Max-Planck-Institut für Kernphysik Heidelberg

Progress Report 2020-2022

Cover: The XENONnT experiment underground in the Laboratori Nazionali del Gran Sasso (LNGS) in Italy with the three-storey service building and the water tank containing the detector and veto systems.

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Progress Report 2020-2022

Imprint

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Foreword

This report for the period of 2020-2022 is intended to provide a broad general overview of the main research areas at MPIK, our technological infrastructure, and selected science highlights. The chapters are organised by scientific topics and fields of research rather than by individual divisions, which cooperate in many areas to achieve common goals.

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

In 2020 a new independent research group on Ultrafast Liquid Crystal Dynamics was launched. Laura Cattaneo, the leader of the new group, joins group leaders Florian Goertz (New Physics, Electroweak Symmetry Breaking, and Flavor), and Brian Reville (Astrophysical Plasma Theory).

These groups complement the spectrum of science at MPIK spanned by the divisions of
- Klaus Blaum (Stored and Cooled Ions)
- Jim Hinton (Non-thermal Astrophysics)
- Christoph H. Keitel (Theoretical Quantum Dynamics and Quantum Electrodynamics)
- Manfred Lindner (Particle and Astroparticle Physics)
- Thomas Pfeifer (Quantum Dynamics & Control)

The period of this report coincides with the global COVID-19 pandemic. Despite the additional challenges raised by this situation, we are extremely happy that the scientific productivity was not negatively impacted, with many key scientific results achieved. Even more importantly, the COVID measures put in place at the institute were fully successful: with no known case of COVID transmission at the institute. Our scientific successes were enabled by the close cooperation of division scientists with our excellent infrastructure staff, consisting of mechanics and electronics workshops, scientific and technical service groups and our administration. I take the opportunity to thank all members of the institute and our partners and colleagues in the town of Heidelberg and all over the world!

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

Jim Hinton
Managing Director

Contents

Astro-particle Physics

1

1.1 The Non-Thermal Universe

Rendering of the southern CTA array. (© G. Pérez Diaz (IAC) / M.-A. Besel (CTAO) / ESO / N. Risinger (skysurvey.org))

Cosmic Accelerators – Astronomy at the Highest Energies

High-energy astrophysics at MPIK is characterized by a close cooperation between experimentalists and 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.

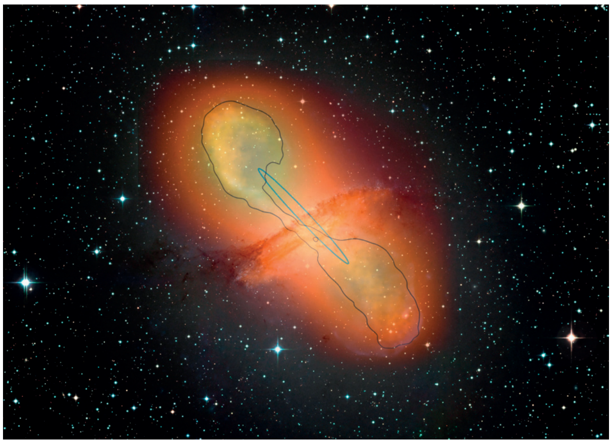
Particles in the VHE range cannot be produced as thermal radiation, as is the electromagnetic radiation in most other wavelength regimes; only in the Big Bang high enough temperatures were reached for a very short time. Charged particles, known as cosmic rays, can obtain VHE energies in many astrophysical 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 MPIK is going into the modelling and theoretical description of processes within the different cosmic accelerators, as well as into VHE observations.

VHE gamma radiation is produced when strongly accelerated charged particles interact with the interstellar gas or photon fields. In contrast to cosmic rays, 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.

H.E.S.S. has detected more than 100 VHE gamma-ray sources – each being a cosmic particle accelerator – arranged along the galactic equator. Many of these sources are connected with the remnants of exploded stars such as supernovae or pulsars and their winds. The supermassive black hole in the galactic centre turned out to be a cosmic "pevatron" that accelerates particles to tremendous energies. A hitherto unidentified galactic source was recently assigned to a massive young star cluster. In 2022, H.E.S.S. reported the first observation of a nova outburst in VHE gamma rays and was able to follow both its growth and subsequent fading. Beyond the Milky Way, H.E.S.S. identified several extraordinarily luminous sources in the Large Magellanic Cloud. In the last years, it could detect and spectrally analyse the afterglow of gamma-ray bursts over many hours. H.E.S.S. also showed that the VHE gamma-ray emission from galaxies with active nuclei extends over several thousand light-years along jets of plasma instead of being concentrated at the central black hole.

HAWC observations complement those of H.E.S.S., providing sensitivity to larger-scale emission and up to higher energies. Recently, HAWC has detected cosmic gamma rays with energies up to at least 200 TeV, (1 TeV = 10^{12} eV) from the direction of a superbubble surrounding the birthplace of massive stars.

The future instruments CTA and SWGO (see below) 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.

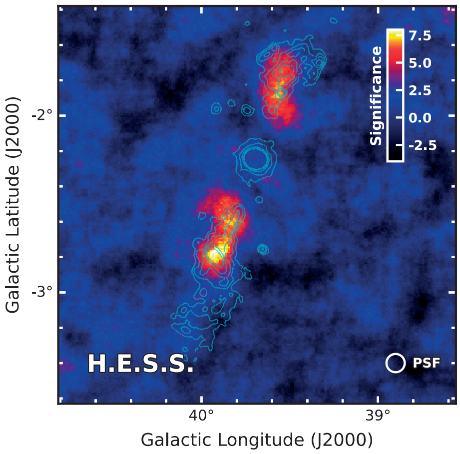


Composite image of Centaurus A, showing the jets emerging from the galaxy's central black hole, together with the associated gamma radiation (Image credits: ESO/WFI (Optical); MPIfR/ESO/APEX/A.Weiss et al. (Submillimetre); NASA/CXC/CfA/R.Kraft et al. (X-ray), H.E.S.S. Collaboration (Gamma)).

Spatially resolved gamma-ray emission from nearby jets

Since its detection in the mid 1970s, the microquasar SS 433 has emerged as one of the most intensively studied systems in the Galaxy. Microquasars, so-called due to their resemblance to the powerful large-scale jets observed emanating from the centres of other galaxies (quasars), offer powerful laboratories to resolve jet processes in our own Galaxy. In the case of SS 433, material from a ~10 solar-mass star is accreted onto a compact object, presumably a low-mass black hole, launching a pair of jets that move at ~25% the speed of light.

Out to distances of 0.1 parsecs from the binary, the inner jets have been resolved down to x-ray wavelengths. As the jets propagate further out, they remain dark until they abruptly reappear as bright x-ray sources at 25 parsecs. How and why this happens is still unclear, but the appearance of several bright x-ray knots, visible in the blue contours that follow the outer jets, suggest recent non-thermal particle acceleration far from the central binary, indicated by the central contours. The detection of the outer jets with the HAWC observatory confirm that electron acceleration to hundreds of TeVs is occurring.



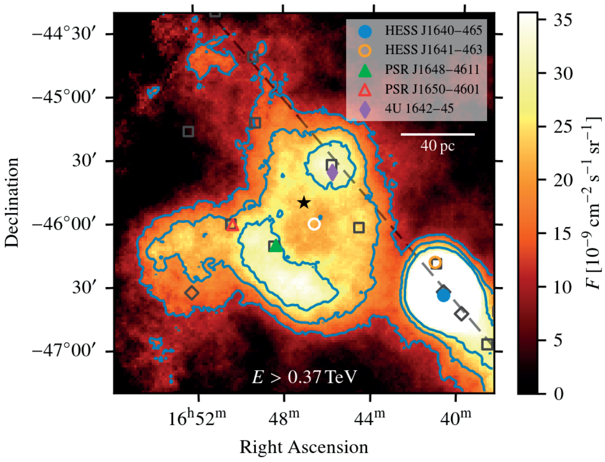
Following up on this discovery, the H.E.S.S. array of imaging atmospheric Cherenkov telescopes performed a deep observation campaign which resulted in the first ever detection of SS 433 by such an instrument. The colours in the figure show the emission detected by H.E.S.S., revealing a close correlation between the gamma-ray and x-ray emission in the outer jets. The superior resolution of H.E.S.S. allows for a detailed study of the morphology and spectral properties of the gamma-ray emission from the SS 433 jets.

In particular, the H.E.S.S. observations can be used to determine both the size and shape of the gamma-ray emission regions from the jets. The flux from each jet was also measured, with no indication of the flux tapering off at the highest energies. The jets are likely emitting gamma rays at even higher energies than those probed with H.E.S.S., a regime soon to be accessible to CTA or SWGO. In order to reach such high energies, the acceleration of particles in the jets of SS 433 must be relatively efficient, a fact which can, in turn, be extrapolated to the much more distant and larger jets launching from the centre of other galaxies.

Reference:
H.E.S.S. Collaboration, in preparation

Westerlund 1: a powerful cosmic-ray accelerator

Young massive star clusters have recently become popular as potential major contributors to the flux of the highest-energy Galactic cosmic rays – as competitors to isolated supernova remnants, the long-term "culprits". Westerlund 1 is the most massive known young star cluster in our Galaxy. Its total mass is about 10^5 solar masses, half of which is contained within a radius of ~1 pc. In 2012, the H.E.S.S. Collaboration reported the detection of an extended gamma-ray source called HESS J1646–458, coincident with Westerlund 1 [1]. However, due to the limited data set available at the time, the emission could not firmly be linked with Westerlund 1. With an increased data set, it was now possible to perform a more detailed analysis, which has recently been published [2].



Gamma-ray map of the HESS J1646−458 region. The position of Westerlund 1 is marked by the black star symbol; the grey, dashed line shows the Galactic plane. Coloured symbols indicate objects listed in the legend, and dark grey symbols indicate further objects detected by the Fermi satellite.

The gamma-ray emission of HESS J1646–458 extends over a region almost 2 degrees across, which corresponds to about 140 pc – much larger than the cluster itself, as shown in the map. Intriguingly, the gamma-ray emission seems to exhibit a shell-like structure, with several bright peaks in addition. A detailed investigation of possible counterparts has revealed that only cosmic rays accelerated by Westerlund 1 can explain the observed gamma-ray emission. The large spatial extent of the emission and its shell-like structure may indicate a connection with the collective wind of the cluster, which forms as a superposition of the stellar winds of the massive stars inside Westerlund 1. If confirmed, it would be the first time that the collective wind of a massive star cluster could be directly linked to high-energy gamma-ray emission, and thus be identified as a cosmic-ray acceleration site.

