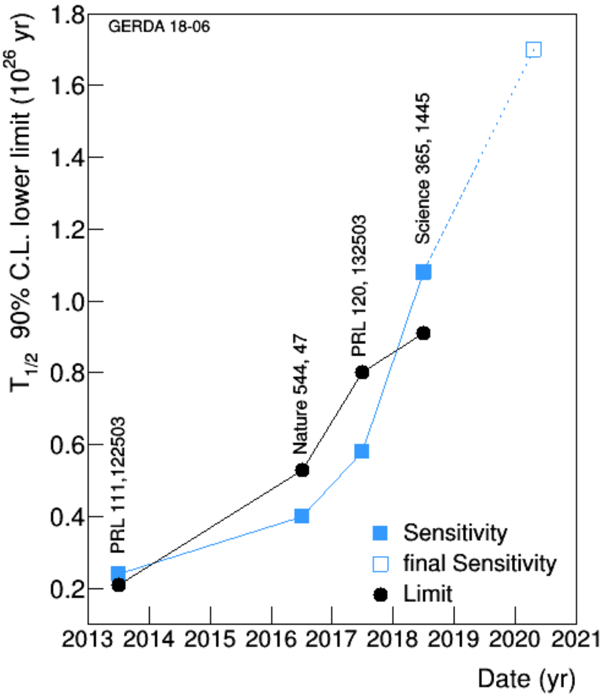
The periodic changeover between the three neutrino flavours electron, muon and tauon neutrino ("neutrino oscillations") is described by so-called mixing angles. The Double Chooz experiment used electron antineutrinos from a nuclear power plant in France to measure one of the three mixing angles. The two identically designed detectors with liquid gadolinium-containing scintillator at different distances from the reactors are sensitive only to electron antineutrinos, the number of which declines from the near to the far detector due to the oscillations. The results confirm that also this mixing angle has a non-zero value which means that all oscillations take place.

Indeed, many experiments in the vicinity of nuclear power plants detect 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 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.

Record sensitivity for the search of neutrinoless double beta decay

The sensitivity of an experiment for a rare decay search depends on the number of background events in the search window. For GERDA, the expected number is about 0.4 for the design exposure – the exposure is the product of active detector mass and measurement time. This value is exceptionally low in comparison to all competing experiments. For values smaller than about 1, the sensitivity for setting a limit on the half-life improves linearly with the exposure rather than with the square root. Such an experiment can therefore be called "background-free" [1].



With the recent publication [2] the low background was confirmed with more statistics. For the first time, a double-beta decay experiment surpassed the threshold of 10^{26} years for the sensitivity of setting a 90% C.L. limit on the half-life – in our case for the isotope ^{76}Ge.

The history of half-life limits and the sensitivity are plotted in the figure. Since 2015, the second phase of GERDA is running stable with the above-mentioned low background. In November 2019 the design exposure was reached and we expect an improvement of the sensitivity by 50%.

The extremely good performance of GERDA in terms of background suppression – but also energy resolution – lead to the formation of the new LEGEND collaboration that adopted the experimental concept of operating germanium detectors in liquid argon. Starting in 2020, our existing infrastructure will be modified by LEGEND to boost the half-life sensitivity for setting a limit to 10^{27} years.

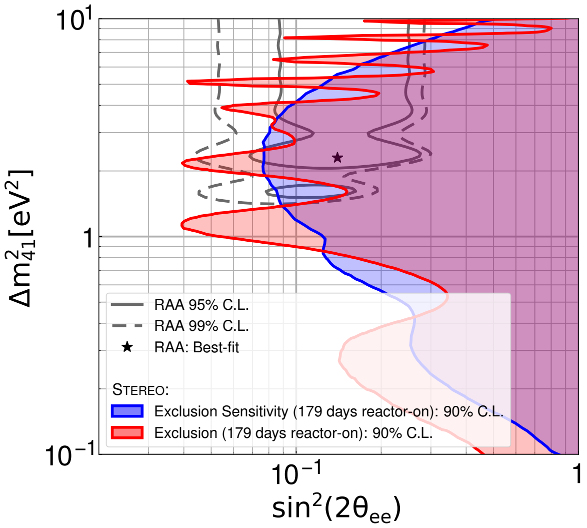
References:

[1] M.Agostini et al (GERDA collaboration), Nature 544, 47-52 (2017), DOI: 10.1038/nature21717

[2] M.Agostini et al (GERDA collaboration), Science 365, 1445-1448 (2019), DOI: 10.1126/science.aav8613

Constraints on the existence of sterile neutrinos

The search for light sterile neutrinos with the Stereo detector [1] started after the installation at the 58 MW_{th} research reactor of ILL Grenoble in November 2016. A first analysis in the phase-I of the experiment using 66 days of data with the reactor turned on already allowed to exclude a large fraction of the parameter region of interest [2]. A very good agreement between experimental data and the simulated antineutrino signal in the Stereo detector could be achieved using FIFRELIN, a Monte Carlo code developed at CEA/DEN Cadarache, France. This code is capable of modelling the emission cascade of gammas and electrons resulting from the de-excitation of the excited nuclei created by neutron capture after the neutrino interactions in the Stereo detector. In this way, the description of the energy measured after selected neutron captures and the understanding of the efficiency for neutrino detection improved notably [3]. With additional optimizations in the neutrino analysis and an extended data taking period including about 180 days of reactor turned on and 230 days of reactor turned off even stronger constraints on the existence of sterile neutrinos are set [4]. The figure shows the excluded combinations of neutrino mass splitting and mixing angle. The Stereo experiment will also deliver a leading precision result on the absolute comparison between the predicted and measured total neutrino rate for a highly enriched ^{235}U reactor. Finally, the extensive calibration of the energy scale allows for an accurate study of the reactor antineutrino spectral shape which is currently under heavy discussion in the field of reactor physics.



References:

[1] N. Allemandou et al., JINST 13 (2018) P07009, DOI: 10.1088/1748-0221/13/07/P07009

[2] H. Almazan et al., Phys. Rev. Lett. 121 (2018) 161801, DOI: 10.1103/PhysRevLett.121.161801

[3] H. Almazan et al., Eur. Phys. J. A 55 (2019) 183, DOI: 10.1140/epja/i2019-12886-y

[4] H. Almazan et al., arXiv:1912.06582

Neutrinos scattering on atomic nuclei

The Standard Model of particle physics predicts six ways of interacting with matter for the tiniest and most elusive particles: the neutrinos. The most intriguing and till 2017 undetected [1] channel is a scattering process of neutrinos with the constituents of atomic nuclei. Due to quantum-mechanical coherency the respective cross section can scale with the squared number of neutrons in the nucleus and thus be enhanced by several orders of magnitude compared to the other interaction channels. This enhancement allows for the first time to build kg-sized neutrino detectors which, however, need the ability to register extremely small nuclear recoils induced by the momentum transfer of the neutrinos.

To this end, we initiated the CONUS experiment, aiming at detecting neutrinos at the nuclear power plant in Brokdorf, Germany. With its 3.9 GW thermal power it is one of the most powerful single reactor neutrino sources world-wide. At the detector site 17 m from the reactor core, the immense neutrino flux is still 10^{13} per second/cm^2. There, we set up 4 specifically designed low-energy-threshold germanium detectors inside an elaborated passive and active shield, and started the operation in April 2018. Since then, data have been collected including few short reactor-off periods. A preliminary analysis of the count rates during reactor on vs. off periods has already provided a first hint of observation of this coherent neutrino-nucleus scattering process [2].

Ongoing activities focus on optimization of the detector operation under extraordinary laboratory conditions, the background understanding [3] and quantifying systematics effects, as prerequisites to a final spectral shape analysis.

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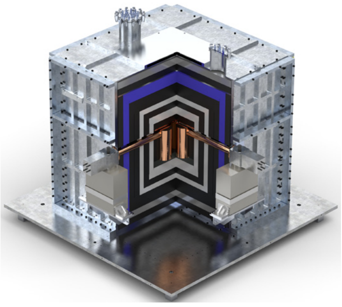
[1] D. Akimov (Coherent collaboration), Science 357, 1123-1126 (2017), DOI: 10.1126/science.aao0990

[2] W. Maneschg (for the Conus collaboration), Proc. to XXVIII Int. Conf. on Neutrino Phys. Astrophys. 2018, DOI: 10.5281/zenodo.1286927

[3] J. Hakenmüller et al. (Conus collaboration), Eur. Phys. J. C 79, 699 (2019), DOI: 10.1140/epjc/s10052-019-7160-2



Three-quarters portrait of the CONUS setup including the germanium detectors, the passive and active shields.

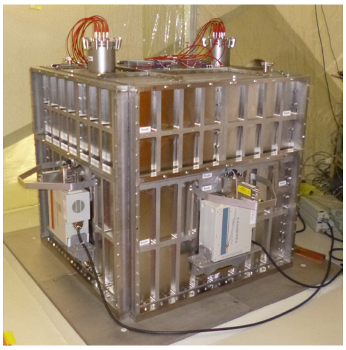
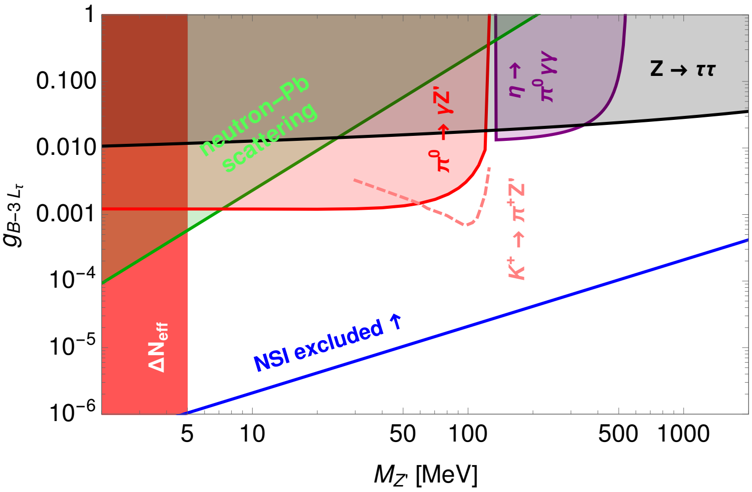


Photo of the CONUS setup after its successful installation at the nuclear power plant in Brokdorf.

Neutrinos and physics beyond the Standard Model

Neutrinos are a window to physics beyond the Standard Model. Mechanisms to generate neutrino mass have a variety of new features such as new particles, new energy scales, new interactions, etc. Within such mechanisms the baryon asymmetry of the Universe can be generated, and connections to dark matter are also very frequent. Other consequences include observable effects in running and future experiments that probe neutrino parameters. The properties of neutrinos also influence several interesting astrophysical objects such as Supernovae. The physics behind neutrino mass may also be related to interesting ideas related to conformal symmetry, or classically scale-invariant theories, that may solve the hierarchy problem. A broad program investigates consequences of neutrino mass and mixing theoretically and phenomenologically. This includes proposing and studying new physics effects in neutrinoless double beta decay or direct mass experiments. The particles related to those new effects would show up at colliders or in rare decays, which provides a way to distinguish the new from standard neutrino physics. Features of supernova neutrino spectra and the possibility to triangulate the position of a supernova via different neutrino arrival times in different detectors was investigated. Additional interactions of neutrinos (NSI) can cause an observable effect in neutrino oscillations. The current constraints were shown by us to be often better than the ones of other probes for such new interactions.



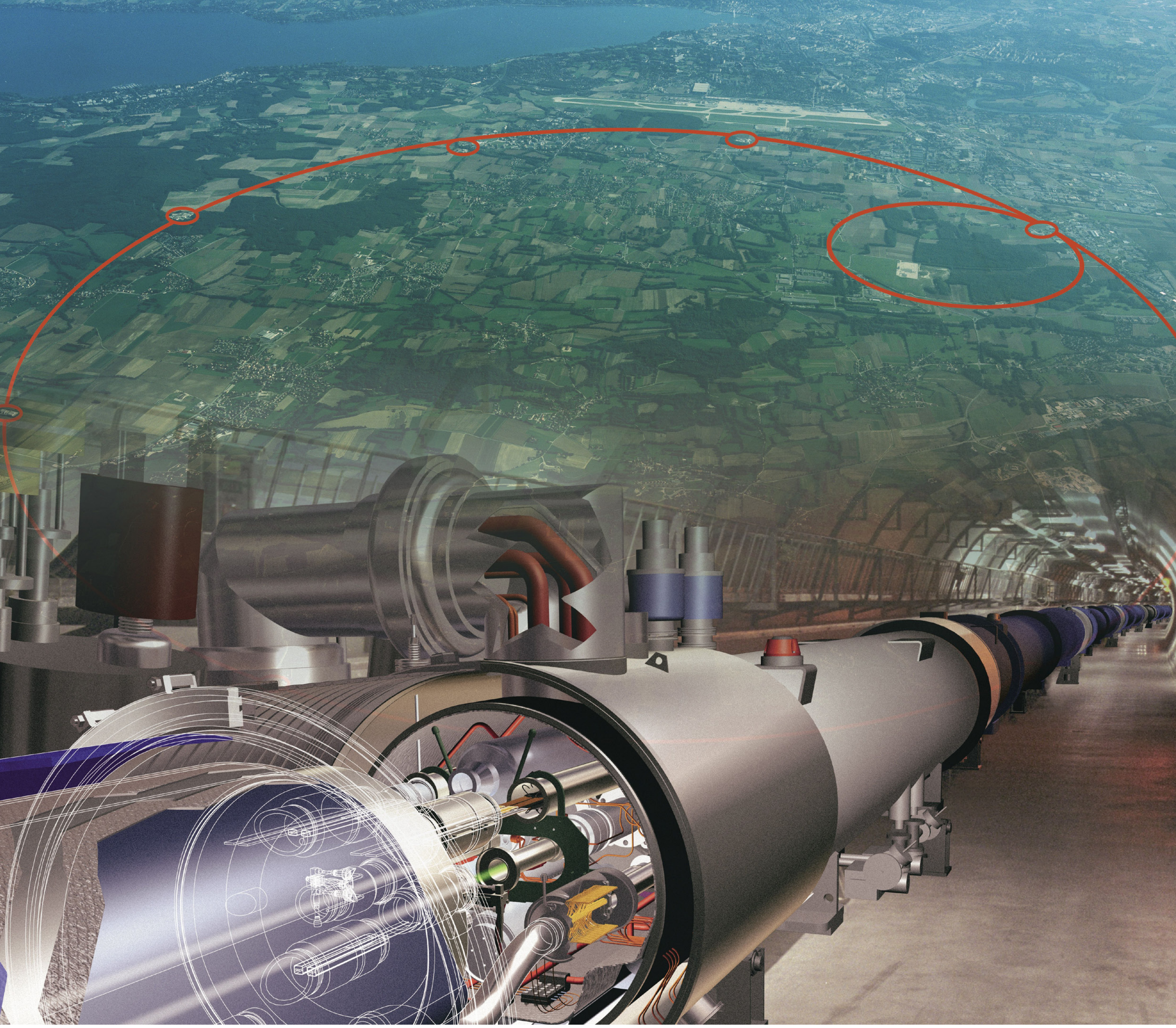
References:

[1] J. Heeck et al., SciPost Phys. 6 (2019) 038, DOI: 10.21468/SciPostPhys.6.3.038

[2] V. Brdar et al., JCAP 1804, 025 (2018), DOI: 10.1088/1475-7516/2018/04/025

[3] V. Brdar et al., Phys. Rev. D99, 055014 (2019), DOI: 10.1103/PhysRevD.99.055014

[4] G. Arcadi et al., JHEP 1901, 206 (2019), DOI: 10.1007/JHEP01(2019)206



1.3 BEYOND THE STANDARD MODEL

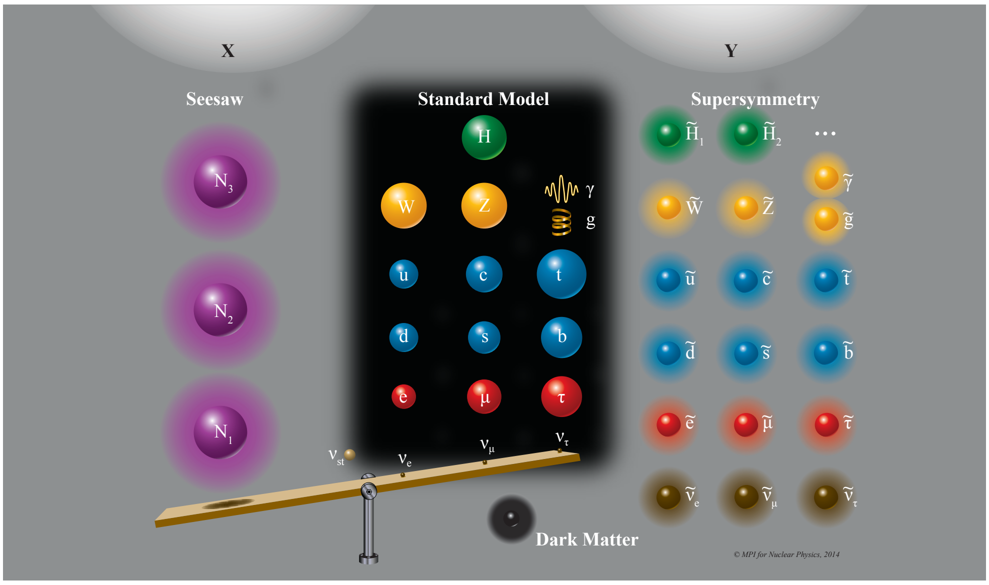
An upgrade of the Large Hadron Collider may detect physics beyond the Standard Model. (Image: CERN)

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.

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.