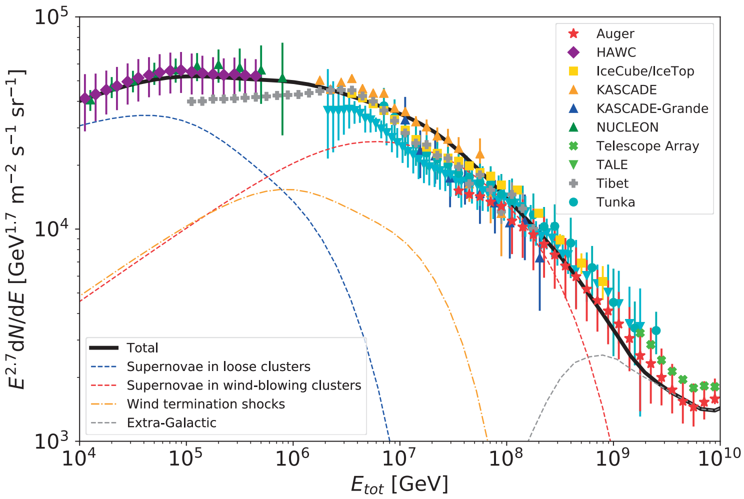
References:
[1] H.E.S.S. Collaboration, Astronomy & Astrophysics 537, A114 (2012), DOI: 10.1051/0004-6361/201117928
[2] H.E.S.S. Collaboration, Astronomy & Astrophysics 666, A124 (2022), DOI: 10.1051/0004-6361/202244323

A superbubble model for galactic cosmic-ray origins

Earth's atmosphere is continuously bombarded by energetic cosmic-ray particles. Their energy spectrum resembles a series of connected power-laws, covering more than eleven decades in energy. Two significant breaks in the particle spectrum are observed at a few PeV (10^{15} eV) and a few EeV (10^{18} eV), the cosmic-ray knee and ankle respectively.

Below the knee, cosmic rays are thought to be energized at supernova remnant shocks, though this theory currently lacks observational confirmation. Above the ankle particles are of extragalactic origin, though we still only speculate on their sources. Between the knee and ankle however, cosmic-ray sources, while Galactic in origin, have received scarce consideration. Recent gamma-ray observations hint that sources may be found in superbubbles: low density cavities blown in the interstellar medium by stellar clusters and their associated supernova explosions.

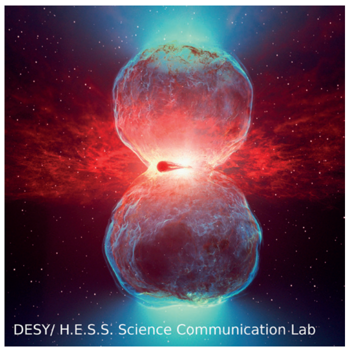
In work developed at MPIK, a promising mechanism to accelerate cosmic rays beyond the knee in young massive stellar clusters has been proposed. The compact clustering of strong winds from many massive stars drive turbulent magnetic field amplification in the core, which is carried out on the cluster's collective wind. After several million years, the supernovae from massive stars launch fast shocks into the magnetized wind, providing favourable conditions to accelerate particles to extreme energies. Using Gaia data, it is inferred that ~15% of massive stellar clusters can generate the winds needed to enable acceleration beyond the knee. Coupled with the expected supernova rate, a physically consistent model (see figure) of cosmic-ray production from Galactic stellar clusters can reproduce well current experimental data.



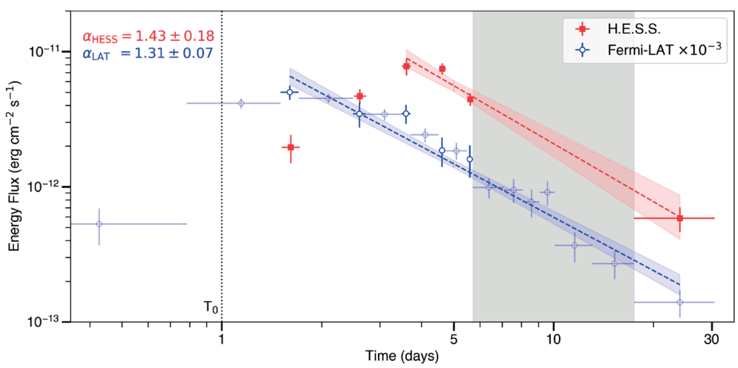
References:
[1] T. Vieu, B. Reville & F. Aharonian, MNRAS, 515, 2256 (2022), DOI:10.1093/mnras/stac1901
[2] T. Vieu & B. Reville, MNRAS in press (2022), arXiv:2211.11625 [astro-ph.HE], DOI: 10.48550/arXiv.2211.11625

Novae - a new class of very-high-energy transients

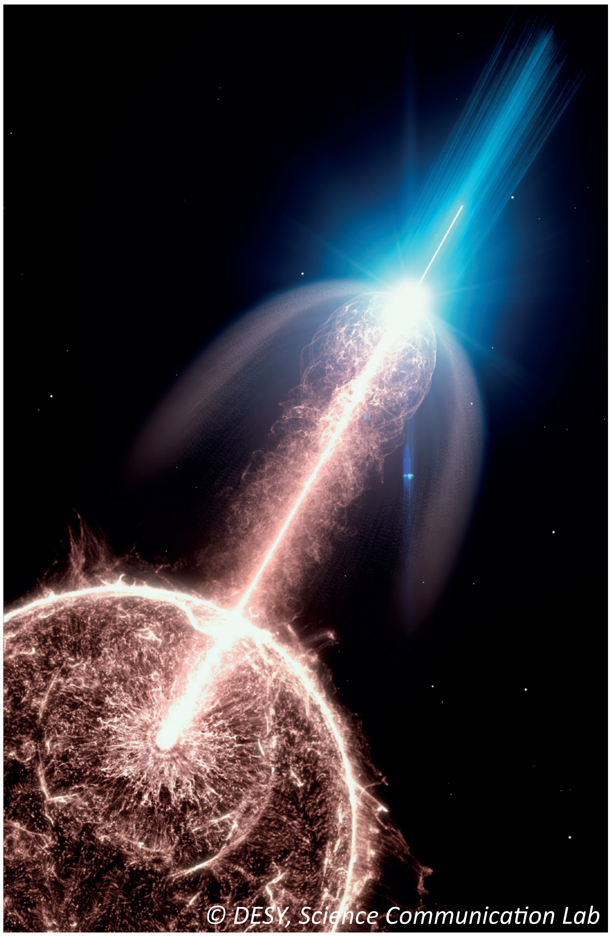
A nova is produced when a white dwarf accretes sufficient material from a stellar companion to ignite a thermonuclear explosion on its surface. Novae are well understood in optical light but the repeated detection by the Fermi LAT satellite confirms also their status as important high-energy astrophysical sources.


DESY/ H.E.S.S. Science Communication Lab

On August 8th 2021 an outburst was reported from the recurring nova RS Ophiuchi triggering H.E.S.S. follow-up observations. This yielded a highly significant detection over several weeks. Consequently, RS Ophiuchi not only established a new source class in TeV astronomy but the data set also allowed detailed time-resolved tracking of the gamma-ray emission. This is evident in the light curve (see figure) with the H.E.S.S emission peaking roughly 3 days after the peak seen in the optical (T0) and 2 days after the peak seen by Fermi LAT at slightly lower energies. The similar shape of the H.E.S.S. and Fermi light curves implies a common origin of the emission over the whole MeV to TeV regime, whereas the delay reflects the expected finite acceleration time. Modelling the combined gamma-ray data showed a clear preference for a hadronic origin of the emission. This demands efficient cosmic-ray acceleration to occur at the fast shock driven by the thermonuclear explosion as it propagates into the dense wind of the red giant companion. The maximum photon energy of ~1 TeV closely matches theoretical limits for such systems. This has important implications for its bigger and more powerful siblings, supernova explosions, strongly supporting the hypothesis, that the primary component of Galactic cosmic rays originates in core-collapse supernova remnants.



Reference:
H.E.S.S. Collaboration, Science 376, 77-80 (2022), DOI: 10.1126/science.abn0567



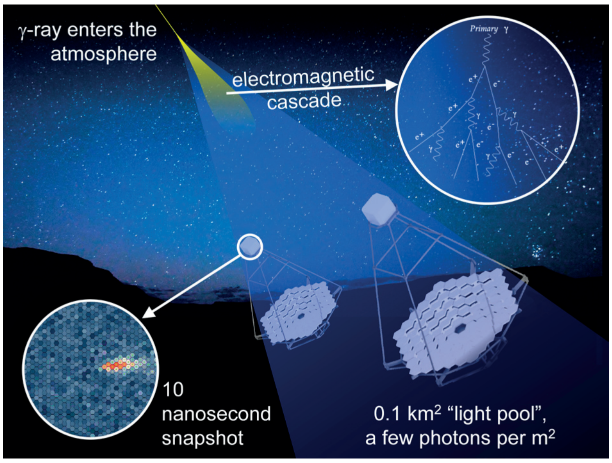
A nearby gamma-ray burst reveals striking features

Gamma-ray bursts (GRBs) are extremely bright events associated to the death of massive stars or mergers of compact objects. These distant events briefly become the brightest objects in the Universe, principally emitting in the soft gamma-ray band. The radiation is produced within relativistic jets of matter that are beamed towards Earth. This initial bright episode is followed by a longer-lasting decay period in their emission, as the propagating jet decelerates and the luminosity decreases.

In 2019, the H.E.S.S. telescopes detected at TeV energies the gamma-ray emission from GRB190829A, one of the nearest GRBs ever observed, at a redshift of 0.0785; more commonly, GRBs are seen at redshifts close to 1. Observations with H.E.S.S. were performed 4 hours after the beginning of the burst, when the GRB was visible in the night sky of Namibia and continued for a second and a third night in which, strikingly, TeV emission was still detected. This late-time detection was possible thanks to the proximity of this GRB to Earth, which allowed the TeV photons to travel without being greatly absorbed by the extragalactic background light. This enabled an unprecedented study of the TeV spectrum from a GRB afterglow. Observations in the x-ray band with the Swift satellite are found to have striking similarities in the temporal evolution and spectral features with the H.E.S.S. observations. This reveals an acceleration and emission mechanism that connects eight orders of magnitude in photon energy and challenges well-known theories of TeV emission in GRBs.

Reference:
H.E.S.S. Collaboration, Science 372, 1081 (2021), DOI: 10.1126/science.abe8560

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 specialized cameras. To determine accurately the direction of the incoming gamma ray, the shower is observed stereoscopically by several of these telescopes.

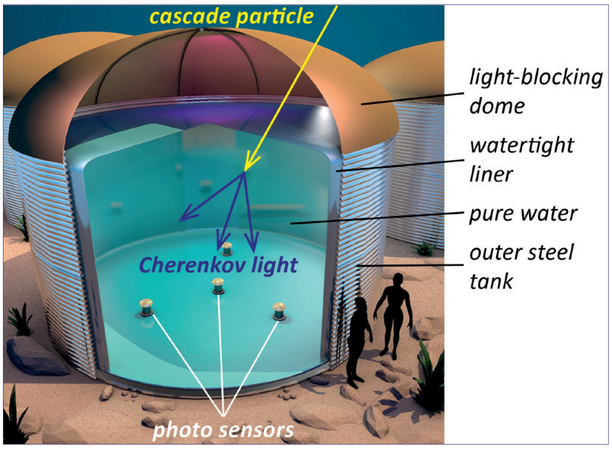
The High Energy Stereoscopic System H.E.S.S. consists of five telescopes, four of them each with 107 m^2 mirror area deployed in a square of side length 120 m. A camera composed of 960 photomultiplier sensors is placed at the focus of each mirror. H.E.S.S. was the first instrument that was able to produce true images of astrophysical gamma-ray sources. In the centre of the array, a fifth, huge telescope with 614 m^2 mirror area has been operational since 2012, enhancing the sensitivity of the system and extending observations to lower energies. In 2019, it has been upgraded using the camera technology developed at MPIK for CTA. The new camera provides increased sensitivity for transient phenomena.