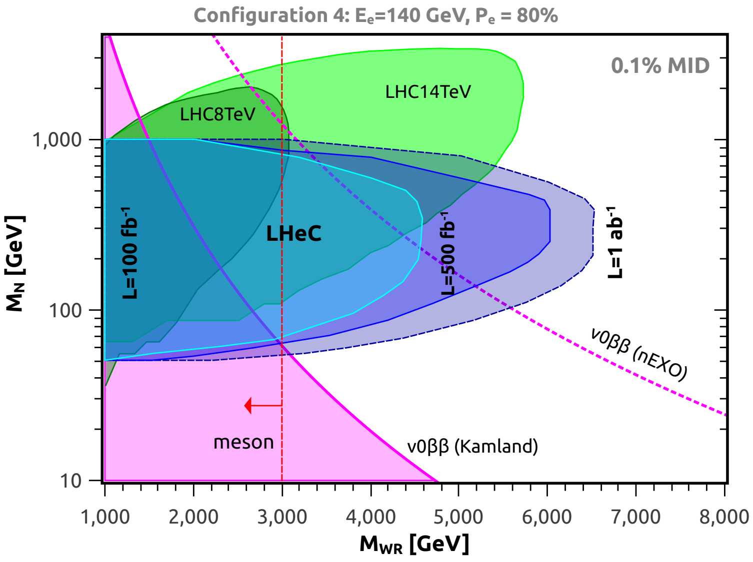
A lot of theoretical work is done at MPIK on the origin of neutrino masses and mixings via basic and phenomenological studies. The so-called seesaw mechanism is a way to explain the smallness of neutrino masses based on the presence of new heavy particles, which are in fact predicted by many theories 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.



Elementary particles of the Standard Model (black background) and their hypothetical supersymmetric and seesaw partners.

Lepton number violation at high and low energy

Essentially all theories beyond the Standard Model predict lepton number violation (LNV). In this case, neutrinoless double beta decay occurs at some level. If the particles mediating LNV are at the TeV scale, present and future colliders can produce them, and half-lifes for neutrinoless double beta decay are generated at a level that is testable in upcoming and running searches [1]. Hence, both approaches are complementary, and allow for tests of the underlying mechanism of LNV if it is observed in one of them.



The LHC might however be blind to certain parameter combinations, leading to a gap in sensitivity that other colliders may close. In particular, we have analysed how a future electron-proton collider, called LHeC, can probe the parameter space and how this would compare to LHC and double beta decay [2]. The chosen framework applied left-right symmetric theories. In the analysis one needs to take into account different values for the polarization of the electrons or the rate of charge misidentification, which are currently not known.

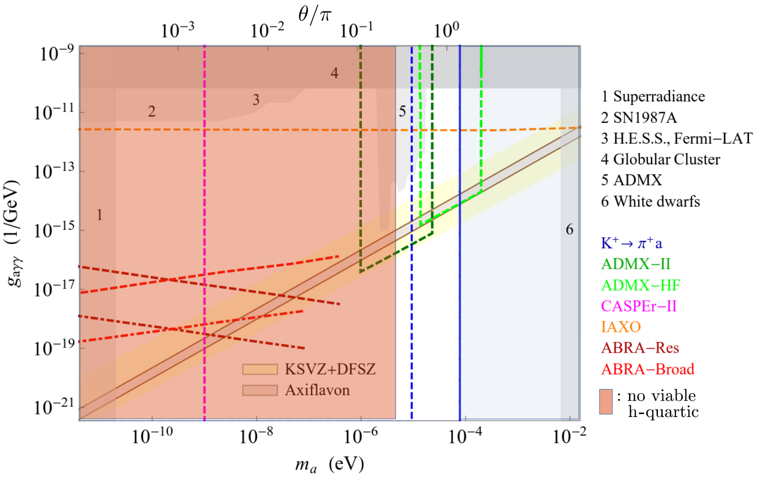
Nevertheless, a sizable part of the reachable parameter space is beyond the expected reach of the LHC and of future neutrinoless double beta decay experiments.

References:

[1] M.J. Dolinski, A.W.P. Poon, W. Rodejohann, Ann. Rev. Nucl. Part. Sci. 69 (2019) 219-251, DOI:10.1146/annurev-nucl-101918-023407

[2] M. Lindner et al., JHEP 1606 (2016) 140, DOI:10.1007/JHEP06(2016)140

Unified solutions to shortcomings of the Standard Model of particle physics



Four of the biggest mysteries in fundamental physics are: the origin of the huge hierarchies in fermion masses, the seemingly fine-tuned vanishing of CP violation in strong interactions, the nature of dark matter (DM), and the dynamics behind electroweak symmetry breaking. A simple and unified solution to these puzzles has been proposed by extending the Standard Model of particle physics with a single scalar multiplet whose vacuum expectation value addresses all these issues. This unified picture makes the model very predictive, such that this “Axiflavon”-Higgs can be fully tested at near-future *axion* and *flavour* experiments, see the Figure, where solid (dashed) lines correspond to current (projected) bounds [1].

In a similar spirit, recently an *effective* DM scenario has been proposed, which explains the smallness of light-quark masses, evades direct detection limits, and features new collider signatures to be searched for [2].

Finally, since standard ideas for realizing the Higgs Boson as a composite particle, which in addition to some of the issues above elegantly solves the famous ‘gauge hierarchy problem’, got in increasingly pressing tension with missing signals of predicted light partner particles of the top quark at the LHC, threatening the idea of a natural composite Higgs, the recent model-building efforts were also focused on exploring ways out of this. In fact, an elegant means to save such models resulted, entertaining a new, softened, way of global-symmetry breaking by completing fermion multiplets to full SO(5) representations, which lifts the anomalously light partners. This allows to construct setups that solve the hierarchy problem, while being in full agreement with current LHC limits on top partners, yet detectable at the LHC upgrade or a future 100 TeV collider [3].

References:

[1] T. Alanne, S. Blasi, F. Goertz, Phys. Rev. D 99, 015028 (2019), DOI: 10.1103/PhysRevD.99.015028

[2] F. Goertz, K.M. Tame-Narvaez, V. Tenorth, Eur. Phys. J. C (2019), DOI: 10.1140/epjc/s10052-019-7374-3

[3] S. Blasi, F. Goertz, Phys. Rev. Lett. 123 (2019), DOI: 10.1103/PhysRevLett.123.221801

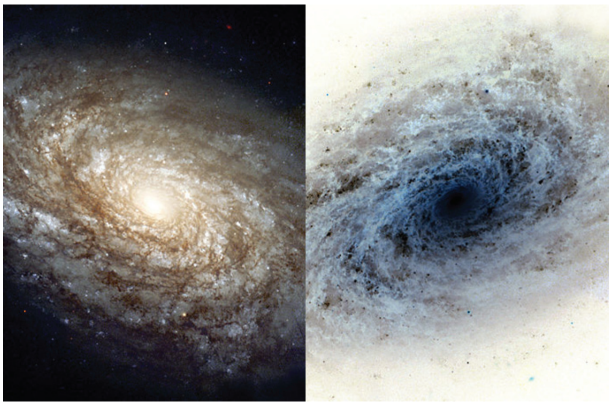
Matter and Antimatter – Search for the Crucial Difference

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.

This symmetry violation must have occurred in the early Universe, but the Standard Model of elementary particle physics can't explain the observed asymmetry. A scenario for this, in which neutrinos play a crucial role, is the so-called leptogenesis which is explored by MPIK theorists. 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 as 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.

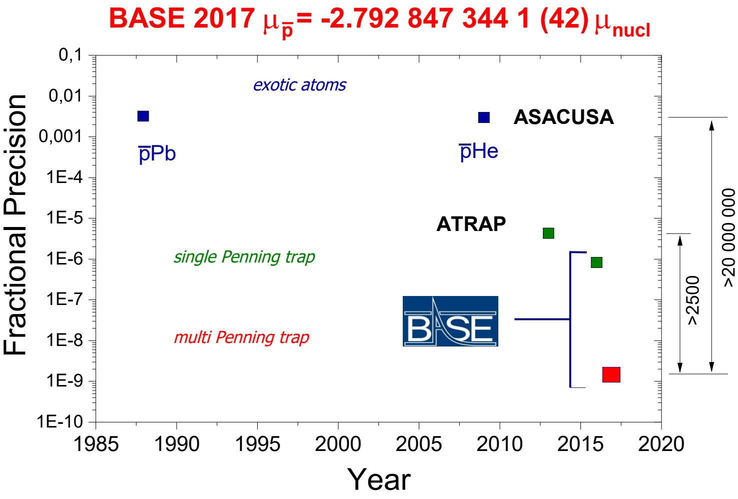


Despite intensive searches, astronomical observations have not provided any evidence of the existence of antigalaxies.

Protons and antiprotons under the microscope

Within the Standard Model of particle physics interactions are believed to be invariant under the combined CPT transformation. Consequently, particle-antiparticle pairs are expected to be created and annihilated in equal amounts and to have identical properties except for signs. This theoretical understanding is, however, in conflict to our astronomical observations, which indicate that our Universe consists almost exclusively of matter. The Standard Model can neither explain this matter-antimatter asymmetry in our Universe, nor reproduce the observed matter excess by any other means. Searching for an additional symmetry breaking or interaction may provide important hints to improve our understanding and explain the matter-antimatter asymmetry.

To this end, we operate several experiments within the BASE collaboration to compare the charge-to-mass ratios and magnetic moments of protons and antiprotons with ultra-high precision. Using single- and multi-Penning traps, we were able to outperform early spectroscopic experiments on exotic atoms. Our results verify that the magnetic moments are equal at the parts-per-billion level and that the charge-to-mass ratios are equal at the 70 parts-per-trillion level. However deviations, that explain the matter-antimatter asymmetry, might be observed at higher measurement precision. Thus, in future novel techniques like sympathetic laser cooling using a common endcap technique and phase-sensitive detection methods will be employed to improve upon the constraints even further.



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[3] N. Nagahama et al., Nature Communications 8, 14084 (2017), DOI: 10.1038/ncomms14084

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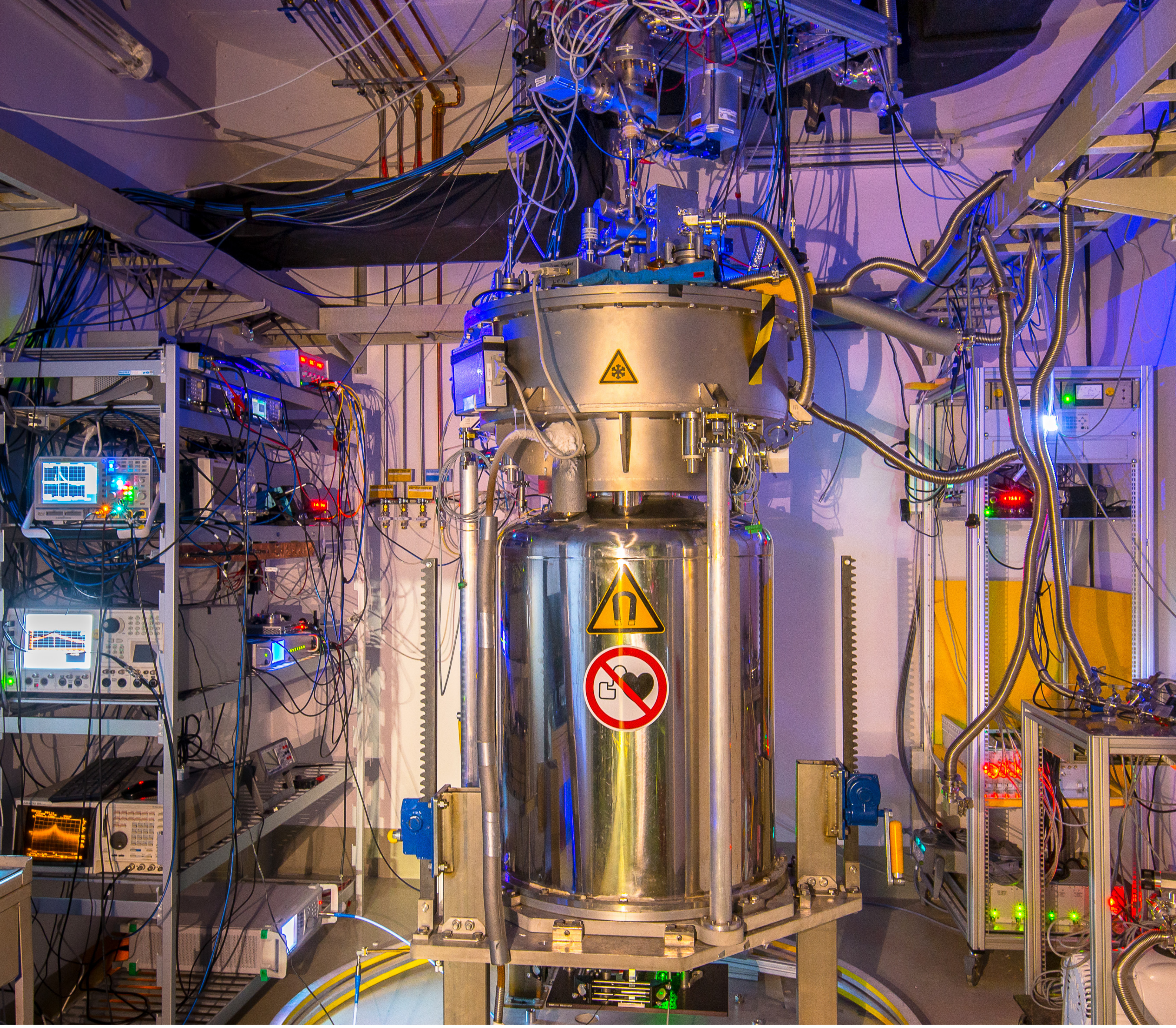
QUANTUM DYNAMICS

2



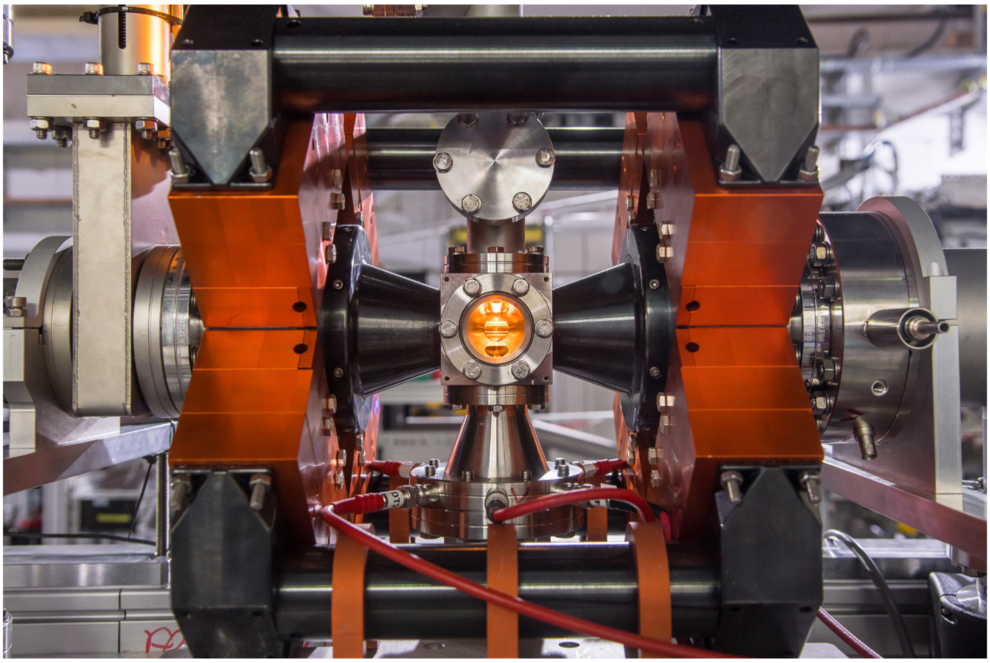
2.1 HIGHEST PRECISION

The ALPHATRAP laboratory.

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 radioactive beam facilities like GSI and CERN.

In an electron-beam ion trap (EBIT), highly charged ions are produced by impact of energetic electrons, then spatially confined, and electronically heated up to temperatures of millions of degrees. Both, stationary and mobile EBITs are used to prepare and study atomic matter under extreme conditions. One of the highlights of the latest EBIT developments at MPIK is the Tip-EBIT at the experiment PENTATRAP where laser desorption and subsequent ionization is applied. It extends the range of available HCIs to rare isotopes, which are synthesized in only sub-nanogram quantities. A suite of accurate spectroscopic instrumentation attached to the EBITs collects precise data. A new cryogenic ion trap (Cryogenic Paul Trap Experiment: CryPTEx) has been built at MPIK in cooperation with the university of Aarhus, in which ion crystals can be produced by means of laser cooling, and highly charged ions cooled therein.



A newly developed miniature EBIT.

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

Penning-trap mass spectrometry at MPIK allowed recently to perform world-record measurements on 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, 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 used to determine nuclear binding energies which are crucial for reaction pathways in nucleosynthesis. In combination with theoretical models, the structure of nuclei even far from stability can be investigated. 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.

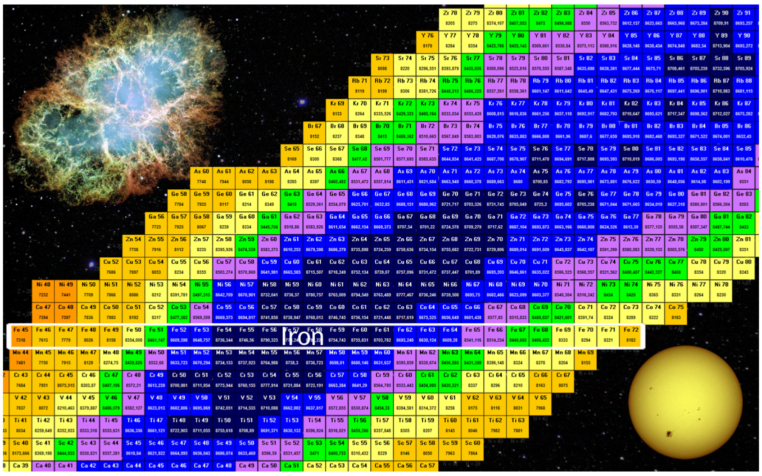
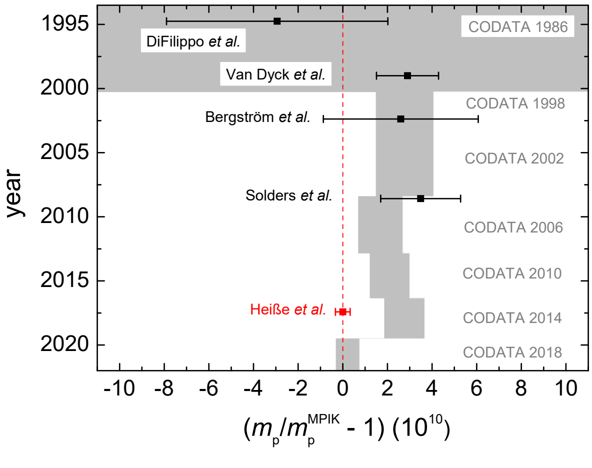


Chart of nuclides with the colour code showing the binding energy per nucleon: the most stable nuclides around iron are in dark blue.