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 La Palma, with – in a first step – 64 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 the small- and medium-sized telescopes.

A key milestone towards establishing the CTA Observatory has been reached in 2022 with the submission of the formal request to the European Commission to establish a European Research Infrastructure Consortium.

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 in Mexico. 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 also playing a major role in the development of a next-generation gamma-ray survey observatory in the southern hemisphere, the Southern Wide-field Gamma-ray Observatory (SWGO). SWGO will make use of the same detection principle as HAWC, but cover a much larger area and a wider range of gamma-ray energies.



How a HAWC tank works as a water Cherenkov counter.

Progress towards SWGO

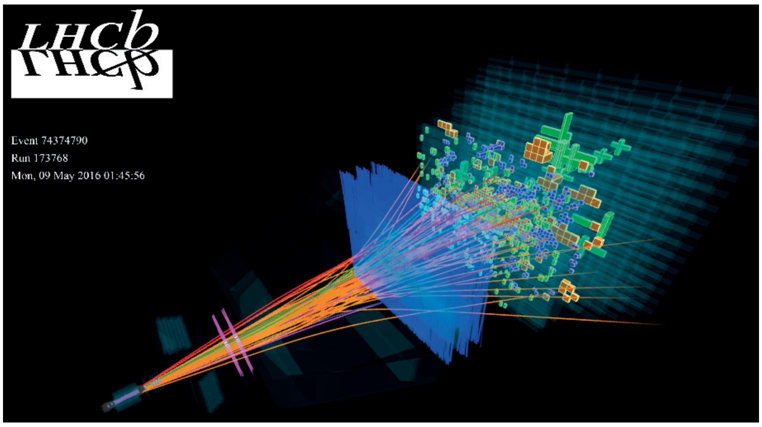
The Southern Wide-field-of-view Gamma-ray Observatory (SWGO) is currently in a design study phase, with the MPIK group strongly involved in the development of the detector design. SWGO will make use of large water-filled units equipped with sensitive light detectors, to measure the Cherenkov light produced by shower particles high in Andes in South America.

A fake lake or Gewässersimulationstank was built at the institute to explore the option of deployment of detector units directly in to a natural or artificial lake (see picture, with MPIK members Hazal Göksu and Fabian Haist). Most aspects of this approach are now demonstrated and it is looking promising in terms of cost and performance. After a decision on site and technology for SWGO, which is planned for 2023, we plan to build an engineering array at the final site. As the first such instrument in the southern hemisphere this will already be extremely exciting in unveiling large-scale emission in the central parts of our own Galaxy.

References:
[1] SWGO website: http://www.swgo.org/
[2] J. Hinton (for the SWGO Collaboration), arXiv:2111.13158 [astro-ph.IM], DOI: 10.48550/arXiv.2111.13158

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.



Visualisation of particle tracks from a collision inside the LHCb detector.

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). It is currently 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 give access to collective phenomena in extended systems consisting of free quarks and gluons, so-called quark-gluon plasmas.

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

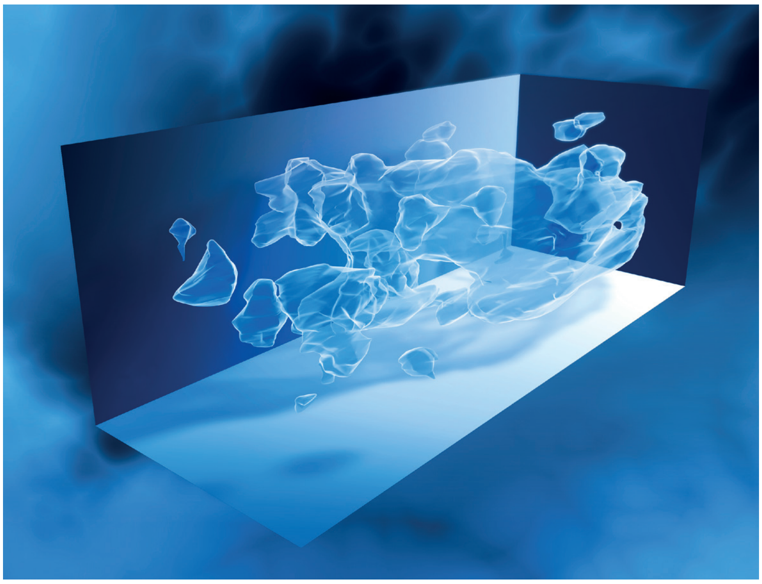
1.2 Dark Matter and Neutrinos

Theoretical proposals to explain dark matter: (clockwise) weak interaction, neutrinos, light bosons, other particles gravitation, and macroscopic objects. Background: Hubble ultra-deep field.

Dark Matter – Structure Forming Agent in the Universe

Based on cosmological observations such as galactic rotation curves, gravitational lensing by galaxy clusters or the cosmic microwave background, it was shown that the Universe consists to about 26.8% of dark matter, while the fraction of ordinary matter is 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 the most promising candidates for dark matter. They are motivated by the so-called WIMP miracle saying that the right amount of dark matter automatically emerges in the hot early Universe, and that they are in addition expected to exist in many extensions of the Standard Model of particle physics. Further solutions studied by researchers are motivated by other theoretical aspects. Examples are 'axions', 'sterile neutrinos' or particles only interacting gravitationally. Combined analyses and interpretation of different particle and astroparticle experiments aim at testing different proposed explanations for dark matter. Furthermore, candidates must fit into consistent theoretical models.



3D map of the large-scale distribution of dark matter, reconstructed from measurements of weak gravitational lensing with the Hubble Space Telescope. (Image: NASA/ESA/Richard Massey (California Institute of Technology))

MPIK is involved in the direct search for WIMPs with the XENON experiments at the Gran Sasso underground laboratory in Italy. The detector uses ultra-pure liquid xenon as detector medium and observes the combination of scintillation light and ionization charge emerging from the rare interactions of WIMPs with Xe atoms. XENON1T reached in 2018 the highest sensitivity of such experiments, deeply probing the most plausible parameter regions where WIMPs and other dark matter candidates are expected. The upgrade to XENONnT is taking data since 2021 and will lead to a ten-fold sensitivity increase. First results using electron recoils instead of the more standard nucleon recoil data set allowed to set world-leading limits on neutrino magnetic moments, solar axions, axion-like particles and dark photons, demonstrating the broad physics potential of dark matter direct detection experiments.

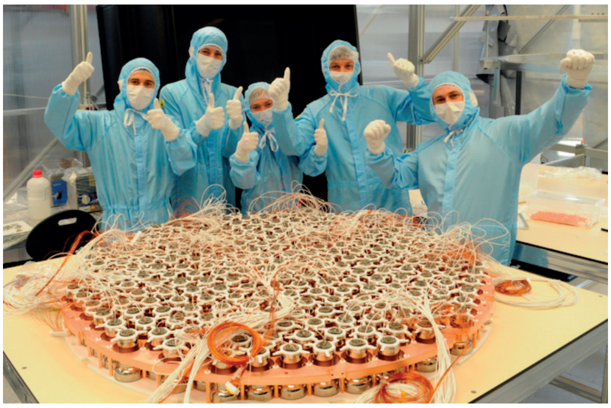
In addition, the H.E.S.S. telescopes look for high-energy gamma rays, produced by the possible annihilation of dark matter particles in the dark matter halo of the Milky Way. CTA and SWGO will reach the critical sensitivity to detect or exclude a WIMP produced under certain assumptions as a thermal relic from the Big Bang. This will lead to a complementary discovery potential about as large as that of XENONnT and related experiments.

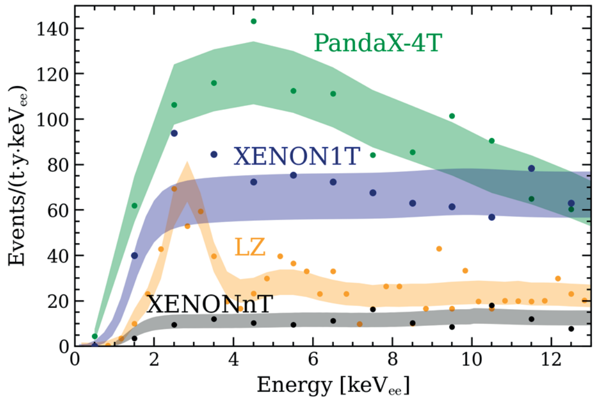
First XENONnT results with the lowest ever achieved background

Understanding the nature of dark matter is one of the most important questions in physics nowadays. The currently running XENONnT detector is the largest and cleanest of the successful series of XENON experiments. Its construction was finished in 2020 (see picture) and it is hunting, since then, for dark matter particles gravitationally bound in our Milky Way.

To unambiguously identify dark matter interactions, an extremely low experimental background is required. Besides a careful selection of detector materials with trace analysis techniques, the purity of the xenon target itself is of great importance [1]. In the last years, radon has become the dominant background in all liquid xenon experiments. In the framework of XENONnT various strategies to avoid, mitigate and remove radon were pursued, which is one of the important contributions of MPIK. The success of this combined approach is visible in the first XENONnT data, which demonstrate the lowest background rate ever achieved in any dark matter experiment [2].

With the data, world-leading limits on new science channels like solar axions, an enhanced neutrino magnetic moment and bosonic dark matter [2] could be derived. Currently, the search for weakly-interacting massive dark matter is ongoing and exciting results are expected in the next years.





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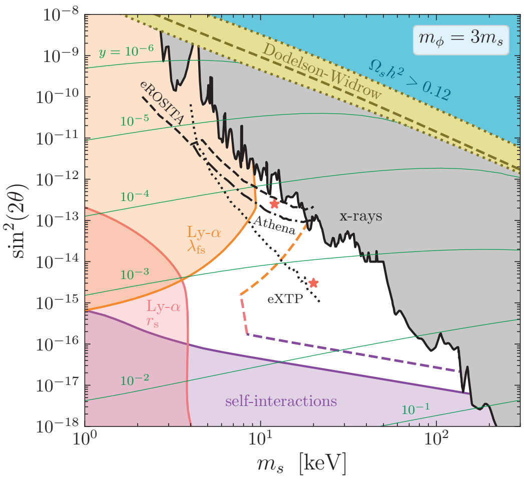
[1] XENON Collaboration, Eur. Phys. J. C 82 (2022) 7, 599, DOI: 10.1140/epjc/s10052-022-10345-6
[2] XENON Collaboration, Phys. Rev. Lett. 129 (2022) 161805, DOI: 10.1103/PhysRevLett.129.161805

Theory of dark matter

In recent years improved limits on WIMP dark matter (DM) from direct and indirect detection as well as collider searches have motivated the exploration of alternative dark matter scenarios. In particular, models with dark matter mass much smaller or larger than the usual WIMP mass of O(100) GeV have been considered. For example, unusually light WIMPs have been shown to be possible using a light second Higgs mediator [1]. Dark matter production mechanisms beyond thermal freeze-out have been studied, e. g. making very heavy DM possible through freeze-in [2].