The atomic mass of the proton: 3 times more precise and 3σ smaller than expected

The electron, proton and neutron are the basic building blocks of the atomic structure of nature. The precise knowledge of their intrinsic properties, e. g., their rest mass, is essential for fundamental tests of quantum electrodynamics and the determination of fundamental constants like the Rydberg and the fine-structure constant. Until now, a combination of the mass measurements on light ions (proton, deuteron, helium-3 and the molecule HD) show a 5σ discrepancy and thus question these measured values. In a new Penning-trap setup, the LIONTRAP (Light ION Trap) experiment, these masses will be determined in a new approach in atomic mass units and with unrivalled precision. Here, we compare the cyclotron frequency of a single trapped carbon ion to the one of a single trapped ion of interest. Alternately, both frequencies are measured in a non-destructive way in a newly designed seven-electrode cylindrical Penning trap.



In the first measurement campaign, the focus was on the proton mass. The strongly differing charge-to-mass ratios of a proton and a carbon nucleus require extraordinarily precise knowledge of the systematic shifts. Great effort has been invested to trap both ions subsequently at the same position by applying the same trapping potential and using two independent but fine-tuned cryogenic ultra-low noise axial detection systems. For the first time, a phase-sensitive measurement of the cyclotron frequency of the proton has been successfully implemented, which was made possible by the exceptionally good harmonicity of the electrostatic trap potential. With a relative uncertainty of 3×10^{-11} the new proton mass is a factor of 3 more precise than the previous literature value. Although our measured value is 3σ smaller than expected, this is not sufficient alone to solve the mentioned light ion mass puzzle, which is a strong motivation for further investigations on the other light ion masses.

References:

[1] F. Heiße et al., Phys. Rev. Lett. 119, 033001 (2017), DOI: 10.1103/PhysRevLett.119.033001

[2] F. Heiße et al., Phys. Rev. A 100, 022518 (2019), DOI: 10.1103/PhysRevA.100.022518

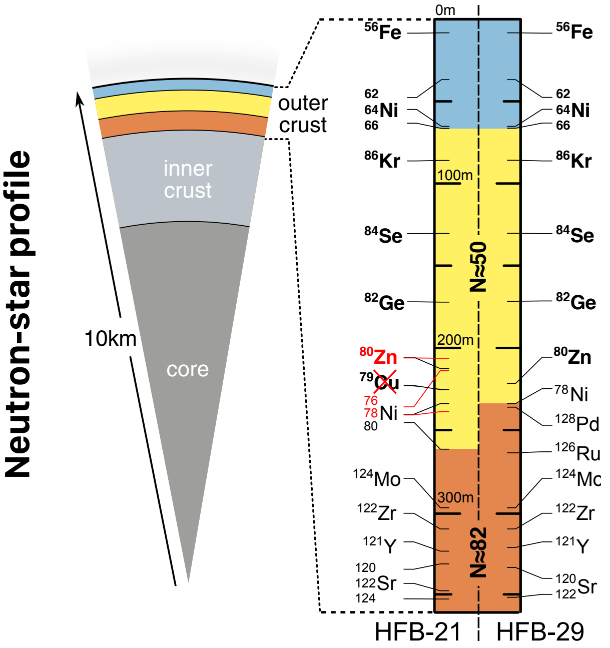
[3] S. Sturm et al., Eur. Phys. J. Special Topics 227, 1425{1491 (2018), DOI: 10.1140/epjst/e2018-800225-2

High-precision mass measurements of short-lived, neutron-rich copper and chromium isotopes

The precise mass determination of radioactive atoms is key to further understanding of the nucleus. Far from nuclear stability, the highly unbalanced proton-to-neutron ratio reveals new nuclear phenomena and allows for nuclear models to be tested.

Hence, in a recent study using the high-precision mass spectrometer ISOLTRAP at ISOLDE/CERN, the masses of neutron-rich copper isotopes $^{75-79}$Cu were measured [1]. With ^{79}Cu located only one proton above the flagship nucleus ^{78}Ni, these measurements offer a first accurate view on the doubly closed-shell nature of ^{78}Ni. Furthermore, the mass values allowed for refined simulations (see figure) of the crust composition of neutron stars, still containing bound atoms in the first hundreds of meters of their outer crust. The knowledge of their composition is important for the element abundance in the Universe as neutron-star and neutron-star-black-hole mergers are possible sites for the rapid neutron-capture process, being responsible for the creation of approximately half of the atomic nuclei heavier than iron.

Besides revealing a smooth development of nuclear ground-state collectivity towards N = 40, the neutron-rich chromium isotopes $^{58-63}$Cr measured in another experimental campaign [2] are also known to play an important role in the cooling and heating of the lower layers of the crust of accreted neutron stars, possibly impacting the associated astrophysical observables.



Simulated neutron-star-crust profile with its isotope content. S. Gorielli, private communication (2017).

References:

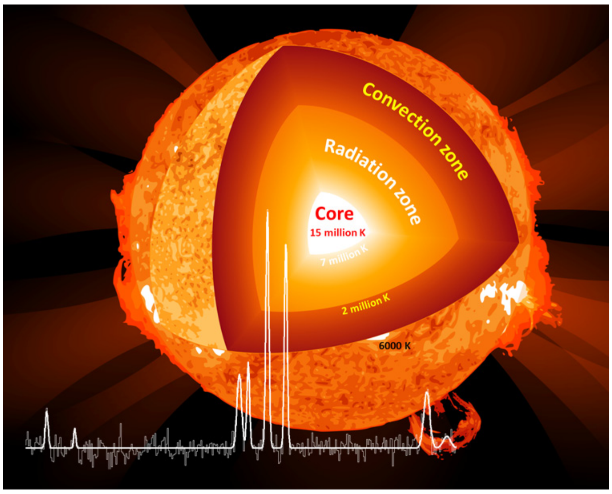
[1] A. Welker et al. Phys. Rev. Lett. 119, 192502 (2017), DOI: 10.1103/PhysRevLett.119.192502

[2] M. Mougeot et al. Phys. Rev. Lett. 120, 232501 (2018), DOI: 10.1103/PhysRevLett.120.232501

Highly Charged Ions – Matter under Extreme Conditions

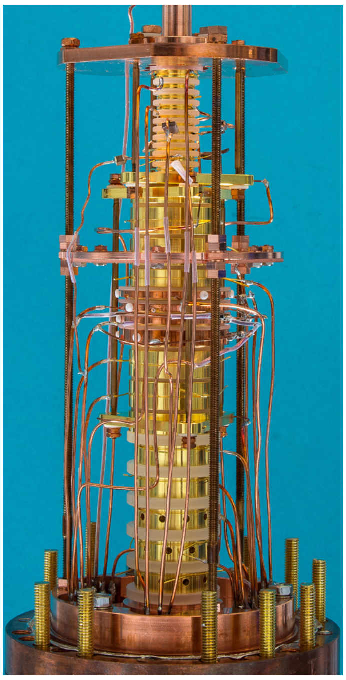
Highly charged ions (HCIs) are found in hot environments of more than one million degrees such as stellar atmospheres and cores, supernova remnants or accretion discs around neutron stars and black holes. In fact, most of the visible matter in the Universe is assumed to be highly ionized. Analysis of 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.

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



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

First results of ALPHATRAP: the magnetic moment and fine structure of boronlike ^{40}Ar^{13+}

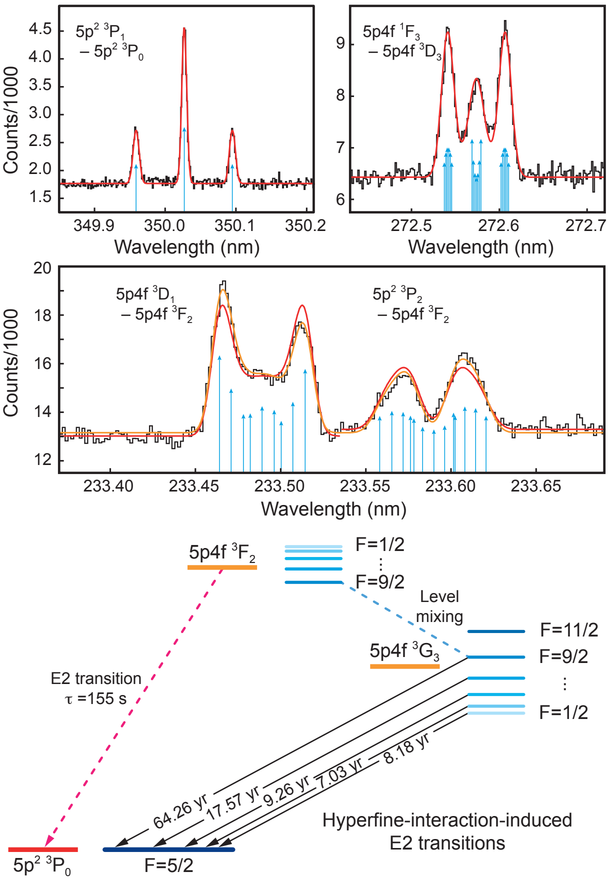


Highly charged ions (HCI) are excellent systems for testing the validity of quantum electrodynamics (QED) in strong fields. Those ions allow for precise calculations and the extremely high electric field strength in heavy HCI provides a unique sensitivity to possible deviations from the Standard Model of physics. The recently developed ALPHATRAP experiment includes a room-temperature electron beam ion trap (EBIT) for medium-Z ions and a connection to the Heidelberg high-energy EBIT (HD-EBIT) for high-Z HCIs. The versatile double Penning-trap system can capture and trap HCIs of any charge state and mass. Ions are injected into the cryogenic trap system inside a superconducting magnet, where they can be stored for several months due to the extremely high-vacuum conditions of $<10^{-17}$ mbar. Apart from the highly homogeneous trap that is used for high-precision spectroscopy, another one is used for spin-state detection via the continuous Stern-Gerlach effect (CSGE). Performing unambiguous spin-state detection was the basis for precise measurements of the ion's magnetic moment (g-factor). The first measurement was of the g-factor of boronlike ^{40}Ar^{13+} with 9-digits precision. We have also performed ab initio calculations of the g-factor, taking into account electron correlation and QED effects. By significantly improving the latter, we arrive to a relative theoretical uncertainty of 9×10^{-7}. The perfect agreement between theory and experiment paves the way toward an independent determination of the fine-structure constant. Additionally, we have shown that the CSGE can be used instead of fluorescence detection, to find and measure optical transitions. For this, laser spectroscopy of the fine-structure transition in the ground state of ^{40}Ar^{13+} was performed. These successful campaigns have demonstrated the potential of ALPHATRAP, which will allow to further explore the boundary of validity of strong-field QED.

References:

[1] I. Arapoglou et al., Phys. Rev. Lett. 122, 253001 (2019), DOI: 10.1103/PhysRevLett.122.253001
[2] A. Egl et al., Phys. Rev. Lett. 123, 123001 (2019), DOI: 10.1103/PhysRevLett.123.123001

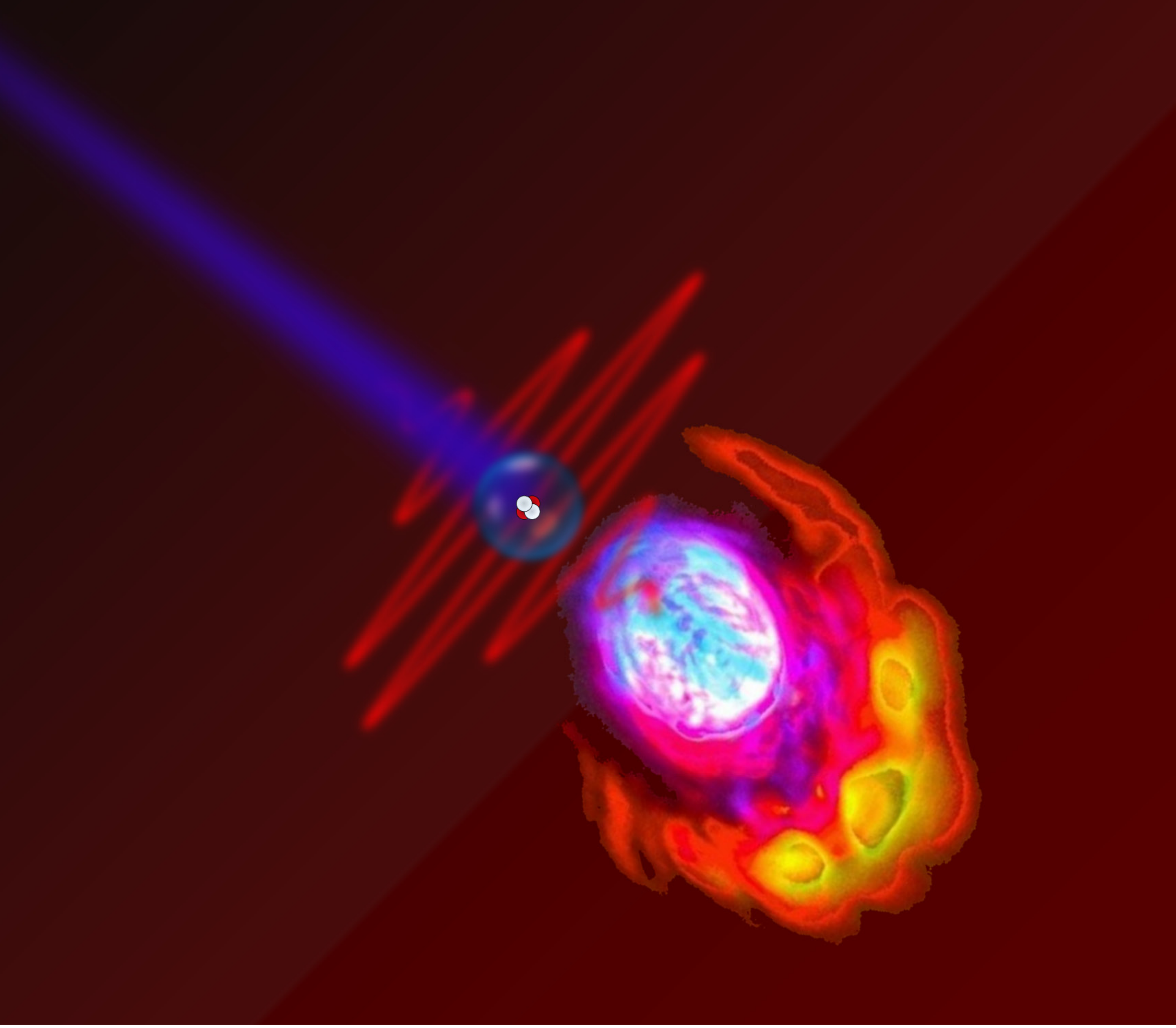
Towards an orbital-crossing clock to test fundamental constants



Optical frequencies in atoms and ions called 'clock transitions' are the most accurately measured quantities in science, and as stable as fundamental constants; 'varying' clocks would challenge the Standard Model of fundamental interactions. Since atomic properties limit the reach of ongoing searches, we look for maximally sensitive optical transitions. Rare 'orbital crossings' present in highly charged ions (HCI) magnify the effect of a 'varying' fine-structure constant α, the best known one, by strongly shifting the initial and final states in the transition [1]. We found in the Pr^{9+} ion the second such crossing, and measured for the first time all spectroscopic levels of its potential clock transition, which has high sensitivity to new physics and the smallest predicted effects of external perturbations [2]. Our large-scale relativistic atomic structure calculations allowed an unambiguously identification of this transition. Its lifetime of about 8 years ensures ultimate clock stability. Since we also newly demonstrated how to sympathetically cool HCI for use in clocks [3], our experiment amply extends the frontiers of such searches for physics beyond the Standard Model.

References:

[1] M. Kozlov et al., Rev. Mod. Physics (2018), DOI: 10.1103/RevModPhys.90.045005
[2] H. Bekker et al., Nature Comm. (2019), DOI: 10.1038/s41467-019-13406-9
[3] T. Leopold et al., Rev. Sci. Instrum. (2019), DOI: 10.1063/1.5100594



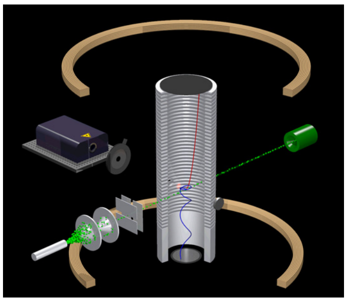
2.2 ATOMIC AND MOLECULAR DYNAMICS

Intense laser light/matter interaction projects the correlated electronic clockwork of atoms and molecules onto photons, electrons and ions, and allows to interfere with and control their dynamics.

Reaction Microscopes and Laser Systems

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"). The instruments are deployed in-house and at external light sources such as free-electron lasers (FELs). For the cryogenic storage ring CSR, a specific reaction microscope was designed and 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/cm^2 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 (and control) of nuclear and electronic quantum motions in chemical reactions.

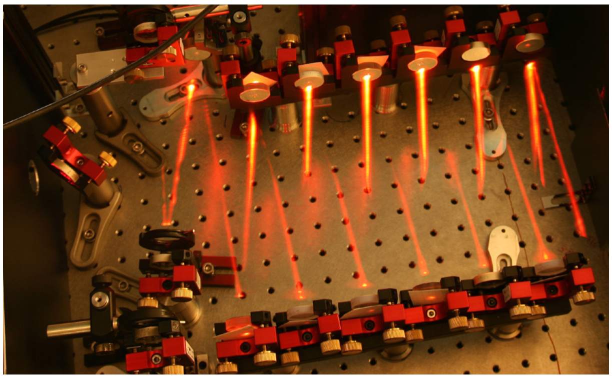


Scheme of a reaction microscope.