New production mechanisms for sterile neutrino dark matter are reviving interest in this DM candidate. It was shown in [3] that self-interacting sterile neutrino dark matter can be exponentially produced by converting the Standard Model neutrinos into sterile neutrinos in the early Universe. This model opens up significant parameter space which can be probed by structure formation, astrophysical, and x-ray observations as demonstrated in the figure. In [4] it was shown that varying the Yukawa coupling in the early Universe can lead to keV sterile-neutrino dark matter consistent with current observations.



The phenomenology of various dark matter models has been studied, considering both conventional direct/indirect/collider WIMP signatures, as well as implications for early Universe cosmology and phase transitions. Moreover, generic dark matter signatures have been considered in the effective field theory framework which can be mapped to UV complete dark matter models. In connection to astrophysics, calculations for dark matter capture in neutron stars [5] and constraints from core-collapse supernovae [6] have been improved.

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[1] J. Herms et al., Phys. Rev. Lett. 129, 091803 (2022), DOI:10.1103/PhysRevLett.129.091803
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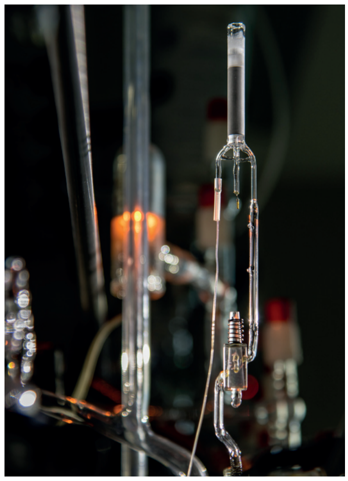
[5] N. F. Bell et al., JCAP 09, 028 (2020), DOI:10.1088/1475-7516/2020/09/028
[6] Y. M. Chen et al., JCAP 11, 014 (2022), DOI:10.1088/1475-7516/2022/11/014

Low Level Techniques

Extremely sensitive low-level techniques are essential for neutrino experiments and dark matter searches which look for very rare events, where identification and reduction of the background plays a key role. At the MPIK, there is a long tradition and internationally recognised 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 are used to check the radiopurity of materials. They are the heart of very sensitive assay techniques for concentrations of radioisotopes which are many orders of magnitude below natural radioactivity in the environment.

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.



A miniaturised quartz proportional counter tube used to perform highly sensitive radon emanation measurements.

Neutrinos – Particles with Striking Properties

Neutrinos are electrically neutral elementary particles with tiny masses which occur in 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 very rarely with matter. Sensitive detectors with excellent shielding against background signals are therefore required to detect them.

Unlike all other elementary particles like electrons or quarks, neutrinos might be identical to their own antiparticles. They would then be so-called Majorana particles which may be related to their tiny masses and which might explain why our Universe is dominated by matter. The best way to establish the Majorana nature – or more generally lepton number violation – is to search for a process called neutrinoless double beta decay. In this decay two neutrons inside a nucleus decay to two protons and two electrons. The electrons leave the new nucleus and their energies are measured. If the sum agrees with the expectation and other environmental processes that mimic neutrinoless double beta decay can be sufficiently suppressed, the Majorana nature is established. MPIK initiated the GERDA experiment that searched for this decay mode using ^{76}Ge. The first phase of the successor experiment, LEGEND, is currently under commissioning at the Laboratori Nazionali del Gran Sasso in Italy.

Topics of neutrino research.

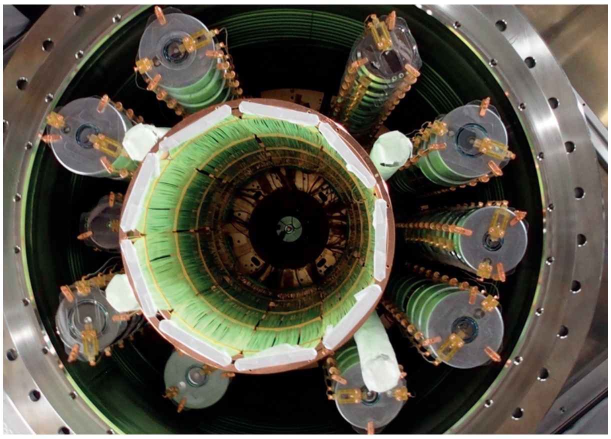
For the masses of neutrinos only limits and differences are known to date. Other experiments to determine the neutrino mass rely on the capture of an electron by a proton in a nucleus. Therefore, the knowledge of the exact mass difference between mother and daughter nucleus is necessary. Penning traps (see section 2.1) are particularly suitable tools for such precision measurements.

Various experiments in the vicinity of nuclear power plants detected about 6% less antineutrinos than expected. This could have been the consequence of oscillations into so-called sterile neutrinos. The Stereo experiment tested the sterile neutrino hypothesis and the results disfavour most of the allowed parameter space. The experiment also clarified another anomaly in the observed neutrino spectrum.

The CONUS experiment uses a very intense flux of reactor antineutrinos close to the core of power reactors to investigate the coherent neutrino-nucleus scattering – scattering of neutrinos with the nucleus as a whole. Highly pure germanium detectors with very low energy threshold were developed to measure the tiny energy transfer due to this scattering process, which, however, is significantly more probable than the interaction of neutrinos with electrons. A very powerful shielding had to be developed to create close to a reactor radio-pure conditions which are usually only achieved in deep underground laboratories with special methods. Strong limits on coherent scattering and world-leading limits on neutrino physics beyond the Standard Model were obtained. An upgrade of CONUS with further improved detectors, even better shielding and more detector mass is being prepared.

The riddle of the neutrino nature: search for neutrinoless double beta decay with ^{76}Ge

The GERDA experiment searched for neutrinoless double beta decay of ^{76}Ge by operating germanium detectors made from material enriched to about 88% in ^{76}Ge. The total mass was 35-40 kg. The detectors were operated in a 64 m^3 cryostat filled with liquid argon. The argon acted as shield against environmental background radiation and – by the detection of scintillation light – also allowed to veto most of the radioactive backgrounds since they typically deposit energy not only in the germanium but also in the argon. The cryostat was inside a 660 m^3 water tank to further suppress environmental backgrounds. The entire setup was located underground to shield against cosmic radiation at the Laboratori Nazionali del Gran Sasso (LNGS) in Italy. Reducing or identifying events from environmental sources that mimic double beta decay is a key to improve the sensitivity of the search. GERDA was a European collaboration founded in 2003 by MPIK. It stopped data taking in 2020. No hint for neutrinoless double beta decay of ^{76}Ge was found and a 90% C.L. lower half-life limit of 1.8×10^{26} yr was extracted. All design goals were met.

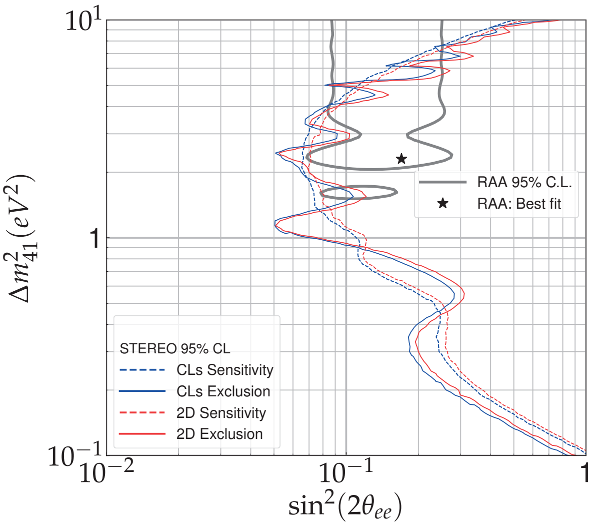


LEGEND-200 germanium detector assembly with fibre argon veto.

The background level achieved by GERDA is the lowest in the field. This motivated to continue the search using the same technique. A new collaboration called LEGEND formed. Institutions from GERDA, the American Majorana experiment and others joined. In a first step, LEGEND will deploy close to 200 kg of germanium detectors in the previous GERDA setup at LNGS. This phase is currently in commissioning. Physics data taking is expected to start by the end of 2022. Several improvements are in place that should allow to reduce the background level relative to GERDA. The sensitivity of this phase called LEGEND-200 is expected to reach 10^{27} yr. Another phase with 1000 kg of germanium detectors in a new setup has been proposed. Its sensitivity will reach 10^{28} yr. Last year the US Department of Energy performed a review of three proposals. LEGEND was rated favourably. Construction could start in a few years from now.

Reference:
M. Agostini et al. (GERDA collaboration), PRL 125, 252502 (2020), DOI: 10.1103/PhysRevLett.125.252502

Constraints on the existence of sterile neutrinos



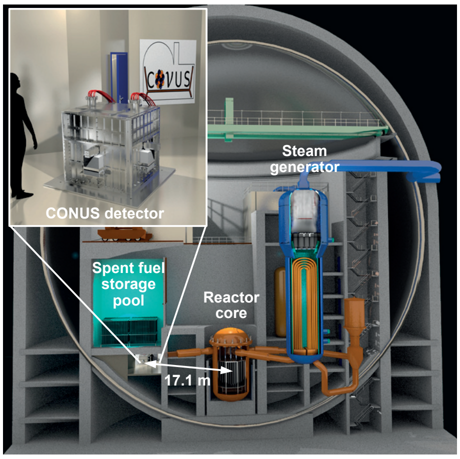
Exclusion contour (solid red) and exclusion sensitivity contour (dashed red) in sterile neutrino parameter plane.

An observed anomaly in the measured neutrino rate emitted by nuclear reactors has triggered the hypothesis of the existence of an additional sterile neutrino state on top of the three known active neutrino flavours. Such a particle would not participate in weak interaction reactions and its existence would require extensions of the Standard Model of particle physics. The Stereo experiment was searching for light sterile neutrinos at the 58 MW research reactor of ILL Grenoble at a distance of only 10 m to the reactor core. Flavour conversion into sterile neutrinos would induce distortions in the measured energy spectrum as a function of the distance to the reactor core. Therefore, the Stereo detector was segmented into 6 identical cells and the sterile neutrino hypothesis tested by the comparison of the 6 measured spectra. This way the analysis is independent of predictions on the emitted spectrum.

Based on the measurement of more than 100 000 antineutrinos detected from 2017 to 2020 including 273 days with the reactor turned on and 520 days with the reactor off, Stereo rejected the hypothesis of a light sterile neutrino [1]. The experiment also delivered leading precision results on the absolute comparison between the predicted and measured total neutrino rate for a highly enriched ^{235}U reactor [1,2]. Furthermore, Stereo established a new reference for the ^{235}U antineutrino energy spectrum. In this way, another anomaly related to the spectral shape could be confirmed. The sensitivity of the shape measurement was further improved by combing the data of the Stereo and Prospect experiments in a joint analysis [3]. In summary, the Stereo results suggest biases in the nuclear data used for the predictions as origin of the anomalies in contrast to explanations based on new neutrino physics.

References:
[1] Stereo Collaboration, arXiv:2210.07664v2 [hep-ex] (2022), DOI: 10.48550/arXiv.2210.07664
[2] Stereo Collaboration, Phys.Rev.Lett. 125 (2020) 20, 201801, DOI: 10.1103/PhysRevLett.125.201801
[3] Stereo and Prospect Collaborations, Phys.Rev.Lett. 128 (2022) 8, 081802, DOI: 10.1103/PhysRevLett.128.081802

Neutrinos scattering on atomic nuclei



CONUS detector set-up within the building of the nuclear power plant at Brokdorf.

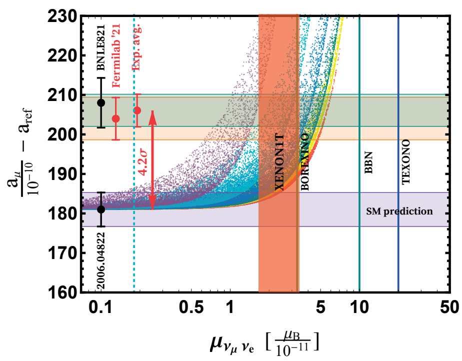
The Standard Model of particle physics predicts a process in which neutrinos, the tiniest and most elusive of the known elementary particles, scatter with the constituents of atomic nuclei. Due to quantum-mechanical coherency the respective cross section is enhanced by several orders of magnitude compared to more commonly applied interaction channels. This enhancement allows in principle 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.

The CONUS experiment aims at detecting neutrinos at the nuclear power plant in Brokdorf, Germany with its 3.9 GW thermal power. The immense neutrino flux was monitored at a distance of 17 m from the reactor core using 4 specifically designed low-energy-threshold germanium detectors inside an elaborated passive and active shield. It would be the first time that this type of interaction is measured for low-energy reactor neutrinos. A new very precise measurement of the ionization quenching in the germanium crystals revealed an unfavourable material parameter, which further challenges the neutrino detection with this technique [1].

So far, with the first analysed CONUS dataset, a strong upper limit on the number of neutrino-nucleus interactions was determined [2]. Moreover, the low background levels in the experiment allowed to constrain neutrino physics beyond the Standard Model of elementary particle physics and to partly set world's best limits on those [3]. In particular, competitive constraints on electromagnetic properties of neutrinos, i. e., upper limits on an effective neutrino magnetic moment and an effective neutrino millicharge were achieved [4]. The Brokdorf reactor stopped operation by the end of 2021. The long period with the reactor turned off in 2022 allows for the precise determination of background events. An analysis update with improved low-energy threshold is in preparation.

References:
[1] A. Bonhomme et al., Eur.Phys.J.C 82 (2022) 9, 815, DOI: 10.1140/epjc/s10052-022-10768-1
[2] CONUS collaboration, Phys.Rev.Lett. 126 (2021) 4, 041804, DOI: 10.1103/PhysRevLett.126.041804
[3] CONUS collaboration, JHEP 05 (2022) 085, DOI: 10.1007/JHEP05(2022)085
[4] CONUS collaboration, Eur.Phys.J.C 82 (2022) 9, 813, DOI: 10.1140/epjc/s10052-022-10722-1

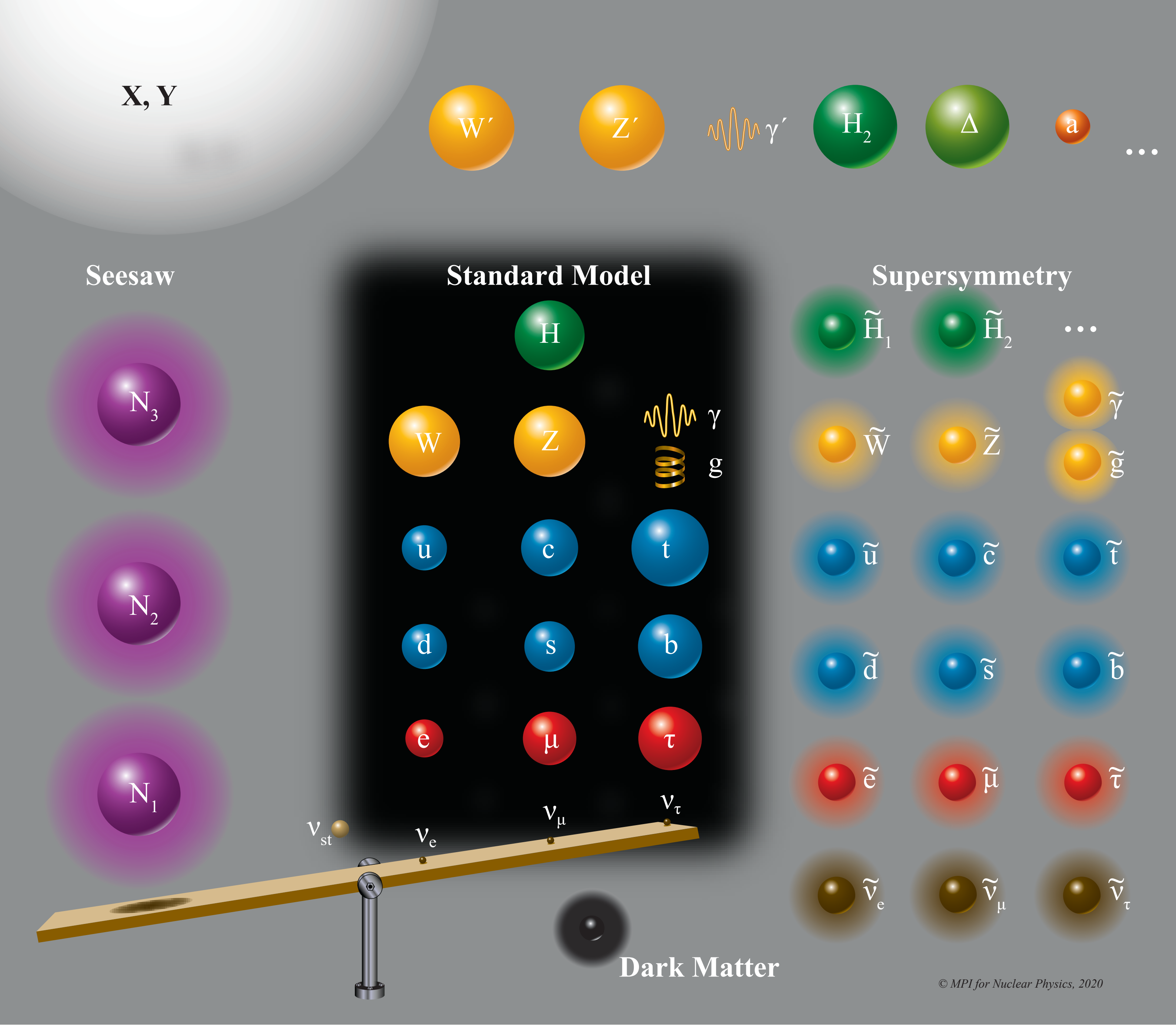
Neutrinos and physics beyond the Standard Model



Correlated theoretical predictions and experimental measurements of the muon anomalous magnetic moment and the neutrino transition magnetic moment.

Neutrinos are one of the most abundant of all known particles in the Universe, but yet the least understood ones. In the Standard Model, neutrinos are massless and interact only via the weak force. However, the discovery of neutrino oscillations implies that neutrinos are massive and mixed. Therefore, the Standard Model must be extended to account for the tiny neutrino masses, and that opens up a gateway to new physics beyond the Standard Model. In these extensions, neutrinos also acquire electromagnetic properties through quantum loop effects. The theoretical and experimental investigation of neutrino electromagnetic interactions can therefore serve as a powerful tool in searching for the fundamental theory behind the neutrino mass generation mechanism [1]. The models that induce neutrino magnetic moments while maintaining their small masses naturally also predict observable shifts in the charged lepton anomalous magnetic moments [2], thereby linking properties of neutral and charged leptons. This shift is of the right magnitude to be consistent with the Brookhaven measurement as well as the recent Fermilab measurement of the muon *g-2*. A broad program investigates the consequences of it in ongoing neutrino and dark matter experiments. The electromagnetic properties of neutrinos also influence several interesting astrophysical objects, such as supernovae [3,4], and can thus be probed by observing a future galactic supernova. It could also lead to testable consequences in future neutrino telescopes, which are designed for EeV cosmogenic neutrino detection [5,6]. Furthermore, the particles related to those new effects would show up at upcoming collider experiments or in rare decays, and moreover generate additional interactions of neutrinos (NSI), which cause observable effects in neutrino oscillations and scattering experiments.

References:
[1] K.S. Babu, Sudip Jana, Manfred Lindner; JHEP 10 (2020) 040, DOI: 10.1007/JHEP10(2020)040
[2] K.S. Babu, Sudip Jana, Manfred Lindner, Vishnu P.K.; JHEP 10 (2021) 240, DOI: 10.1007/JHEP10(2021)240
[3] Sudip Jana, Yago P. Porto-Silva, Manibrata Sen; JCAP 09 (2022) 079, DOI: 10.1088/1475-7516/2022/09/079
[4] Evgeny Akhmedov, Pablo Martínez-Miravé; JHEP 10 (2022) 144, DOI: 10.1007/JHEP10(2022)144
[5] Guo-yuan Huang, Sudip Jana, Manfred Lindner, Werner Rodejohann, arXiv: 2204.10347 [hep.ph]
[6] Alexei Y. Smirnov, Andreas Trautner, arXiv: 2211.00634 [hep-ph]



1.3 Beyond the Standard Model

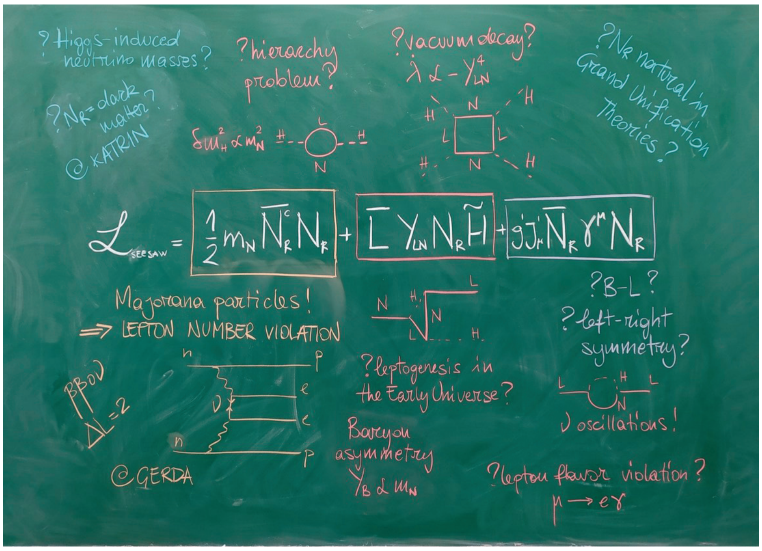
Elementary particles of the Standard Model (black background) and hypothetical particles.

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 in 2012 opened a number of fundamental questions that are addressed by theoreticians at the MPIK.