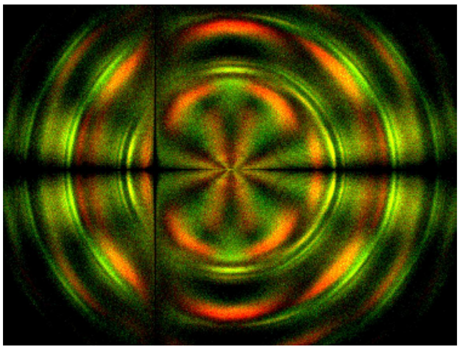
Ultrashort Laser Pulses – the Microcosm in Extremely Slow Motion

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 ($1\,\mathrm{fs} = 10^{-15}\,\mathrm{s}$), while the electrons which mediate the chemical bond are even faster: here, attoseconds ($1\,\mathrm{as} = 10^{-18}\,\mathrm{s}$) are the characteristic time scale.

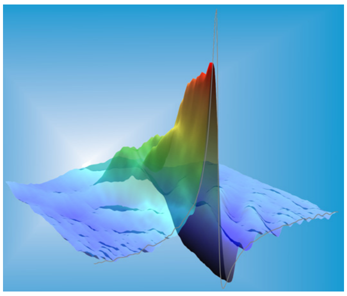
A key tool for time-resolved experiments are ultrashort intense laser pulses which are used to steer the atomic or molecular dynamics with extremely high precision. An electron released from an atom by a strong laser field is driven back and forth and revisits its parent ion while probing its structure. 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.



„Chirped mirror" setup for generating ultrashort laser pulses.



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



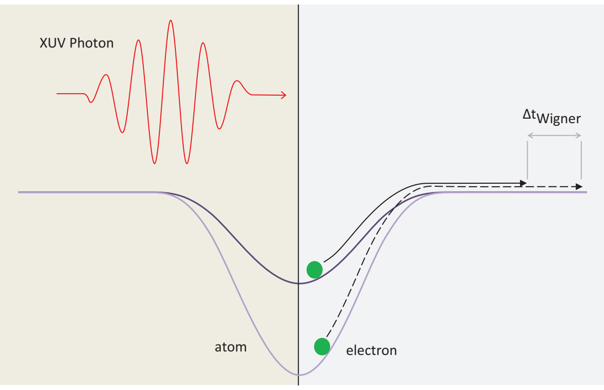
The buildup of a Fano resonance in real time, measured by strong-field-gated attosecond XUV absorption spectroscopy.

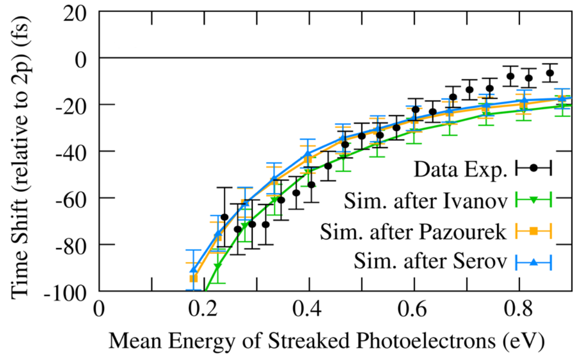
In most cases, a “pump-probe” scenario is applied, where the first “pump” laser pulse prepares the system in the desired way and starts the time evolution which is then probed by the second laser pulse. Molecular motions like vibration and rotation can thus be traced. Observing chemical reactions in real time at femtosecond resolution is a very promising research area. In combination with reaction microscopes even the ultrashort time span needed for an isomerization reaction – rearrangement of atoms within a molecule – which is essential also in eye-vision or photosynthesis could be observed.

To observe the motion of electrons, however, even shorter light pulses on the order of attoseconds are required. One possibility therefore is 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 nanometers 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 are observed 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.

Field-induced time delays in photoionisation





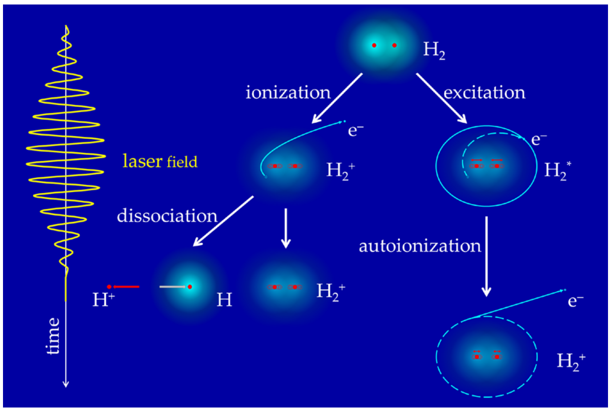
Photoionisation of matter is a subject of research since 1905 when Einstein discovered the quantum nature of light. The question about the intrinsic time-scale of photoionisation, however, has only been discussed after the discovery of attosecond laser-physics a few years back. How much time does it take for an electron to leave an atom after the absorption of a single photon? Answers to this question are now in reach with most modern methods. Time-delays are measured with the streaking scheme where a short XUV-pulse leads to the emission of a photoelectron which is then driven or probed by a superimposed long-wavelength laser field. The resulting photoionisation time-delay is the sum of the quantum mechanical Wigner time-delay (Δt_{Wigner}) and a contribution arising from a coupling of the electron with the probe laser in the presence of the atomic Coulomb field. In an experiment at the free-electron laser FLASH in Hamburg we succeeded in measuring the Coulomb-Laser contribution only exploiting a XUV pump – Terahertz (THz) probe scheme. At a photon energy of 59.4 eV, neon 2p and valence shake-up photoelectrons were emitted into the THz probe-field with 152 µm wavelength. Using a reaction microscope, the 3D momentum vector of the photoelectron was measured as a function of the pump – probe delay-time. We observed a time shift due to the Coulomb-laser coupling between direct 2p photoelectrons and slow shake-up electrons of up to 100 fs depending on the electron energy. Overall, the experimental results are in agreement with theoretical predictions for the Coulomb-probe-field coupling induced time-shifts in atomic photoemission.

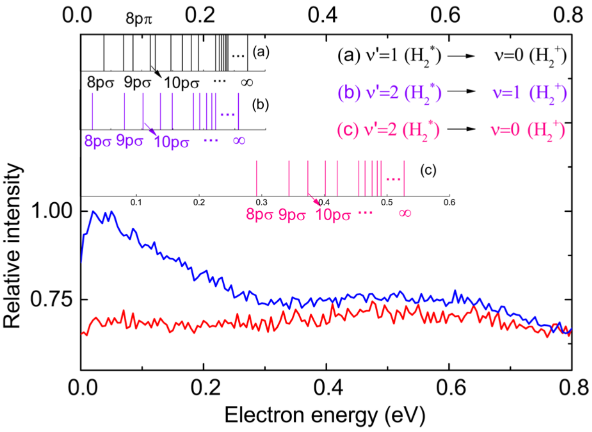
Reference:
G. Schmid et al., Phys. Rev. Lett. 122, 073001 (2019), DOI: 10.1103/PhysRevLett.122.073001

A new mechanism in strong-field ionization of molecules

Strong-field photoionisation of atoms and molecules with short laser pulses is usually described as an electronic tunnelling or multi-photon transition from a bound molecular valence-state into the continuum. But is this the most probable ionization mechanism in the case of a molecule like H_2, or do other more subtle ionization pathways contribute significantly? To answer this question, we measured the 3D photoelectron momentum distribution in coincidence with the ionic fragments for strong-field ionization of H_2 using a reaction microscope.

Two major fragmentation channels can be distinguished. The molecule may stay either bound leading to H_2^+ (bound ionization), or it fragments into a proton and a neutral H atom after the ionization (dissociative ionization). Surprisingly, we observed a significant enhancement of photoelectrons in the low-energy regime for the bound-ionization channel. By further inspection of well known asymmetries in electron emission using two-colour laser pulses, this enhancement was found to be due to a delayed electron emission, at times longer than the pulse duration. The results are in perfect agreement with autoionisation of vibrationally excited states in neutral H_2, that are populated by the interaction with the strong laser pulses. Vibrational energy in the nuclear motion is effectively transferred to the electronic system leading to the emission of a low-energy electron on time-scales that are longer than 10 femtoseconds.

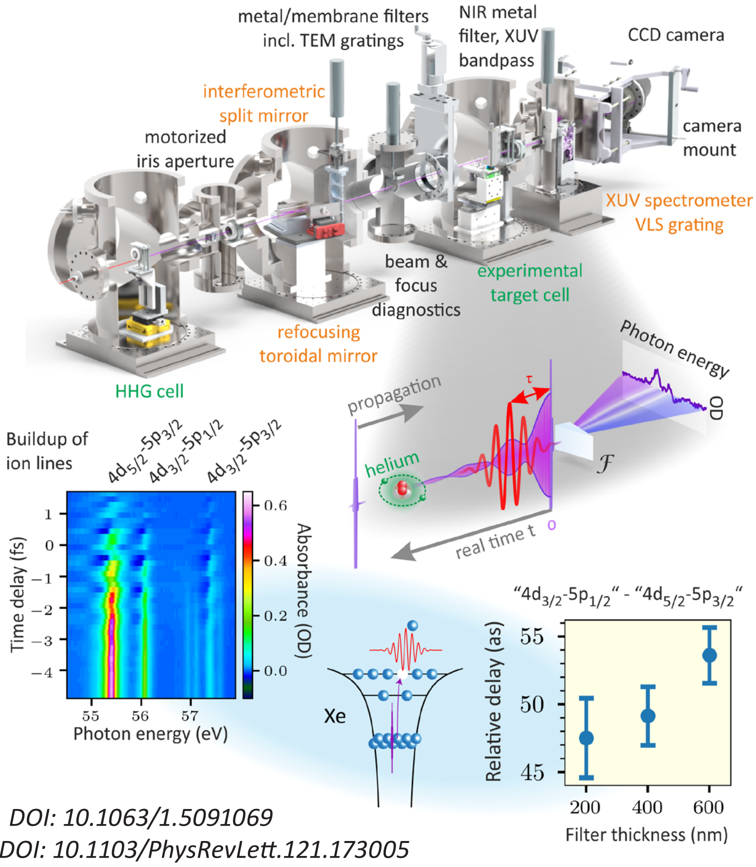




Reference:
Y. Mi et al., Phys. Rev. Lett. 118, 183201 (2017), DOI: 10.1103/PhysRevLett.118.183201

Attosecond precision by resonant transient absorption

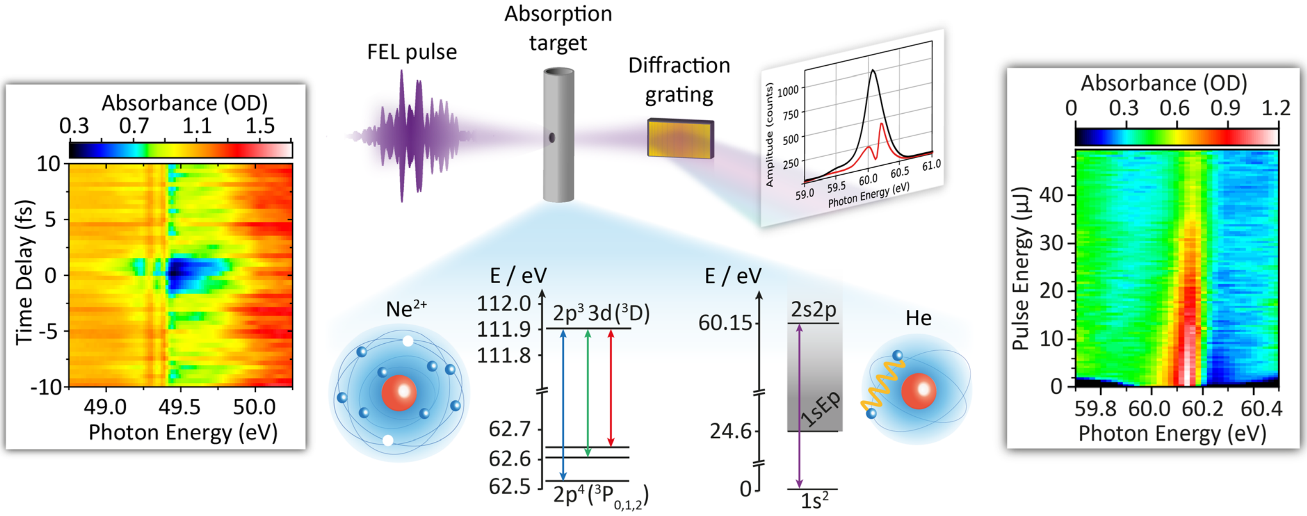
Using moderately strong ultrashort optical laser pulses, it is possible to control the most fundamental dynamics of electrons bound in matter at the femtosecond and attosecond timescale. Such measurements are realized with the technique of extreme-ultraviolet (XUV) attosecond transient absorption spectroscopy. A dedicated vacuum beamline has recently been upgraded with an in-situ XUV beam splitter for recording precision time-resolved absorption spectra of ultrafast electron dynamics [1]. For the case of autoionising doubly excited states in helium, a new method of extracting the laser-driven dipole response in real time has thus been demonstrated [2]. With even higher laser intensities, xenon is strong-field ionized which leads to sub-cycle attosecond oscillations in the ionization yield. By deliberately changing the dispersion of the probing XUV attosecond pulse, a precision and accuracy of only a few attoseconds has been achieved with transient absorption spectroscopy [3]. This opens new perspectives for attosecond delay measurements across resonant atom-specific transitions in atoms and molecules.



References:

[1] V. Stooß et al., Rev. Sci. Instrum. 90, 053198 (2019), DOI: 10.1063/1.5091069
[2] V. Stooß et al., Phys. Rev. Lett. 121, 173005 (2018), DOI: 10.1103/PhysRevLett.121.173005
[3] M. Hartmann et al., Opt. Lett. 44, 4749-4752 (2019), DOI: 10.1364/OL.44.004749

Distorting atomic resonances by intense XUV light



When atoms are subject to external electromagnetic fields, their quantum structure and dynamics can be distorted. With intense short-wavelength extreme-ultraviolet (XUV) light from the Free-Electron Laser in Hamburg (FLASH) it is possible to selectively couple to the innermost electronic structure of atoms, here carried out in two recent measurements in neon (left) and helium (right). In these experiments, characteristic energy shifts and changes of the shape of spectral absorption lines have been observed, which reveal XUV-induced ac Stark shifts of atomic energy levels. Supported by theoretical modelling, for instance in helium a transient population inversion of a correlated two-electron state was achieved [1]. On the other hand, in neon, transient coherence effects through plasma diffraction of ionized electrons on the few-femtosecond timescale have been revealed [2]. Observing such ultrafast resonant nonlinear effects in the XUV spectral range is a decisive step towards the quantum control of chemical reactions in general, with atomic site selectivity within a molecule.

References:

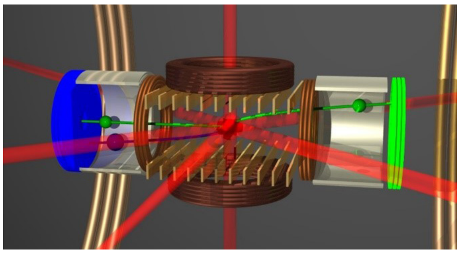
[1] C. Ott et al., Phys. Rev. Lett. 123, 163201 (2019), DOI: 10.1103/PhysRevLett.123.163201

[2] T. Ding et al., Phys. Rev. Lett. 123, 103001 (2019), DOI: 10.1103/PhysRevLett.123.103001

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.

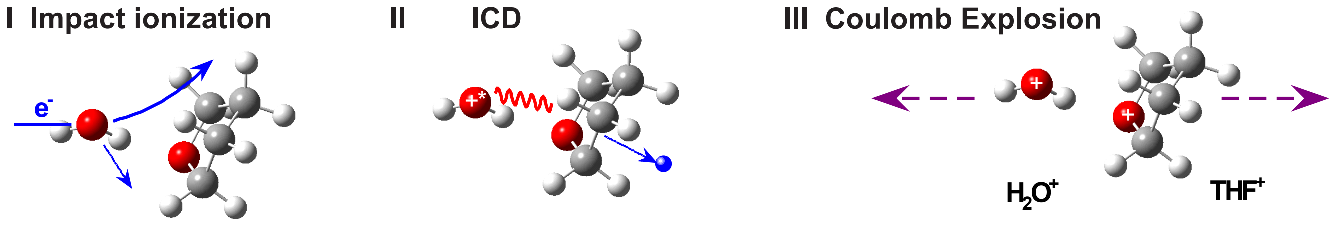
Ultracold Dynamics – Investigating Exotic Quantum Gases

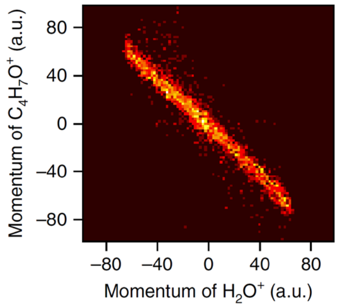

Scheme of the magneto-optical trap combined with a reaction microscope.

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 is 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.

Ultrafast energy transfer in hydrated biomolecules

Damage of biological tissue by ionizing radiation relies to a large part on secondary particles such as radicals, ions and the abundantly produced slow electrons which can cause, e. g., DNA single and double strand breaks. We have observed that the aqueous environment in biological tissue can enhance molecular ionization and fragmentation via a hitherto unrecognized damage mechanism called intermolecular Coulombic decay (ICD). As a model system to study this process we use complexes consisting of one water and one tetrahydrofuran molecule (THF) which is a surrogate for deoxyribose in the DNA backbone. In the first step the water molecule is ionized by electron impact in the oxygen inner-valence shell (I). Then, within a few tens of femtoseconds the inner-valence vacancy is filled by an outer-valence electron and the released energy is transferred to the neighbouring THF molecule ionizing it as well (II). The charged ions repel each other and gain kinetic energy in the subsequent Coulomb explosion (III). Altogether two energetic ions (see the experimental momentum correlation diagram of the H_2O^+ and THF^+ ions) are produced in addition to the three reactive secondary electrons all of which can cause further damage in the vicinity. Thus, dense and therefore particularly harmful ionization clusters of several ionization processes within a volume typical for a biomolecular system like DNA can be produced. Future studies aim at determining the relative importance of ICD with respect to other damage mechanisms. Furthermore, we want to test theoretical calculations which indicate that ICD can be triggered by inner valence ionization of carbon atoms in organic molecules as well. Therefore, ICD is expected to be a widespread phenomenon in loosely bound organic matter that can provide a functional mechanism for the direct damage of biomolecules such as DNA.