An extension of the Standard Model of elementary particle physics is required by dark matter, non-zero neutrino masses, the baryon asymmetry of the Universe and other experimental facts. Furthermore, there exist theoretical deficiencies which also require an extension. This leads to new physics which could either show up at high energies or at precision measurements testing so-called hidden sectors. Theoreticians of the MPIK are studying such extensions which can explain the experimental effects beyond the Standard Model or the theoretical shortcomings. Examples are based on extended symmetries such as conformal or 'grand unified' theories.

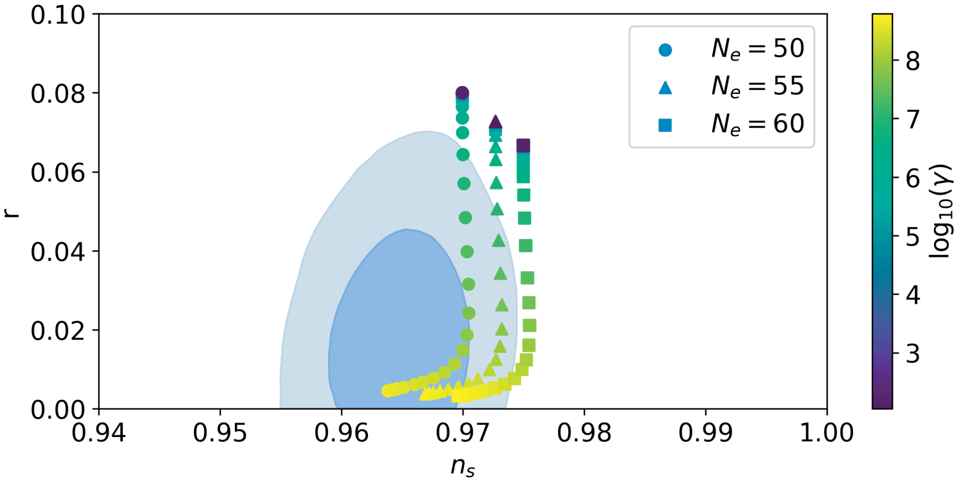
A lot of theoretical work is done on the origin of neutrino masses and mixings via basic and phenomenological studies. The so-called seesaw mechanism is a way to explain the smallness of neutrino masses based on the presence of new heavy particles, which are in fact predicted by many theories beyond the Standard Model. Another focus topic are theories and the phenomenology of various dark matter candidates and interconnections to the other problems of the Standard Model. Neutrino masses and dark matter may, for example, have a common origin. Similarly, alternative electro-weak symmetry breaking mechanisms or the thermal history of the Universe often lead to constraints or connections between the various topics. The overall aim is a deeper understanding of the fundamental laws of nature by including all available experimental facts and hints for new physics of laboratory experiments, cosmology and astronomy.



Blackboard sketch of a theorist's discussion about the various implications of new elementary particles, in the case, massive right-handed neutrinos.

Conformal models of inflation

Two of the most puzzling unresolved issues in high-energy physics today are the hierarchy problem and the scale-invariant nature of the primordial power spectrum. A gravitational model based on global conformal symmetry has been proposed that addresses both issues by dynamically generating the Planck scale, electroweak scale, and inflationary potential. When scale-invariant quadratic gravity is coupled to an external scalar field (the inflation), it has been shown that quantum effects arising from the Coleman-Weinberg potential give rise to the very notion of mass, relate the two of most important mass scales in physics, and lead to inflationary predictions that satisfy the most stringent modern experimental constraints. This model is also able to generate masses for both Standard Model and additional right-handed neutrinos, the latter of which were shown to produce a satisfactory dark matter abundance.



Predictions for the scalar spectral index n_s and the tensor-to-scalar ratio r with varying number of e-folds N_e. The value of the Ricci scalar squared coupling γ is indicated by the colour scale. Experimental constraints from Planck collaboration are given by the shaded blue regions at 68% and 95% confidence levels.

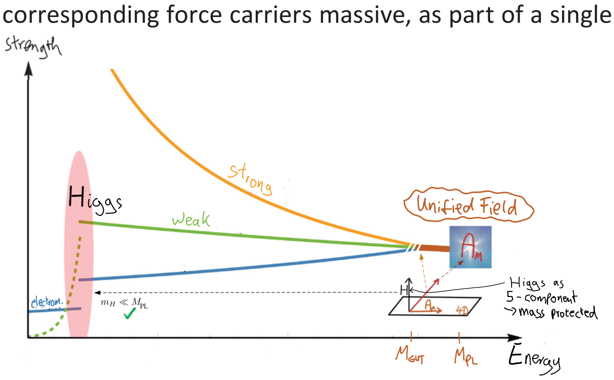
Reference:
Kubo, J.; Kuntz, J.; Lindner, M.; Rezacek, J.; Saake, P.; Trautner, A., JHEP 16 (2021), DOI:10.1007/JHEP08(2021)016

Constructing a viable theory that unifies the fundamental interactions of nature

The fundamental interactions observed in nature – the electromagnetic interaction, the weak and the strong nuclear force, as well as gravity – can be described in terms of 'gauge' symmetries in a mathematical language. It is a long-standing dream of fundamental physics to unify these basic interactions in a single fundamental structure at high energies. For the first three forces, this has been achieved in a so-called 'grand unified theory' (GUT), based on a single symmetry group with the prominent minimal example of a special unitary SU(5) group. Such straightforward realisations, however, come with various problems, some of which include too fast proton decay and the so-called hierarchy problem.

The latter denotes the fact that the scale suppressing the weak interactions (i. e., the Higgs scale) receives large quantum corrections that pull it towards the (way too large) scale of grand unification or the Planck scale MPL, which would make the corresponding interaction strength by many magnitudes smaller than it is found to be.

In [1,2,3] we presented a novel GUT that solves the mentioned problems (and more), by taking the concept of unification one step further. The proposed model describes (unified) gauge interactions and the famous 'Higgs' sector, which makes the corresponding force carriers massive, as part of a single structure – namely a five-dimensional gauge field AM (see figure).



By employing a warped extra dimension and a novel symmetry pattern, all problems of earlier attempts are solved, the Higgs gets naturally much lighter than MPL and also a successful model of flavour is presented [3] – predicting a viable hierarchical pattern of fermion masses and quark mixings.

Exciting signatures of the setup would be new resonances at the teraelectronvolt scale, in reach of future colliders, unveiling the unified structure. Moreover, the extended scalar sector could help to address further puzzles, like the emergence of a Universe full of baryons, which we will explore connecting to the analysis we recently completed in a related context [4].

References:
[1] Angelescu, Bally, Blasi, Goertz, Phys. Rev. D 105, 035026 (2022), DOI: 10.1103/PhysRevD.105.035026
[2] Angelescu, Bally, Blasi, Goertz, PoS 398 ((EPS-HEP2021)698 (2022), DOI: 10.22323/1.398.0698
[3] Angelescu, Bally, Goertz, Weber, arXiv:2208.13782 [hep-ph], DOI: 10.48550/arXiv.2208.13782
[4] Angelescu, Goertz, Tada, J. High Energy Phys. (2022), DOI: 10.1007/JHEP10(2022)019

Matter and Antimatter – Search for a Crucial Difference

There is no indication that anywhere in the visible Universe considerable amounts of antimatter exist. This is a problem since particles and antiparticles are expected to be created in equal amounts in the Big Bang and they should have completely annihilated, leaving a Universe filled only with radiation. Today's Universe requires therefore a new mechanism able to explain the so-called baryon asymmetry.

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.

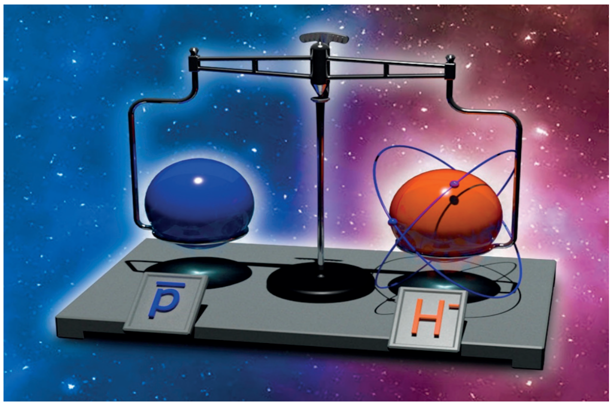


Illustration of the experimental comparison of the mass-to-charge ratios of the antiproton and the negative hydrogen ion. (Graphics: BASE collaboration)

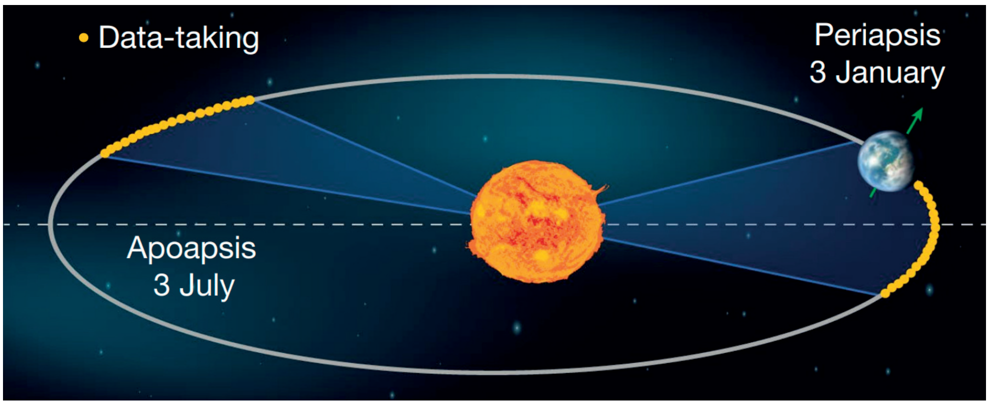
The LHCb experiment at the Large Hadron Collider (LHC) of CERN in Geneva searches for matter/antimatter differences. Besides many other particles, in proton-proton collisions so-called B-mesons are created, heavy particles consisting of each a light quark and a heavy antiquark; and reversely for their 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 will test this puzzle more stringent.

Record measurement of antiproton charge-to-mass ratio constrains anomalous antiparticle gravitation

The striking imbalance between matter and antimatter in our Universe is one of the mysteries in modern physics, since we expect to find equal amounts of matter and antimatter from our theory. Moreover, we also expect that matter and antimatter experience the same gravitational force – a hypothesis that has however never been experimentally observed so far.

Researchers of the MPIK and the BASE collaboration reported in 2022 on the most precise comparison of the charge-to-mass ratio of protons and antiprotons with 16 parts per trillion uncertainty and a factor of four times more precise than before. This measurement also provided constraints on the anomalous gravitational behaviour of the antiproton because the measurement consists in total of about 24 000 proton and antiproton cyclotron frequency measurements, taken over the course of 1.5 years. During this period the antiproton was placed in a different gravitational potential due to the elliptic orbit of the Earth around the Sun. Since we did not find any deviation in the cyclotron frequency of proton and antiproton along the orbit of the Sun, we concluded that the difference in the gravitational force must be smaller than 3%. This study constitutes the first differential test of the weak equivalence principle for baryonic matter/antimatter clocks.



Positions along the elliptic orbit of the Sun where the antiproton and proton charge-to-mass ratio was measured.

Reference:
M. J. Borchert, J. A. Devlin, S. R. Erlewein et al., Nature 601, 53–57 (2022), DOI: 10.1038/s41586-021-04203-w

Quantum Dynamics

2

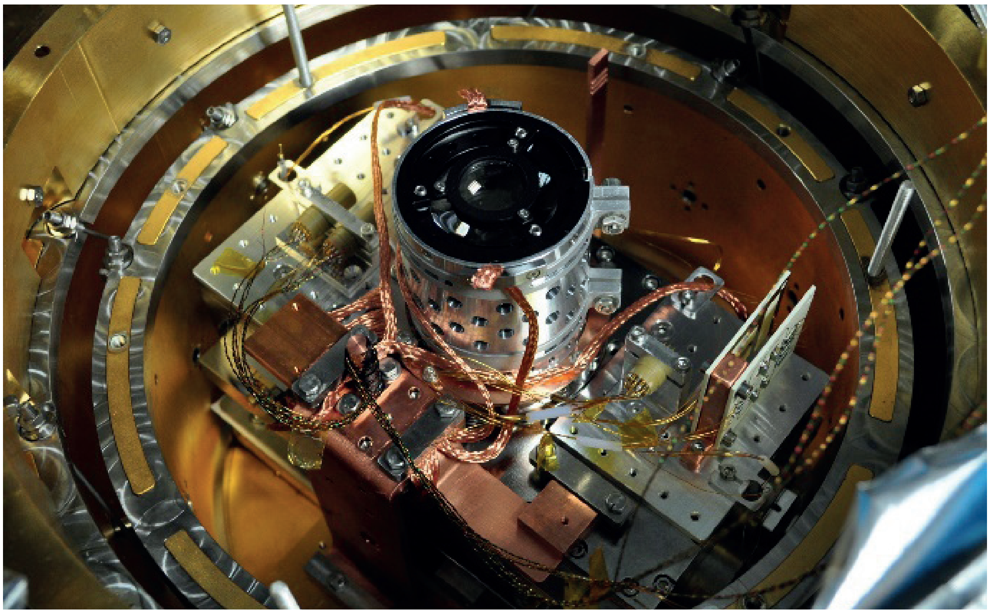
2.1 Highest Precision

An extremely precise atomic balance: PENTATRAP consists of five identically constructed Penning traps arranged one above the other. In these traps, two ions can be simultaneously measured in comparison. In order to minimise uncertainties, the ions are moved back and forth between different traps.

Ion Traps

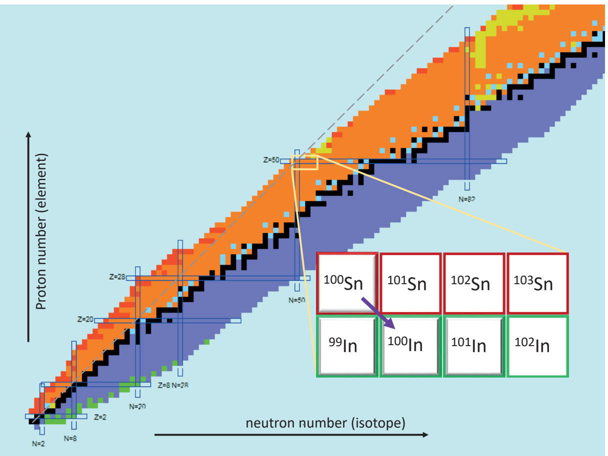
Ions can be stored in traps by the superposition of electric and magnetic fields in an extreme vacuum. Penning traps allow storage of a single ion that performs a characteristic oscillating motion in the trap. The ion's mass and further properties like magnetic moments of the bound electron in highly 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 nuclei 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 the framework of the BASE collaboration at CERN a new method for sympathetically cooling of protons using laser-cooled beryllium ions was implemented. In the future, this method will also be applied to antimatter. Recently, the charge-to-mass ratios of antiprotons and protons were found to be identical to eleven significant digits.

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 a novel superconducting trap for precise frequency measurements. Crystals of highly charged ions can be prepared with laser light and kept almost undisturbed over a longer period of time: a promising realisation of long-lived qubits. It is part of the BMBF quantum technology project Many-Frequency Control of Ultra-stable Qubits in Superconducting Ion Traps which started at the MPIK on 1 September 2021.



Superconducting radio-frequency ion trap in a vacuum chamber inside cryogenic thermal shields for operation at 4 K.

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



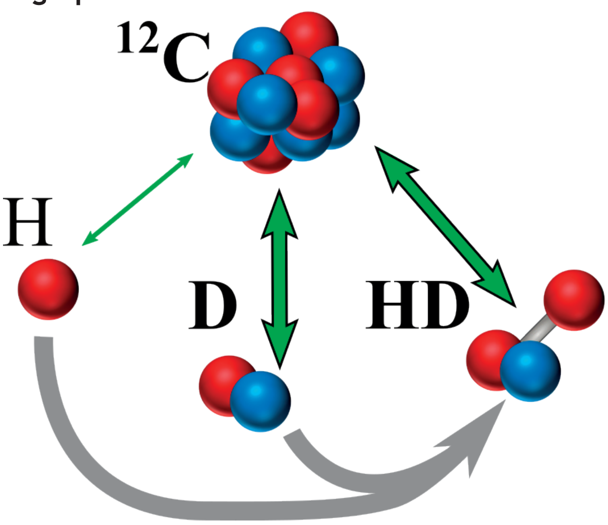
The exotic tin-100 and some of its measured and calculated neighbouring isotopes as an enlarged section of the nuclear chart (nuclei marked in black are stable, the other colours stand for different decay modes; the blue open bars mark the magic numbers and the dashed grey line connects nuclei with the same proton and neutron number). The purple arrow shows the decay of tin-100 to indium-100.

Penning-trap mass spectrometry at MPIK allowed to perform world-record measurements of the atomic masses of the electron and hydrogen isotopes. Both the proton and deuteron masses were found to be smaller than the previously accepted values. 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.

High-precision measurement of the deuteron's atomic mass



Summary of all currently measured light ion masses referenced to ^{12}C with the LIONTRAP experiment (green arrows). The agreement of the HD mass based on its constituents' masses and the binding energy (grey arrows) realises an independent internal cross check.

The rest masses of the proton, deuteron, triton and helion are very important to verify our understanding of physics for example to test quantum electrodynamics (QED) and search for 5th forces. The most precise 3-body QED tests compare rovibrational energies of the HD^+ molecular ion with their corresponding theoretical predictions at the low 10^{-11} level [1]. For these tests, accurate particle masses at the same level are required as input parameters. Recent inconsistency in these masses, determined with different mass spectrometers known as light ion mass puzzle, strongly calls for additional independent measurements.

The deuteron mass measurement was carried out at the LIONTRAP experiment, where the proton's atomic mass has already been determined with a relative precision of 3×10^{-11} [2]. Here a non-destructive comparison of the cyclotron frequencies of a single trapped highly charged carbon ion and the ion of interest is carried out. The inhomogeneous magnetic field has been the dominant systematic uncertainty of the proton mass measurement, but it was reduced by a factor of 50 for the deuteron campaign. This enabled the so far most precise mass measurement in atomic mass units resulting in a relative uncertainty of only 9×10^{-12} [3]. Although the value for the deuteron mass is 5σ smaller than the previous literature value, it is confirmed by another direct measurement of the HD^+ mass. Additionally, it also reduces the light ion mass puzzle and agrees with the recent HD^+ spectroscopy results [1]. This measurement encourages further investigations of the remaining light ion masses at the LIONTRAP experiment.

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[1] M. Germann et al., Phys. Rev. Res. 3, L022028 (2021), DOI: 10.1103/PhysRevResearch.3.L022028
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[3] S. Rau et al., Nature 585, 43-47 (2020), DOI: 10.1038/s41586-020-2628-7

How magnetic is ^{3}He?

The hyperfine structures of hydrogen-like ions are a unique gateway to access nuclear magnetic moments and nuclear structure. Hence, while eliminating the ignorance of essential links in metrology due to insufficiently known moments, at the same time these ions provide complementary insight into the dynamic and static properties of the inner nucleon. The very recently started ^{3}He experiment exploits these characteristics to provide a new standard for absolute precision magnetometry and determine the nuclear charge and current distribution of ^{3}He.

To this end, a novel Penning-trap experiment was designed and built. Using novel techniques the advanced four Penning-trap system enables non-destructive measurements of the nuclear quantum state and is prepared to perform sympathetic laser cooling of single, spatially separated ions to sub-thermal energies [1].

In the first measurement campaign, ^{3}He was investigated by exciting microwave transitions at 140 GHz likewise 4 GHz between the ground-state hyperfine states. This enabled us to determine the nuclear g-factor, the electronic g-factor and the zero-field ground-state hyperfine splitting of ^{3}He$^+$ with a precision of 5×10^{-10}, 3×10^{-10} and 2×10^{-11}, respectively [2].

Our measurement constitutes the first direct determination of the ^{3}He$^+$ nuclear magnetic moment. The result is of utmost relevance for absolute precision magnetometry, as it allows the use of He NMR probes as an independent new standard with much higher accuracy. In addition, the comparison to advanced theoretical calculations enables us to determine the size of the ^{3}He nucleon with a precision of 2.4×10^{-17} m.

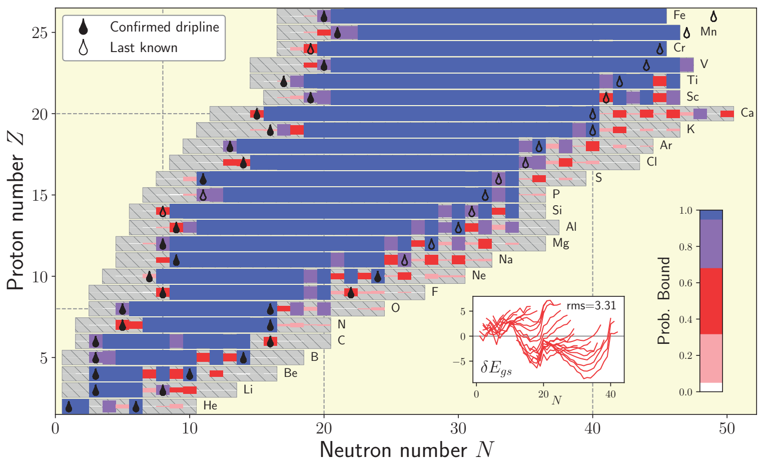
In future, the magnetic moment of the bare ^{3}He^{2+} nucleus will be measured employing sympathetic laser cooling. To this end, a novel 13-pole Penning trap for an improved coupling of spatially separated ions as well as a Penning trap for improved detection fidelities for the nuclear spin state have been designed and built [3].