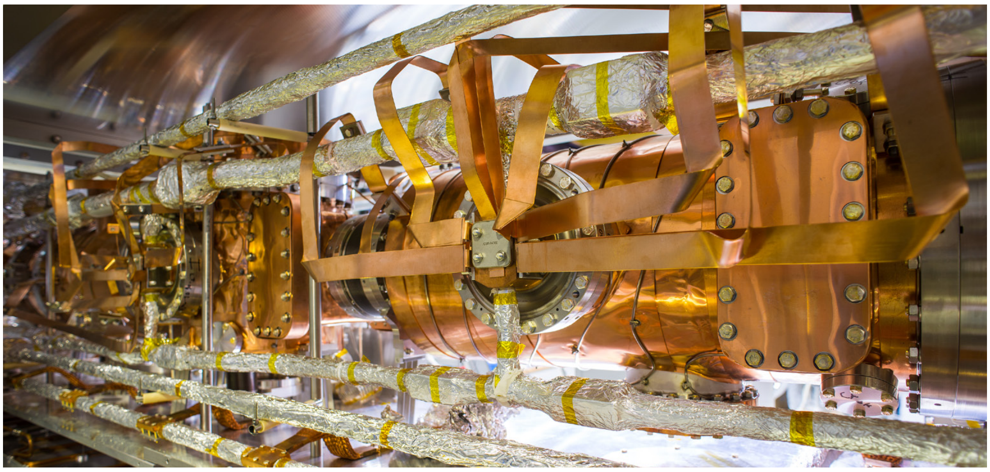




Reference:
X. Ren et al., Nature Physics 14, 1062 (2018), DOI: 10.1038/s41567-018-0214-9

The Cryogenic Storage Ring

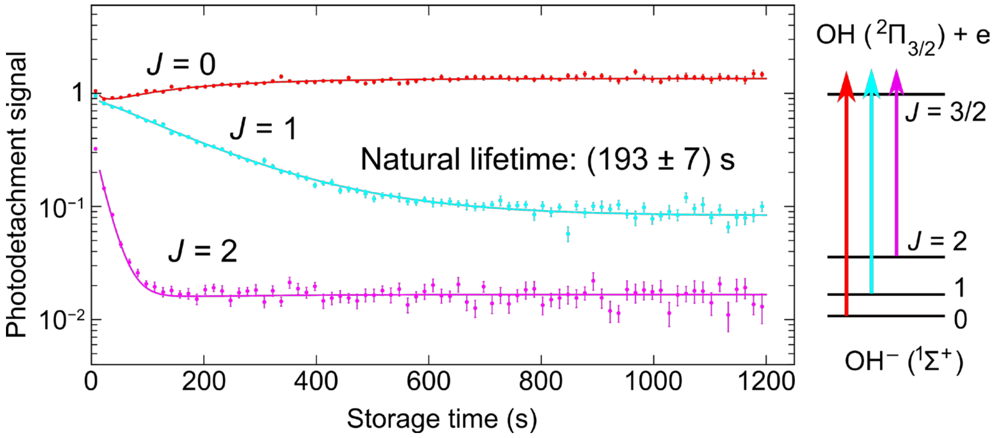
In the electrostatic cryogenic storage ring, CSR, beams of cold molecular ions of any size and highly charged ions can be investigated essentially without any influence of the environment. This is achieved by purely electrostatic ion optics, keeping the ring under extremely low pressure and at a temperature 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. The innovative mechanical concept of the CSR was developed and realised in close cooperation with MPIK's engineering design office and precision mechanics shop.



Copper strips distribute the cold among the chambers in the ultracold storage ring CSR.

Internal cooling of molecules in the Cryogenic Storage Ring

Storage-time dependent photodetachment at the CSR sensitively probes important properties of diatomic molecules that could not be accessed in earlier measurements. These include the molecular dipole moment and the precise free-space radiative lifetime of rotationally excited levels, which becomes very long for the lowest excited quantum states. With a laser tuned in its wavelength very close to the detachment threshold of the OH^- anion, the detachment signal can individually probe the population in excited rotational levels while they are decaying. This becomes possible as levels live shorter the higher they are excited: of the levels the laser can photodetach, only the lowest one will be left after sufficient storage time. For more than a few minutes of storage, the remaining levels are J = 0 and 1, only. A detailed analysis of the CSR data, taken for 20 min of storage at 9 laser wavelengths, yielded the relative photodetachment cross sections and the population fraction remaining in J = 1, which also quantified the blackbody field in the CSR. Indeed, this revealed that stimulated emission through the blackbody field accelerated the decay of the J = 1 level by about 12%. Only with this information its natural lifetime, excluding blackbody effects, could be extracted. As the first measurement of its kind, this revealed as much as 10% deviation from the rotational lifetimes predicted for OH^- from quantum chemical calculations and yielded the dipole moment of this molecule with as little as 1.5% uncertainty.

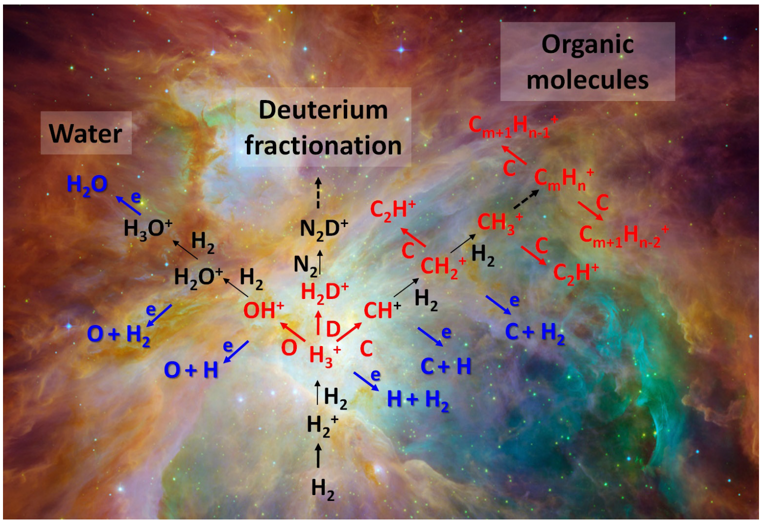


Reference:
C. Meyer et al., Phys. Rev. Lett. 119, 023202 (2017), DOI: 10.1103/PhysRevLett.119.023202

Laboratory Astrophysics – the Chemistry of Space

One puzzling question is the formation of organic compounds in interstellar clouds. The gas-phase chemistry is driven by reactions involving ions and radicals which are created in collisions with photons and cold electrons. Here, the H_3^+ 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 new cryogenic storage ring CSR, for the first time, conditions are reached that correspond to interstellar temperatures where many types of internal motion are in fact frozen in molecular ions.

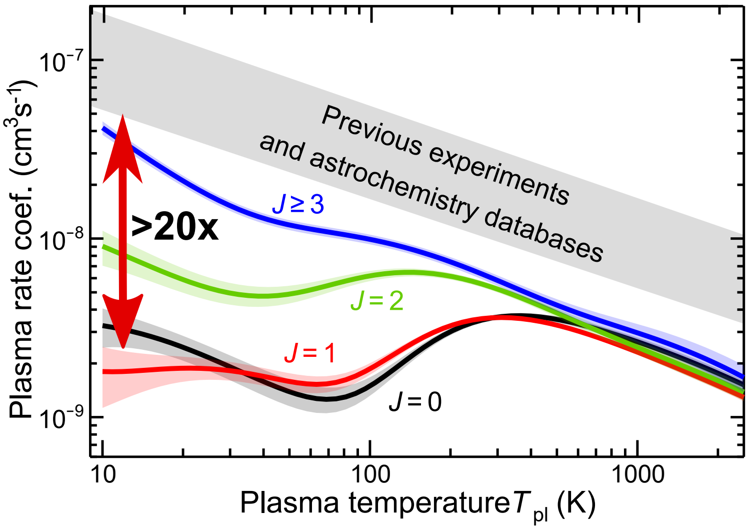
The positive ions of interest range in size from small atoms and molecules up to organic compounds. Also, negatively charged molecular ions (anions) are of interest here as they represent an important source of slow electrons. Provided sufficient inner excitation (vibration), they can literally “evaporate” 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.

State-resolved dissociative recombination measurement improves predictions on primordial HeH^+

Molecules play an important role in the formation of the first stars. This is due to their ability to cool gas clouds by the collisional excitation of molecular rotational levels and subsequent radiative emission. The cooling leads to gravitational collapse of the cloud, an inevitable step for star formation. From the few elements available in the early Universe, namely H, He, and traces of Li, only a handful of molecules could combine. Here HeH^+ is an important candidate for a strong molecular coolant given its large dipole moment and predicted abundance. The abundance calculations rely on molecular reaction data for various formation and destruction processes, in particular at low (~10 K) temperatures. Here the dominant HeH^+ destruction channel is via capturing a free electron, a process called dissociative recombination (DR). For this reaction all previous data have been obtained in room-temperature experiments, i. e., for ions with several rotational states populated. Given the resonant nature of DR, however, the DR reaction rate was predicted to be strongly rotational-state dependent for many ions. To resolve this issue we have performed HeH^+ DR measurements using the newly implemented electron cooler beam in the Cryogenic Storage Ring (CSR). In the CSR radiation field, where ~99% of the relevant spectral density represents the 6 K wall temperature and 1% radiation leakage from 300 K, HeH^+ ions relax radiatively to reach >92% in the $J = 0$ ground state within ~50 s. From the radiative cooling model and the detailed time-dependent measurement of the HeH^+ recombination rate we derive rotational-state resolved absolute rate coefficients. At ~10 K the new HeH^+ destruction rates are >20 times lower than the data used in early Universe models previously. Correspondingly, the primordial HeH^+ abundance at redshifts relevant to the formation of the first stars and galaxies should be >20 times higher than thought so far.



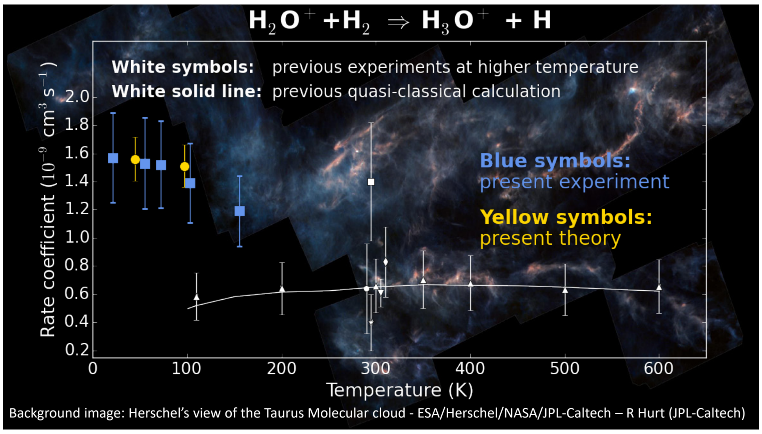
Reference:
O. Novotný et al., Science 365, 676-679 (2019), DOI: 10.1126/science.aax5921

Low-temperature rates for key reactions of interstellar gas-phase water formation

The formation of water in the diffuse interstellar medium proceeds through a series of ion-neutral reactions involving the light molecular ions OH^+ and H_2O^+. The full reaction chain reads as follows,

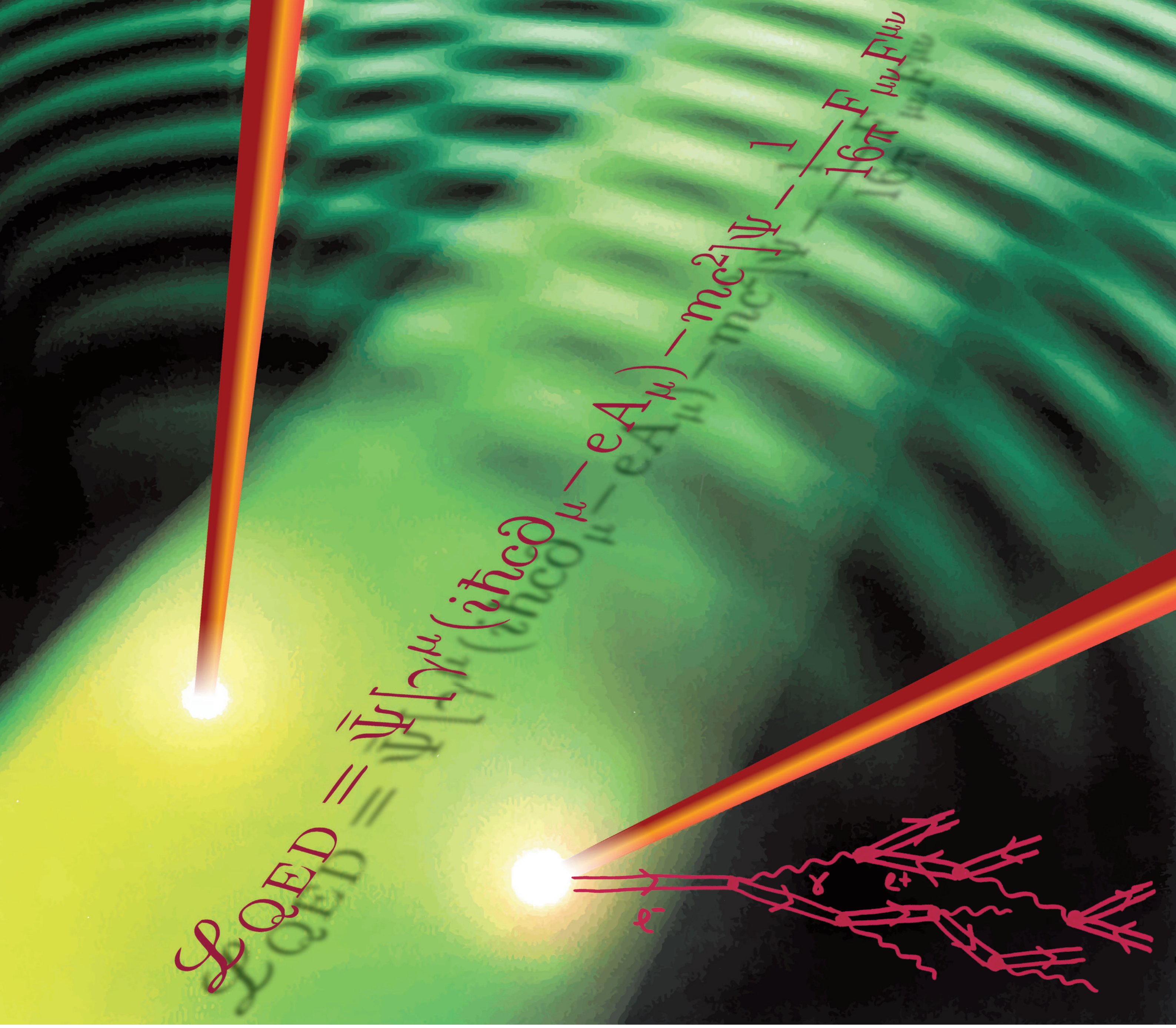
$OH^+ + H_2 \longrightarrow H_2O^+ + H,$ (1)
$H_2O^+ + H_2 \longrightarrow H_3O^+ + H,$ (2)
$H_3O^+ + e \longrightarrow H_2O + H,$ (3)

and it is terminated by the electron-recombination of H_3O^+, resulting in the formation of interstellar water in the gas phase. Besides the relevance of water for life as we know it, it is also an important reservoir of oxygen in space. Furthermore, the recent detections of OH^+ and H_2O^+ ions by the Herschel space telescope have been used to constrain important parameters like the cosmic ray ionization rate and the fraction of atomic to molecular hydrogen. For this purpose, accurate reaction rates for the above reactions are needed. Previous analyses have used rates derived at room temperature, which were extrapolated to interstellar temperatures (10 K to 100 K). We have measured the rate coefficients of reaction (1) and (2) in a cryogenic 22-pole ion trap, between 20 K and 150 K. Our experimental results reveal significantly faster low temperature reaction rates in both cases. These findings are in excellent agreement with calculations of a collaborating theory group from Cyprus and the USA, who use a modern ring-polymer-molecular-dynamics (RPMD) approach, which takes into account quantum effects that prove to be crucial at low temperatures. Our results show that extrapolation can introduce large uncertainties and errors into the interpretation of observational data, and that quantum effects should not be neglected at low temperature, even in the case of seemingly simple barrier-less ion-neutral reactions.



Background image: Herschel's view of the Taurus Molecular cloud - ESA/Herschel/NASA/JPL-Caltech – R Hurt (JPL-Caltech)

Reference:
S. Kumar, F. Grussie, Y.V. Suleimanov, H. Guo, H. Kreckel, Sci. Adv. Eaar3417 (2018), DOI: 10.1126/sciadv.aar3417



2.3 Matter in Extreme Fields

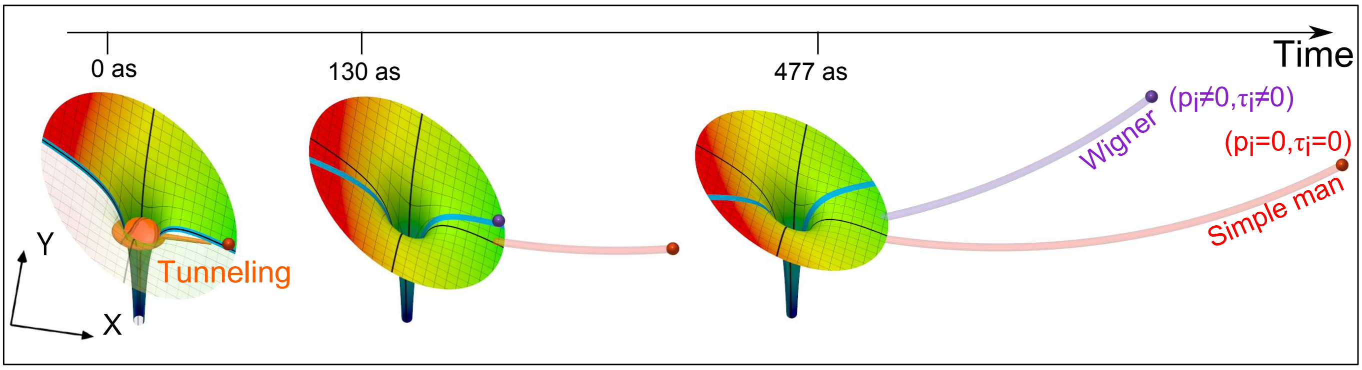
According to quantum electrodynamics the properties of matter and even of vacuum are altered by intense laser fields.

Matter in Strong Laser Fields – at the Frontiers of Feasibility

The investigation of the interaction of matter with laser pulses and x-ray sources 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 this 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.

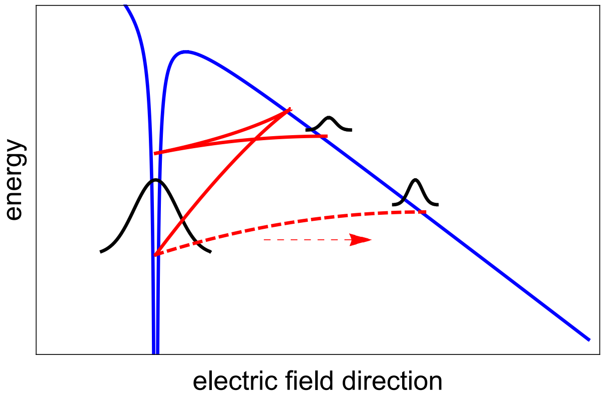
One typical topic of interest is the fully relativistic understanding of quantum processes during tunnel ionization of an atom in a very strong field. A simple model of this process claims that the electron tunnels instantaneously through the laser-generated quantum barrier and appears at its exit with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

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 as $= 10^{-18}$ s). Our more recent calculations intuitively explain Wigner's tunnel exit momentum via a higher-order strong-field approximation with interferences of recolliding trajectories under the tunnel barrier.



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.

Signatures of under-the-barrier dynamics in tunnelling ionisation



Schematic picture of laser-induced tunneling ionization: (dashed) the direct trajectory, and (solid) the under-the-barrier recolliding trajectory. The interference of the direct and the rescattered trajectories induces a shift of the peak of the photoelectron momentum distribution. The tunneling is nonadiabatic, when the energy is not constant during the tunneling process.

In a strong laser field ionization of an atom takes place via tunnelling of the electron from the atomic bound state into the continuum through the potential barrier formed by the atomic potential and the laser field. Although the under-the-barrier dynamics is a small part of the whole laser-electron interaction in this process, it imprints its gentle signatures in the photoelectron momentum distribution at the detector. High resolution of momentum detection, better than 0.01 atomic units, is required to observe these signatures. One of these signatures is the time delay in the attoclock, which recently has been measured in a mixture of gases in [1]. In the latter, the systematic experimental errors have been canceled by measuring the difference of the time delay for two gases. While there are debates how to interpret the attoclock time delay, we put forward a simple straightforward interpretation in [2]. The time delay is equivalent to a shift in the transverse momentum distribution of the attoclock and we have shown that the latter emerges when the interference of the direct ionization path with the under-the-barrier recolliding one is accounted for, see Figure. We have also predicted another signature of the under-the-barrier dynamics due to the non-dipole effect of the laser magnetic field. The peak of the electron momentum distribution along the laser propagation direction is shifted forward at the tunnel exit during the under-the barrier wave packet formation. It has a consequence for the photon momentum partition between the ion and the electron in the ionization process. Our fully relativistic prediction has been recently confirmed by an external group in an ultrahigh precision measurement in [3].

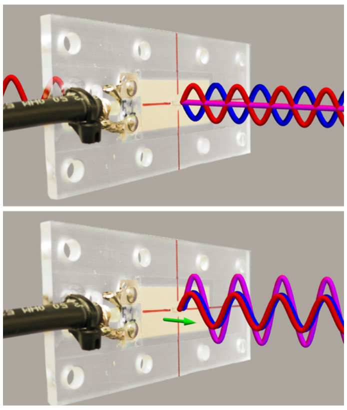
References:
[1] N. Camus, et al. Phys. Rev. Lett. 119, 023201 (2017), DOI: 10.1103/PhysRevLett.119.023201
[2] M. Klaiber, K.Z. Hatsagortsyan, C.H. Keitel, Phys. Rev. Lett. 120, 013201 (2018), DOI: 10.1103/PhysRevLett.120.013201
[3] A. Hartung et al. Nat. Phys. (2019), DOI: 10.1038/s41567-019-0653-y

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. Spectroscopy – the measurement of the absorption and emission of light as it interacts with matter – 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 driving fields with a small energy spread.

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 theoretical and experimental follow-up work exploited such improved x-ray pulses to coherently control the quantum dynamics of matter. In particular, the controlling pulses could switch the dynamics of nuclei in a second target between the elementary processes of absorption and stimulated emission. 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.

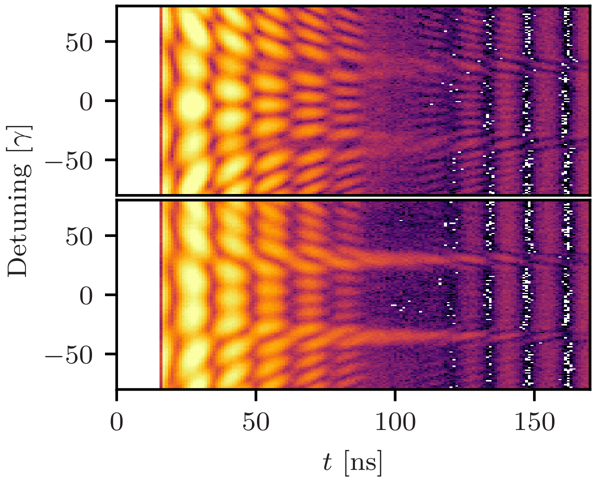
Extremely narrow nuclear transitions are also of interest for accurate measurements. A prime example is the nuclear clock based on thorium-229, which promises to improve the accuracy of the best atomic clocks available today. Recently, a team at the LMU Munich measured with increased precision the previously 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.



Control of x-ray light via mechanical motion of a resonant target. Before motion (top), the light scattered by the target (blue) extinguishes the excitation (red). After the motion (bottom), the scattered light is displaced and the waves enhance each other (magenta).

Coherent x-ray-optical control of nuclear dynamics

Mößbauer nuclei feature resonances with extremely narrow spectral line widths, which form the basis for a broad range of applications across the natural sciences. On the other hand, the narrow linewidth causes a lack of strong resonant x-ray driving and control fields for the nuclei. To address this issue, we developed and implemented a method to simulate strong control fields in certain settings using precisely controlled mechanical motions of a nuclear target. This motion allows us to impose a time-dependent phase on the x-ray pulse. In a first experiment together with the group of Ralf Röhlsberger (DESY, Hamburg), we used the mechanical control to enhance the resonant intensity of given x-ray pulses, by redistributing off-resonant photons onto the resonance [1]. Such optimised pulses allow for stronger driving of the nuclei, and enhanced signal rates. After having demonstrated this control over the x-ray light, in a follow-up experiment, we in turn demonstrated the control of nuclear dynamics [2]. For this, we generated tunable x-ray double-pulse sequences via the motion. This double-pulse was then used to drive the nuclei in a second target. After the first pulse excited the nuclei, we controlled the relative phase of the second pulse to switch the subsequent nuclear dynamics between stimulated emission and further absorption. Using a multi-dimensional spectroscopic measurement technique, we demonstrated the exceptional few-zeptosecond stability of this coherent control. As future applications, we envision advanced spectroscopy methods and pump-probe techniques using the extremely narrow nuclear transitions.



Experimentally recorded time- and energy-resolved spectra of nuclear resonances. The upper and lower panels compare two different motions applied to the nuclei. The effect of the motion on the spectra is clearly visible in the modifications of the interference structures.

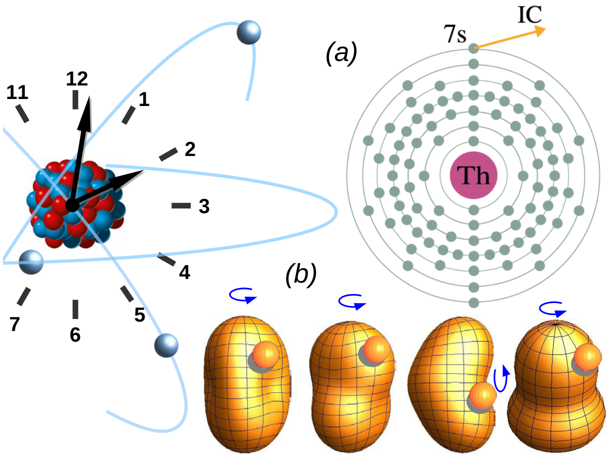
References:
[1] K.P. Heeg et al., Science 357, 375 (2017), DOI: 10.1126/science.aan3512
[2] K.P. Heeg et al., submitted

Towards a nuclear clock with ^{229}Th

Throughout the entire nuclear chart, ^{229}Th presents the lowest-lying excited state at approximately 8 eV, being accessible for vacuum-ultraviolet lasers. This metastable state offers the unique opportunity of a nuclear clock which is expected to outperform present technology. Such a clock would have a large variety of applications, ranging from relativistic geodesy over dark matter research to the observation of potential temporal variation of fundamental constants.

Understanding how such an anomalous low-lying state could occur in this actinide isotope is paramount for the prediction of its properties. We have developed a theoretical model which can reproduce the level structure of the entire energy spectrum of ^{229}Th up to 400 keV. This model shows that the isomeric state occurs due to a very fine interplay of the collective motion of the even-even core, which presents quadrupole-octupole deformation (see Fig.), and the single odd neutron [1, 2]. The Coriolis interaction occurring between core and odd neutron renders possible the nuclear clock transition.

The very recent direct measurement of the clock transition energy yielded 8.28 ± 0.17 eV. It employed spectroscopy of the internal conversion (IC) electrons emitted in-flight during the decay of the excited nucleus in neutral ^{229}Th atoms [3]. In the IC process, the ^{229}Th nucleus transfers its energy to the electronic shell, ionizing an outer shell electron (see Fig.). Due to the complicated electronic level schemes occurring in the experiment, our IC calculations were essential to extract the nuclear transition energy from the measured electronic spectra. This energy determination is the starting point for high-resolution nuclear laser spectroscopy and the development of a nuclear optical clock of unprecedented accuracy.



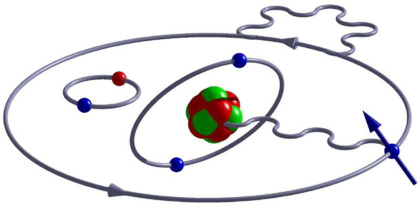
a) IC decay ejects the 7s electron. b) Nuclear quadrupole-octupole deformation of the collective core and additional odd neutron.

References:
[1] N. Minkov, A. Pálffy, Phys. Rev. Lett. 118, 212501 (2017), DOI: 10.1103/PhysRevLett.118.212501
[2] N. Minkov, A. Pálffy, Phys. Rev. Lett. 122, 162502 (2019), DOI: 10.1103/PhysRevLett.122.162502
[3] B. Seiferle et al., Nature 573, 243 (2019), DOI: 10.1038/s41586-019-1533-4

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. Another 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. At the same time, QED is the to date best tested theory in physics at all.

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. Our 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.

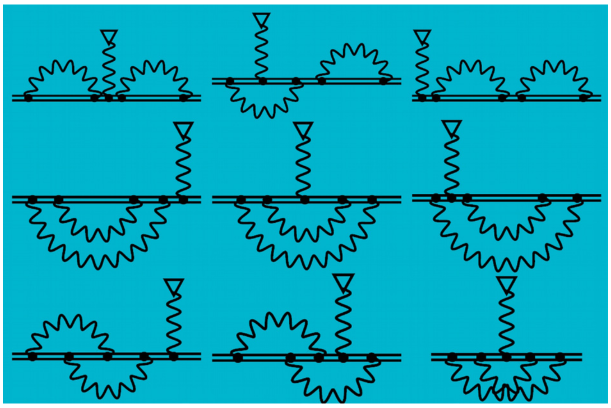


Scheme of the QED contributions to the electronic structure of highly charged ions: the electrons (blue balls) interact with each other and themselves via virtual photons (wave lines). In the field of the nucleus, also particle-antiparticle pairs (blue and red balls) may be virtually created.

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 trapped and stored 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.

Quantum electrodynamics in strong Coulomb fields

In highly charged ions (HCI), the inner-shell electrons experience extreme electromagnetic fields of the nucleus. Effects of relativity and of quantum electrodynamics (QED) are boosted in these ions as compared to their neutral counterparts, rendering HCI an ideal system for testing the validity of the Standard Model in strong fields. In high-precision calculations, we predict the structural properties of HCI considering the self-interaction of electrons and corrections due to the virtual creation and annihilation of dilepton pairs. In many-body systems, the electrons also exchange photons between each other, and such correlation effects are treated by large-scale atomic structure calculations and by QED perturbation theory.



Of particular interest is the magnetic moment of HCI, which can be measured to ultimate precision in Penning traps, by employing the newly constructed ALPHATRAP setup of the Institute. Beyond successful tests of QED, these studies yield values of fundamental constants. In order to further improve the determination of the electron mass with a record-breaking precision, we put forward further ionic systems [1], and push forward the boundaries of theory by evaluating multi-loop QED loop corrections in a non-perturbative manner, i. e. in a framework which is valid in strong Coulomb fields [2]. Another fundamental access to QED and electronic structure effects is given by the investigation of energy levels. This became recently possible by means of precision mass spectroscopy: the electronic binding energy can be directly determined by comparing the masses of different ions. We perform high-precision calculations of the binding energy of the outermost electron of the Xe^{17+} ion, and find a perfect agreement with the very first measurement of this kind performed with the recently built PENTATRAP experimental setup of the Institute [3]. Besides testing our understanding of the structure of HCI, such studies are expected to deliver improved mass differences in nuclear physics as well as a refined test of the mass-energy equivalence.

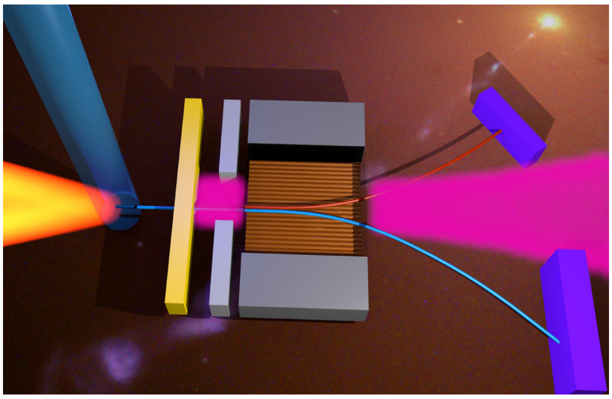
References:

[1] B. Sikora et al., Phys. Rev. Research 2, 012002(R) (2020), DOI: 10.1103/PhysRevResearch.2.012002
[2] A. Rischka et al., submitted (2019)
[3] J. Zatorski et al., Phys. Rev. A 96, 012502 (2017), DOI: 10.1103/PhysRevA.96.012502

High-Energy Laser Physics and Laboratory Astrophysics – Cosmic Accelerators in the Laboratory Scale

With increasing laser intensity, the underlying physics has been continuously transferring from atomic to high-energy physics. Our many-particle quantum, quantum plasma and semiclassical particle-in-cell (PIC) codes incorporate especially radiative reaction, spin dynamics, pair cascades as well as deviations from the locally constant field approximation. Cascades of electron-positron pairs were seen as a risk to generate extremely strong laser pulses and we have put forward means to prevent those via suitably chosen focus areas. In particular, most recently various concepts have been developed to generate polarized intense lepton and gamma GeV beams. They are based on spin-dependent radiative reaction and are likely to find applications in high-energy, solid-state and astrophysics.

Already to date, highly intense laser fields enable the acceleration of particles to energies up to the order of giga-electronvolts (GeV). This opens the possibility to reproduce physical conditions in the laboratory, as they prevail in extreme astrophysical processes. 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 as well as gamma rays. Thereby, the conversion of bremsstrahlung to electron-positron pairs could be identified as a substantial mechanism and in addition the emission of the gamma rays to significantly slow down the ultrarelativistic electrons. The investigation of such highly energetic processes on laboratory scale is of great importance also for astrophysics: Cosmic gamma-ray bursts for example, to our present knowledge emerge from the extremely collimated ultrarelativistic leptonic jets which are emitted along the rotation axis of certain types of collapsing stars.

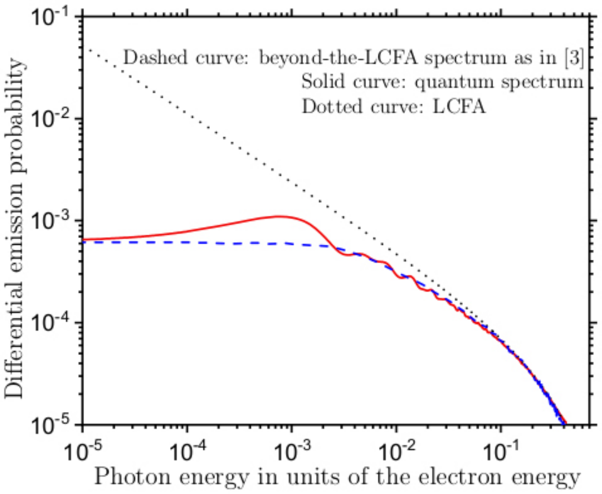


Laboratory production of ultrarelativistic electron-positron beams by laser-accelerated electrons hitting a metal target.

Quantum radiation reaction and strong-field QED beyond the local constant field approximation

A pioneering experiment has been carried out where ultra-relativistic electrons (energy up to 2 GeV) head-on collided with an ultra-intense laser beam (intensity $I_0 \approx 10^{21}$ W/cm^2) [1], with our team being responsible of the theoretical interpretation of the experimental data. Our numerical simulations were of crucial importance to identify the experimental regime of interaction approaching for the first time the so-called "quantum radiation-reaction regime" in laser-electron collision, where each electron emitted several high-energy photons. Our quantum simulations, unlike pure classical ones, provided good agreement with the experimental data. Moreover, our simulations hinted to a failure of the so-called local constant field approximation (LCFA) which has always been implemented in quantum numerical codes and which consists in treating the emission process as perfectly localized in space and time.

Following up on the above results, we developed the first scheme to go beyond the LCFA in the infrared part of the photon emission spectrum [2, 3], where non-local effects are more severe (see Figure). The result is a fully local scheme to investigate the emission of radiation beyond the LCFA in arbitrary background electromagnetic fields. The improvement of the model developed in [2, 3] as compared with the LCFA is clear from the numerical example in the figure, where the LCFA spectrum differs from the exact one by more than one order of magnitude in the infrared part.

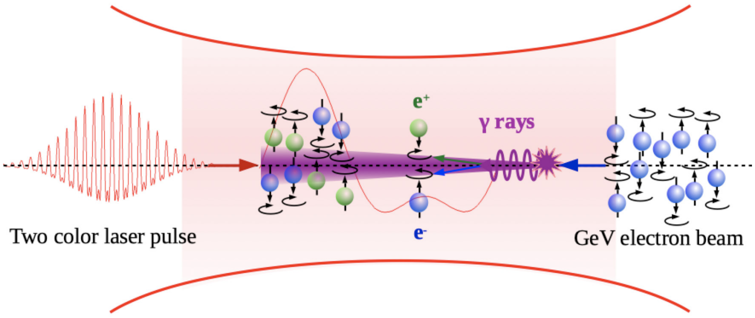


Photon emission spectra as functions of the photon energy.

References:
[1] K. Poder, M. Tamburini et al., Phys. Rev. X 8, 031004 (2018), DOI: 10.1103/PhysRevX.8.031004.
[2] A. Di Piazza, M. Tamburini et al., Phys. Rev. A 98, 012134 (2018), DOI: 10.1103/PhysRevA.98.012134
[3] A. Di Piazza, M. Tamburini et al., Phys. Rev. A 99, 022125 (2019), DOI: 10.1103/PhysRevA.99.022125

Laser-induced polarisation of electron and positron beams

Relativistic polarized electron and positron beams are fundamental experimental tools to test symmetry properties in physics. Recently we have shown a way to polarize electron and positron beams with currently available realistic laser fields [1, 2]. Nonlinear interaction of electrons with an elliptically polarized laser field with a small ellipticity has been shown to result in splitting of the beam with respect to polarization due to the spin dependence of radiation reaction, which yields up to 70% polarization [1]. Moreover, in strong external fields the electron-positron pair production probabilities possess much higher asymmetry with respect to the spin of the created particles than the radiation. The latter property is harnessed for generation of highly polarized positrons in a two-colour asymmetric laser field [2]. The pair generation is a nonlinear process, which is strongly suppressed in the minor cycle of the asymmetric field, and allows (see figure) up to 60% polarization of the generated positrons. Furthermore, a way of generating high-intensity polarized electron beams is shown in [3], employing molecular gas targets polarized in a laser field. In such a target, polarized electrons can be accelerated to high energies in the wakefield of an intense laser pulse. While the magnetic field generated in the wake may cause beam depolarisation, we find conditions under which the accelerated electrons are strongly bunched along the beam axis, where the role of the magnetic field is minor. Limiting the depolarisation to around 10%, in this way polarized electron currents in the kiloampere range are achievable.



An intense linearly polarized two-color laser pulse head-on collides with an unpolarized relativistic electron beam, resulting in emission of photons, which decay into polarized e^+ and e^-, with spin parallel and anti-parallel to the laser's magnetic field direction, respectively.

References:

[1] Y.-F. Li et al., Phys. Rev. Lett. 122, 154801 (2019), DOI: 10.1103/PhysRevLett.122.154801

[2] Y.-Y. Chen et al., Phys. Rev. Lett. 123,174801 (2019), DOI: 10.1103/PhysRevLett.123.174801

[3] M. Wen, M. Tamburini, C.H. Keitel, Phys. Rev. Lett. 122, 214801 (2019), DOI: 10.1103/PhysRevLett.122.214801

INFRA-STRUCTURE

3

3.1 SCIENTIFIC AND TECHNICAL INFRASTRUCTURE

Aerial view of the Institute's campus in spring. In the background the city of Heidelberg.

Campus

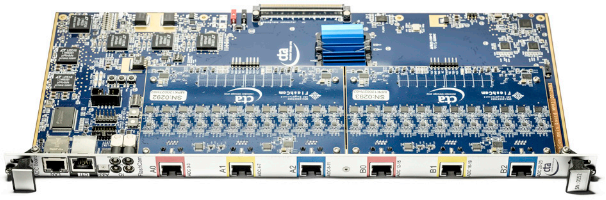
The institute campus is situated in the forest 200 m above the city of Heidelberg. The main buildings are the Walther Bothe and the Wolfgang Gentner Laboratories with office and laboratory space. The library building with a lecture hall and a seminar room suitable for small conferences lies at the centre of the campus. Other significant buildings are the experimental hall complex, the electronic and mechanical workshop buildings, the kindergarten and guest houses. The neighbour to the south is the European Molecular Biology Laboratory (EMBL). See page 58 for a map of the site.

Central IT Services

The central IT infrastructure provides computing power and storage space. A Linux cluster and several special-purpose servers with 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.

Four water-cooled racks containing the 272 servers of the two clusters.

Electronics



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

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 respective board, which is then usually produced externally and tested before its integration into an experiment. The central 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 digitisation systems needed to capture the data from many experiments. Maintenance and repair of electronic devices is also performed. Some of the electronic technicians are permanently engaged in specific experiments.

Precision Mechanics and Engineering Design

CNC 5-axis milling machine.

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.

Many of the components for scientific instruments that are built in the 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.

FlashCam @ H.E.S.S.: new camera for CT5

Concluding the development, prototyping and system integration phase, a pre-series "FlashCam" fully digital camera for Cherenkov telescopes has made its way into a data taking astroparticle physics experiment, see Section 1.1. The electronics workshop has been heavily involved in the development of the FlashCam readout system and all the subsequent stages towards the installation at the experiment. The modular and scalable FlashCam readout system is based on a motherboard featuring a low-cost logic IC (field programmable gate array, FPGA) providing a large number of fast digital I/O ports and the corresponding short-term data buffers and logic processing. From an external server, the FPGA can be accessed through a 1 Gbit LAN interface. Combining the motherboards with application-specific daughter boards (ADC, DAC, trigger, clock distribution), a fully featured readout system for the 1764 photomultiplier tubes of the FlashCam camera can be set up.

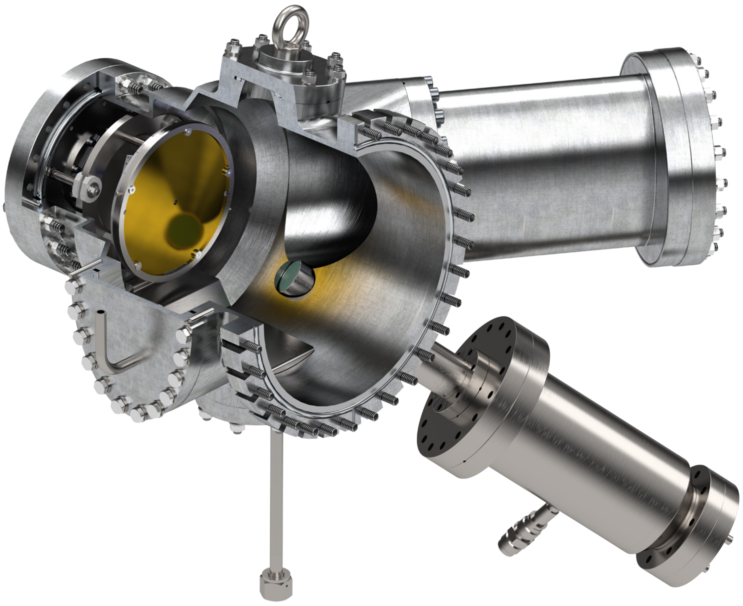
Due to its high versatility, this system is already being used in totally different experiments as well: the "outrigger array" of the HAWC gamma-ray observatory in Mexico, medical imaging research at the Heidelberg Ion Beam Therapy Center HIT, germanium and active veto readout of the double-beta decay experiment LEGEND at LNGS in Italy, to name just a few.

The picture shows the re-installation of the delicate light sensors into the FlashCam camera body after transport to Namibia. Subsequently, some initial electrical tests were performed and the camera was finally mounted into the large central telescope and integrated into the H.E.S.S. data acquisition system. Only a few days later, the FlashCam camera successfully recorded its first high-resolution image of the crab nebula.

Components for the calibration and monitoring system (CMS) of KATRIN

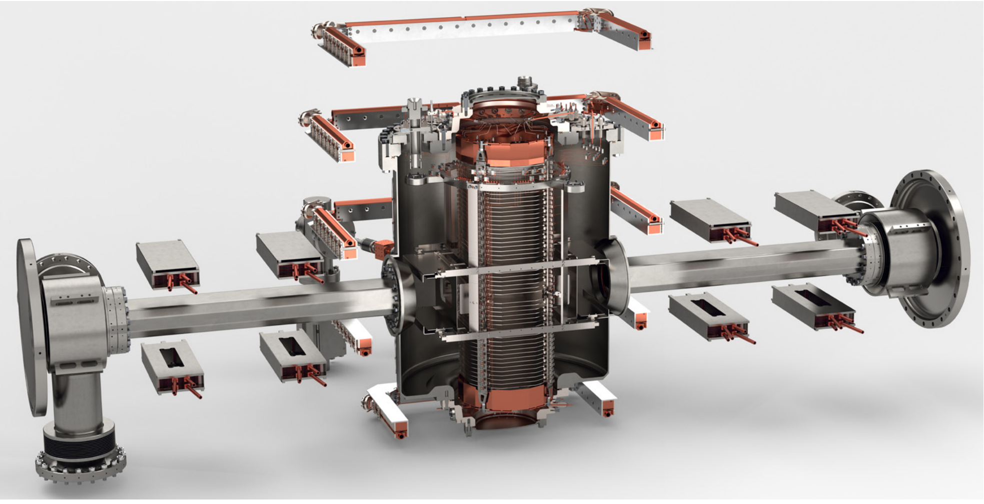
For the Karlsruhe Tritium Neutrino Experiment (KATRIN), a so-called rear-wall chamber has been designed and produced at MPIK. Amongst other things, this chamber contains sensors for monitoring the source activity and a highly sensitive gold-plated electrode which defines the potential of the tritium source. The specific challenge of this piece was to mill it from a forged block of stainless steel 316L rather than realise it as a welded assembly.

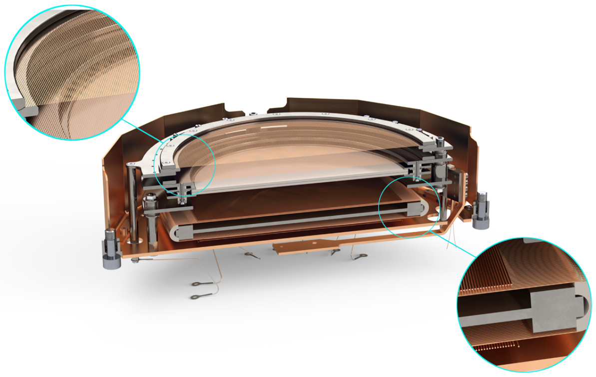
In addition to the chamber, the engineering design office and precision mechanics shop were involved in the development and manufacturing of many further components for this part of KATRIN. As an example, this included the implementation of the UV lighting mount including optical path and focusing, the magnetic field shielding, and an adjustment device.



The CSR reaction microscope: setup and multi-channel plate detector

The worldwide first cryogenic reaction microscope, the CSR-REMI, was designed for the cryogenic storage ring CSR and is presently under construction. The complete design and the production of most of the vacuum chambers as well as the mechanical components have been done in MPIK's engineering design office and precision mechanics shop. Besides the vacuum chambers, the production comprises the spectrometer electrode arrays, the large-area multi-channel plate detectors, coils for generating magnetic fields and a large number of thermal shields. Due to the requirements of operation at cryogenic temperatures of about 10 K and the need to use low-permeability materials, the components have been precision fabricated preferentially from stainless steel 1.4435 BN2, titanium, AlMg4.5Mn and high-purity copper. Nearly all parts have been high-temperature vacuum annealed. Following extensive tests, titanium-ceramics hard-solder connections could be produced successfully. Electron-beam welding and construction of prototypes were also required.





Scientific Information Service

View into the MPIK library.

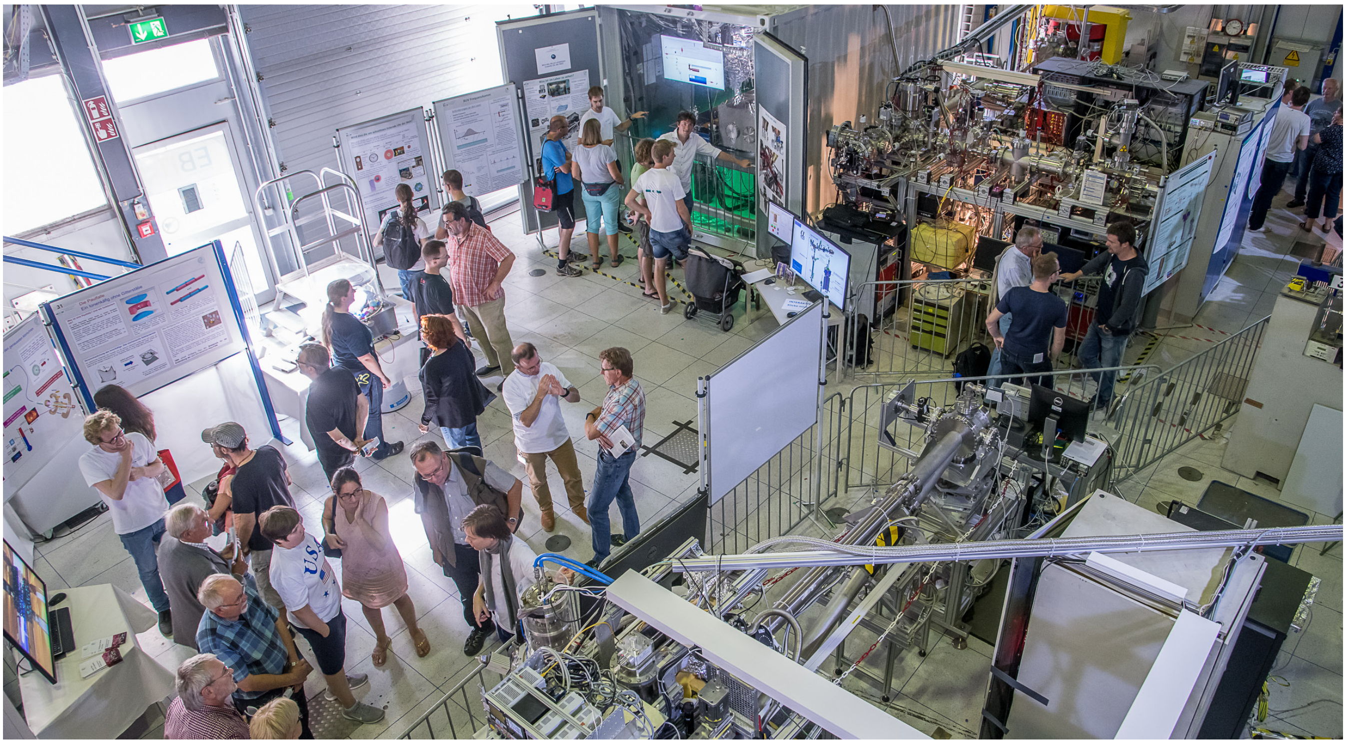
The Institute's library presently holds about 26 200 monographs, book series, conference proceedings, theses prepared at the MPIK and about 6 200 journal volumes. Via the Max Planck Society, the library provides access to e-books, online dictionaries, databases and more than 40 000 e-journals. MPIK actively 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.

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. A dedicated 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 are welcome for guided institute tours; for school students, we provide the "Saturday morning physics" courses.

Open Day in September 2018

On the occasion of its 60th birthday, the MPIK performed an open day on September 16, 2018. The weather conditions were ideal, and more than 3000 visitors came to the institute to see the 69 stations and talk to MPIK's scientists and technicians. The visitors were enthusiastic and mostly stayed for many hours. The stations comprised demonstration and hands-on experiments, laboratory visits, displayed objects, posters and talks.



Publication Statistics

The publication output of the Institute is documented via the Max Planck wide publication repository PuRe (https://pure.mpg.de/), which presently contains about 8000 datasets related to the MPIK. 1165 entries have been added in the years 2017-2019, of which 700 contain the full text and 345 provide a link to the full text of the publication.

While the total number of publications has fluctuated over the years, the yearly number of citations to all publications ever published by MPIK scientists continues to increase.

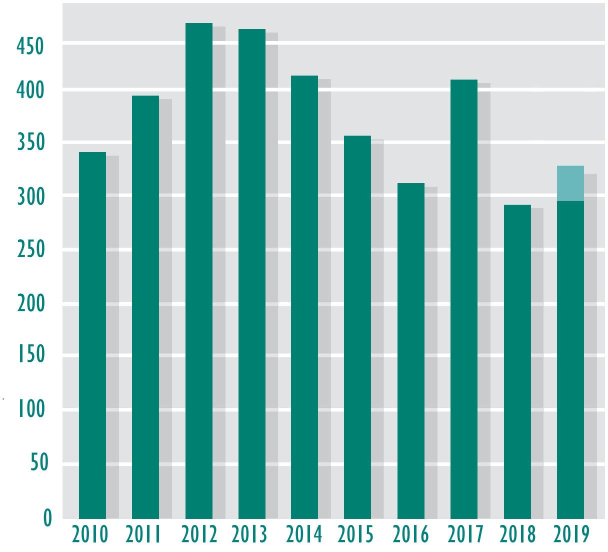
In the years 2017-2019, overall 48 papers were regarded as being of interest for the general public and therefore accompanied by a press release.

The following table lists the most favoured journals during the years 2017 to 2019 together with the numbers of papers published therein. The second table indicates the number of theses of various types completed at MPIK over the three years.

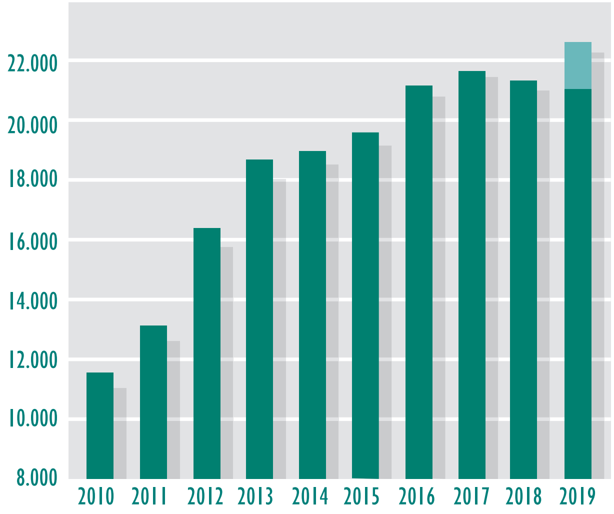
Journal	Papers
Physical Review Letters	87
Physical Review D	80
Physical Review A	68
Astronomy & Astrophysics	54
Journal of High Energy Physics	54
Physical Review C	45
AIP Conference Proceedings	41
European Physical Journal C	33
Monthly Notices of the Royal Astronomical Society	31
Nature, Nature Photonics, Nature Physics, Nature Communications	27
Science	7

	2017	2018	2019
Bachelor theses	18	11	16
Master theses	20	8	13
Dissertations	14	19	19
Habilitations	0	0	1

Published Items in Each Year



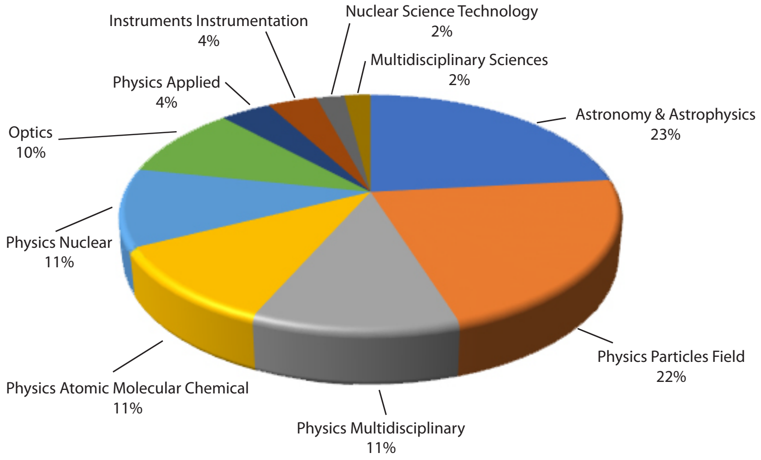
Citations in Each Year

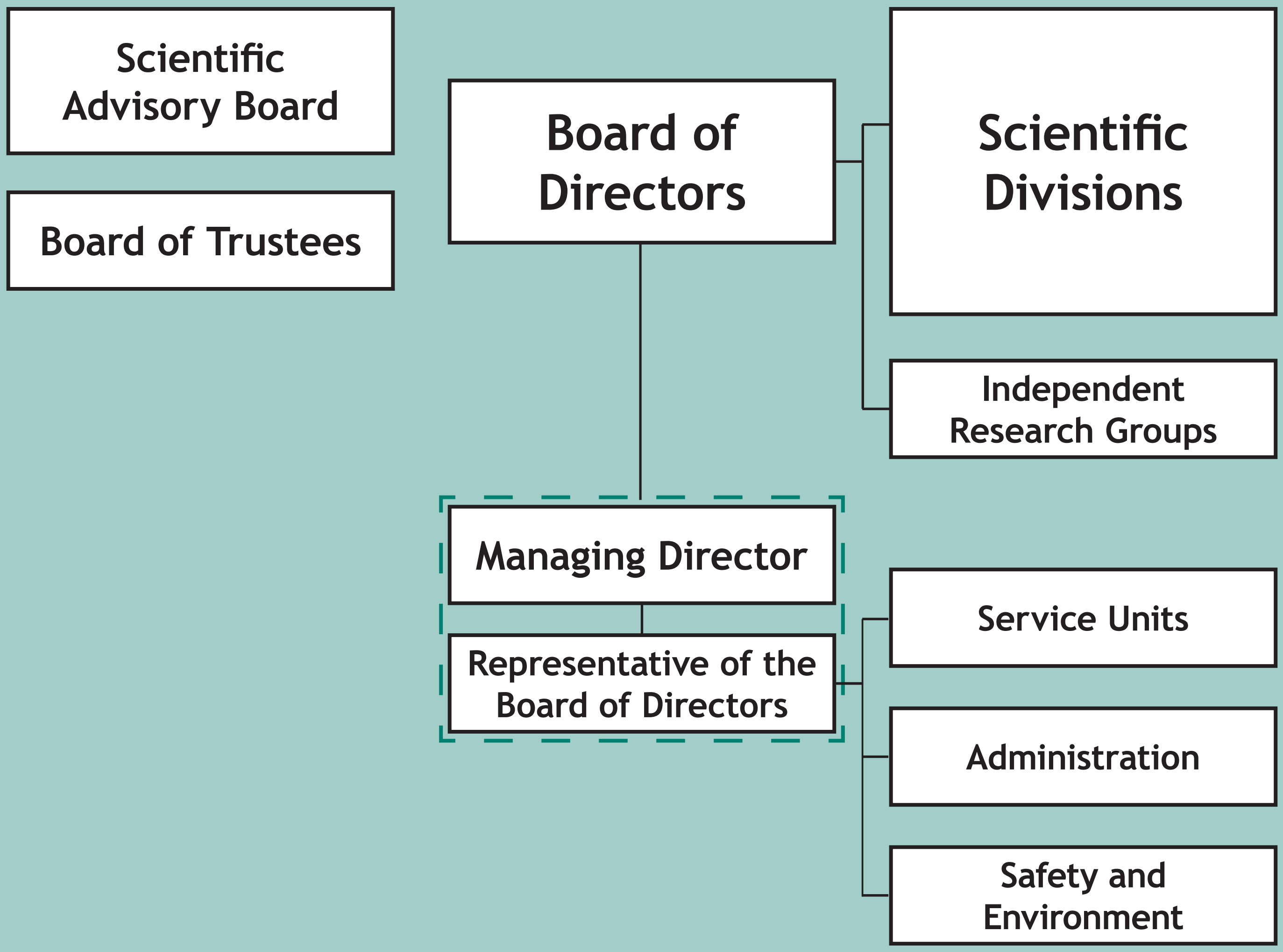


Source: ISI Web of Science™, December 2019

🟦 estimated

Distribution of the publications by Web of Science™ categories





3.2 PERSONNEL

Organisational diagram of the Institute.

Prizes awarded to MPIK Members

Prof. Dr. Klaus Blaum: External Member of the Physics Class of the Royal Swedish Academy of Sciences; ERC Advanced Grant
Prof. Dr. Till Kirsten: Enrico Fermi Prize of the Italian Physical Society
PD Dr. Adriana Pálffy-Buß: Hertha-Sponer-Preis der Deutschen Physikalischen Gesellschaft 2019; Röntgen-Preis der Justus-Liebig-Universität Gießen 2019
Dr. Kilian Heeg: ESRF Young Scientist Award 2018; Carl Zeiss Award for Young Researchers 2018; IBAME Young Scientist Award 2017
Dr. Andreas Mooser: IUPAP Young Scientist Prize in Atomic, Molecular and Optical Physics 2019
Dr. Lisa Schmöger: Otto-Hahn-Medaille der MPG and Otto Hahn Award 2018
Dr. Jonas Gunst: Otto-Hahn-Medaille der MPG 2017
Dr. Ludwig Rauch: Ruprecht-Karls-Preis der Stiftung Universität Heidelberg

Appointments of MPIK Scientists

PD Dr. Jörg Evers: Außerplanmäßiger Professor at Heidelberg University
Dr. Carlos Esteban Yaguna Toro: Professor in Physics at Pedagogical and Technological University of Colombia, Tunja, Colombia
Dr. Sunil Kumar Sudhakaran: Assistant Professor at Indian Institute of Science Education and Research, Tirupati, India
Dr. Farinaldo da Silva Queiroz: Junior Professor with tenure track at International Institute of Physics, Natal, Brasilia and International Centre for Theoretical Physics dof the South American Institute for Fundamental Research, São Paulo, Brasilia
Meng Wen: Associate Professor at Hubei University
Yue-Yue Chen: Tenure-track Full Professor at Shanghai Normal University
Jian-Xing Li: Tenure-track Full Professor at Xi'an Jiaotong University

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Prof. Dr. Dr.h.c. Manfred Lindner – Particle and Astroparticle Physics
Prof. Dr. Thomas Pfeifer – Quantum Dynamics and Control

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Prof. Dr. Volker Soergel, Heidelberg
Prof. Dr. Joachim H. Ullrich, Braunschweig
Prof. Dr. Christof Wetterich, Heidelberg
Prof. Dr. Daniel Zajfman, Rehovot

Managing Director

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Prof. Dr. Thomas Pfeifer, from 01.01.2018

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Dr. Holger Kreckel, subsequent to ERC Starting Grant
Dr. Brian Reville, from 01.05. 2019

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Dr. Hardy Simgen
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Dr. Sven Sturm
Dr. Richard J. Tuffs
Dr. Felix Werner
Dr. Richard White
Prof. Dr. Andreas Wolf

A complete list of people working at the MPIK may be found in the electronic annex.

International Max Planck Research Schools

The MPIK is involved in three International Max Planck Research Schools (IMPRS). Two of them are coordinated by the institute, while the third one is coordinated by the MPI for Astronomy (MPIA). The IMPRS are part of the Heidelberg Graduate School for Physics (HGSFP) at the University of Heidelberg.

IMPRS-QD: quantum dynamics in physics, chemistry and biology
Spokesperson: Christoph H. Keitel
Coordinator: Jörg Evers
Institutions: MPIK, Heidelberg University, German Cancer Research Center, MPI for Medical Research, GSI Helmholtzzentrum für Schwerionenforschung (Darmstadt)

	2017	**2018**	**2019**
PhD students	45	41	47
female	6	10	11
from foreign countries	26	24	28
funded by IMPRS-QD	11	10	11
graduations	6	16	10

IMPRS-PTFS: precision tests of fundamental symmetries
Spokespersons: Manfred Lindner and Klaus Blaum
Coordinator: Werner Rodejohann
Institutions: MPIK, Heidelberg University

	2017	**2018**	**2019**
PhD students	25	23	21
female	4	5	7
from foreign countries	7	7	6
funded by IMPRS-PTFS	14	6	7
graduations	4	6	8

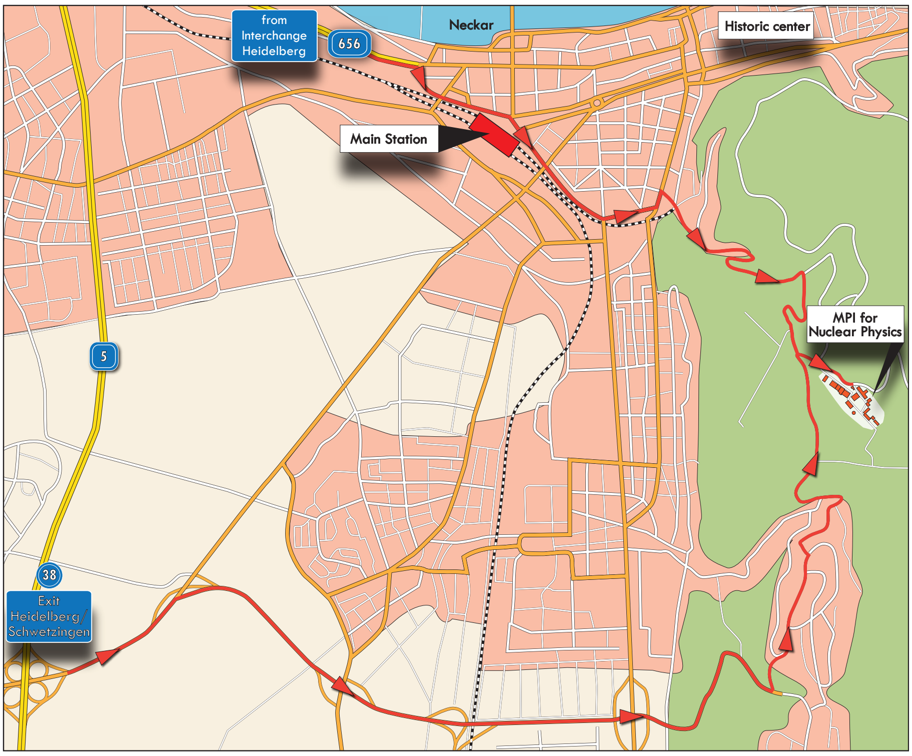
IMPRS-HD: astronomy and cosmic physics @ MPIA

During the reporting period, 15 PhD students (of which 4 female, 6 from foreign countries, 2 funded by IMPRS-HD, 7 graduations) were working at the MPIK.

Electronic Annex

The electronic annex provides lists of personnel, publications, theses, invited talks at conferences and symposia or at other institutes, teaching activities, jointly organised conferences and workshops, as well as institutional collaborations. Both the annex and the report itself can be downloaded from MPIK's web pages:
www.mpi-hd.mpg.de/mpi/en/public-relations/reports-and-information-material

How to reach the Institute



By car: Autobahn A5 from the north until Autobahnkreuz Heidelberg, turn to A656 (from Mannheim) direction Heidelberg; at the end of the Autobahn turn right (direction "Zentrum, Altstadt, Schloss"), keep straight ahead at the main station and follow Kurfürstenanlage until Adenauerplatz (hotel Crowne Plaza), turn right into Rohrbacher Straße, after about 1 km turn left into Steigerweg, and follow the direction signs to Max-Planck-Institut für Kernphysik about 2.5 km uphill.

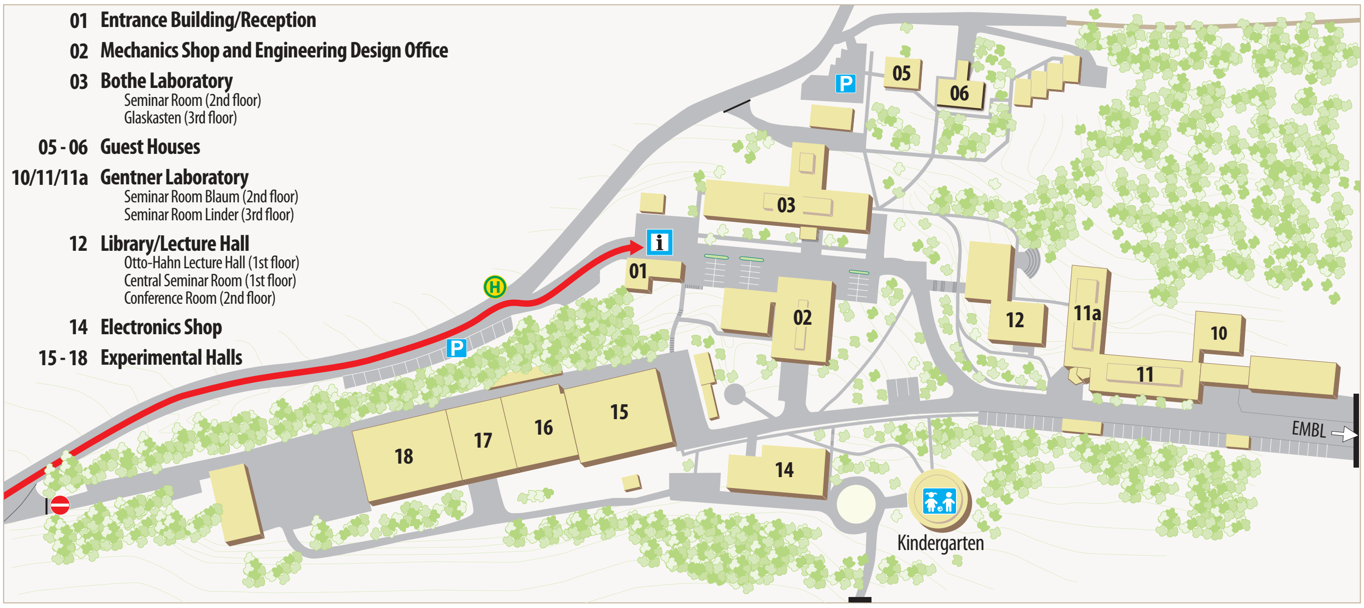
From the south leave A5 at the exit Heidelberg/Schwetzingen, turn on B535 direction Heidelberg/Leimen, then right direction Leimen and keep straight ahead for about 4.5 km (at last uphill) to the Aral station, there turn left to Boxberg and follow the direction signs to Max-Planck-Institut für Kernphysik.

By train: Arriving at the main station Heidelberg Hauptbahnhof which can be reached either directly by long-distance trains or via Mannheim and S-Bahn, take a taxi to the institute, or tram or bus to Bismarckplatz, change to bus 39 direction Königstuhl until stop "MPI Kernphysik" (about 15 min).

By plane: Airport Frankfurt/Main; take either an express train (ICE, IC) at Flughafen Fernbahnhof or the Lufthansa Airport Shuttle to Heidelberg which arrives at Crowne Plaza hotel, Kurfürstenanlage 1. Continue with a taxi or bus 39.

By taxi: Taxis are available outside the main station or can be called: +49 6221 302030. Please tell the taxi driver MPI für Kernphysik, Saupfercheckweg, as there are three other MPIs in Heidelberg.

Site Map of the MPIK



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HEIDELBERG

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