References:

[1] A Mooser et al., J. Phys.: Conf. Ser. 1138, 012004 (2018), DOI: 10.1088/1742-6596/1138/1/012004
[2] A. Schneider et al., Nature 606, 878 (2022), DOI: 10.1038/s41586-022-04761-7
[3] A. Schneider et al., Ann. Phys. 531, 1800485 (2019), DOI: 10.1002/andp.201800485

Strong interactions and exotic nuclei

In the physics of nuclei, there have been rapid advances in the past years combining ab initio many-body methods with nuclear forces based on chiral effective field theory of the strong interaction, QCD. We have proposed and developed a powerful and flexible ab initio approach, the in-medium similarity renormalization group (IMSRG), which has enabled systematic calculations of nuclei up to 100 nucleons. Using the IMSRG, we explored the limits of existence of nuclei, the proton and neutron drip lines, from the light through medium-mass nuclei, based on a chiral effective field theory interaction and including theoretical uncertainties [1]. This first global ab initio calculation up to iron is shown in the figure. Remarkably, where the drip lines are known experimentally, our predictions are consistent within estimated uncertainties.



Global ab initio calculations of nuclei up to iron [1]. The gray region indicates all 700 nuclei calculated with the IMSRG, while the colour and height of each square corresponds to the estimated probability that a given nucleus is bound. This is compared to the experimentally confirmed drip lines or the last known isotope.

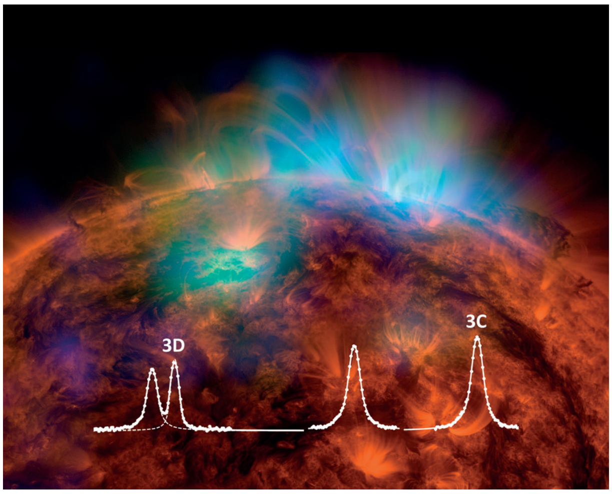
These advances have great synergies with the experimental frontiers in exotic nuclei, as neutron-rich nuclei are sensitive to new aspects of nuclear forces. For example, three-nucleon forces are key to explain the limits of bound isotopes and how magic numbers emerge. Recent highlights of our joint experiment-theory investigations focused on nickel and indium isotopes: We have explored the evolution of charge radii from $^{58\text{-}70}$Ni [2], the emergence of the doubly magic nature of ^{78}Ni [3], and the masses of indium isotopes near ^{100}Sn [4].

References:

[1] S.R. Stroberg, J.D. Holt, A. Schwenk, J. Simonis, Phys.Rev.Lett. 126, 022501 (2021), DOI: 10.1103/PhysRevLett.126.022501
[2] S. Malbrunot-Ettenauer et al., Phys.Rev.Lett. 128, 022502 (2022), DOI: 10.1103/PhysRevLett.128.022502
[3] R. Taniuchi et al., Nature 569, 53 (2019), DOI: 10.1038/s41586-019-1155-x
[4] M. Mougeot et al., Nature Phys. 17, 1099 (2021), DOI: 10.1038/s41567-021-01326-9

Highly Charged Ions – Matter under Extreme Conditions

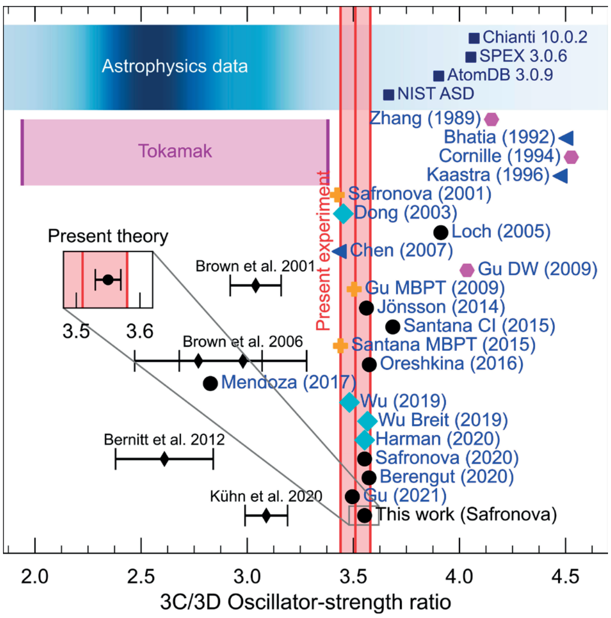
In fact, most of the visible matter in the Universe is assumed to be highly ionized. Analysis of the observed light (visible, UV, or x-ray) from these ions needs support by theoretical structure calculations which are often not accurate enough to determine, e. g., the temperature of the hot environment. The controlled production of highly charged ions (HCI) 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 resolved a key astrophysical problem.



X-ray fluorescence spectrum of highly charged iron ions, background: the Sun in x-ray light (© NuStar, NASA).

The cryogenic ion trap CryPTEx provides efficient cooling of trapped HCIs by means of laser-cooled Be^{+} ions 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 next generation of CryPTEx focuses on extremely stable trapping conditions by isolating mechanical vibrations. Furthermore, a novel superconducting Paul trap resonator will enable precise localisation and strong confinement of HCIs in low-noise trapping potentials. With PENTATRAP, tiny differences in mass between different quantum states are measured providing new insights into heavy atoms. Thereby, a previously unobserved quantum state in rhenium was discovered, which could be interesting for future atomic clocks. At ALPHATRAP, the ground-state *g*-factors of highly charged ions can be measured with uncertainties at the 10^{-12} level. This provides an impressively precise test of the Standard Model of particle physics, allowing conclusions regarding the properties of nuclei and setting limits for new physics and dark matter.

A tale of two lines



Our new experimental data (vertical band) confirm recent large-scale calculations that demonstrated numerical convergence and unequivocally point to problems in earlier measurements, astrophysical observations, and theory.

Megakelvin plasmas are ubiquitous in the Universe and drive its evolution together with gravitation. X-ray observatories already in space, and upcoming missions aim at diagnosing them. To do so, theoretical models have to be benchmarked by experiments simulating those conditions. Highly charged ions (HCI) of iron (Fe) are crucial for this: Near black holes, x-rays from Fe^{25+} ions are the last visible spectroscopic signal of matter, and soft x-ray lines from Fe^{16+} dominate in a multitude of other hot objects. Plasma diagnostics based on Fe^{16+} is an essential tool, in spite of having suffered from a puzzle over four decades: Astrophysical and laboratory data on its two strong transitions dubbed 3C and 3D showed intensity ratios incompatible with calculations. This casted doubt into the general methods needed for calculating many-electron ions. In a series of experiments [1,2], we performed measurements at PETRAIII (DESY) with a miniature electron beam ion trap (EBIT) storing Fe^{16+}. We reached the highest ever reported soft x-ray resolution, and revealed extended wings of the lines, containing hitherto unaccounted-for intensity. With unprecedented accuracy, these results confirmed advanced atomic structure theory calculations. Two independent, numerically massive calculations reached convergence and agreed mutually, as well as with the experiment. This finally solves the long-standing mystery, and proves that such state-of-the art calculations for complex many-electron systems including quantum electrodynamics corrections and relativistic mass shifts can be trusted at the 3% level.

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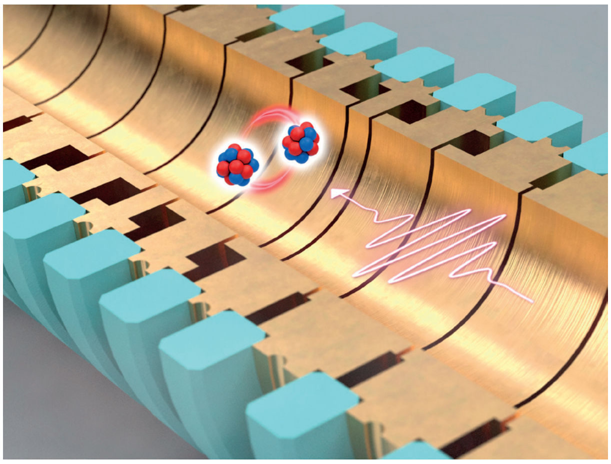
[1] S. Kühn et al. PRL 124, 225001 (2020), DOI: 10.1103/PhysRevLett.124.225001

[2] S. Kühn et al., 129, 245001 (2022), DOI: 10.1103/PhysRevLett.129.245001

Measurement of the bound-electron *g*-factor difference in coupled ions

From the beginnings of quantum electrodynamics, the electron's magnetic moment has played an extraordinary role for the understanding of the fundamental laws of atomic and subatomic physics. The precise determination of the *g*-factor, which expresses the magnetic moment relative to the Bohr magneton, has enabled stringent tests of the foundations of the Standard Model. By binding the electron to a highly charged nucleus, we are able to extend these tests to the regime of the strongest electromagnetic fields. With the ALPHATRAP experiment at MPIK we have pushed the precision to 11 significant digits, where a growing number of tiny, but fundamentally interesting effects becomes visible. At that point, unavoidable fluctuations of the magnetic field impede further progress. Recently however, we have achieved a conceptual breakthrough by crystallising two ions in the same trap (in this case two isotopes of hydrogenlike neon), which largely rejects magnetic field fluctuations. This new technique allowed us to directly determine the difference of *g* for the two ions with 13 digits sensitivity, 2 orders of magnitude better than ever before. At that level, exciting new effects, such as the QED recoil, can be observed. The measured value still agrees with the theoretical prediction even at that precision. This means the Standard Model not only, once again, passes with flying colours – but, beyond that, our result strongly bounds the properties of dark matter candidates.



Two hydrogenlike neon ions, one $^{22}Ne^{9+}$ and one $^{20}Ne^{9+}$, are trapped on a common crystal orbit around the trap centre. This way, both ions see exactly the same magnetic field, enabling us to measure the difference of their magnetic moments with utmost precision.

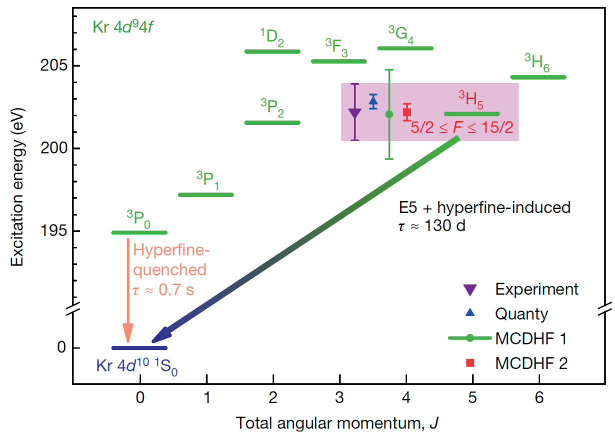
Reference:
T. Sailer, V. Debierre, Z. Harman, F. Heiße, C. König, J. Morgner, B. Tu, A. V. Volotka, C. H. Keitel, K. Blaum & S. Sturm, Nature 606, 479–483 (2022), DOI: 10.1038/s41586-022-04807-w

Detection of metastable electronic states by Penning trap mass spectrometry

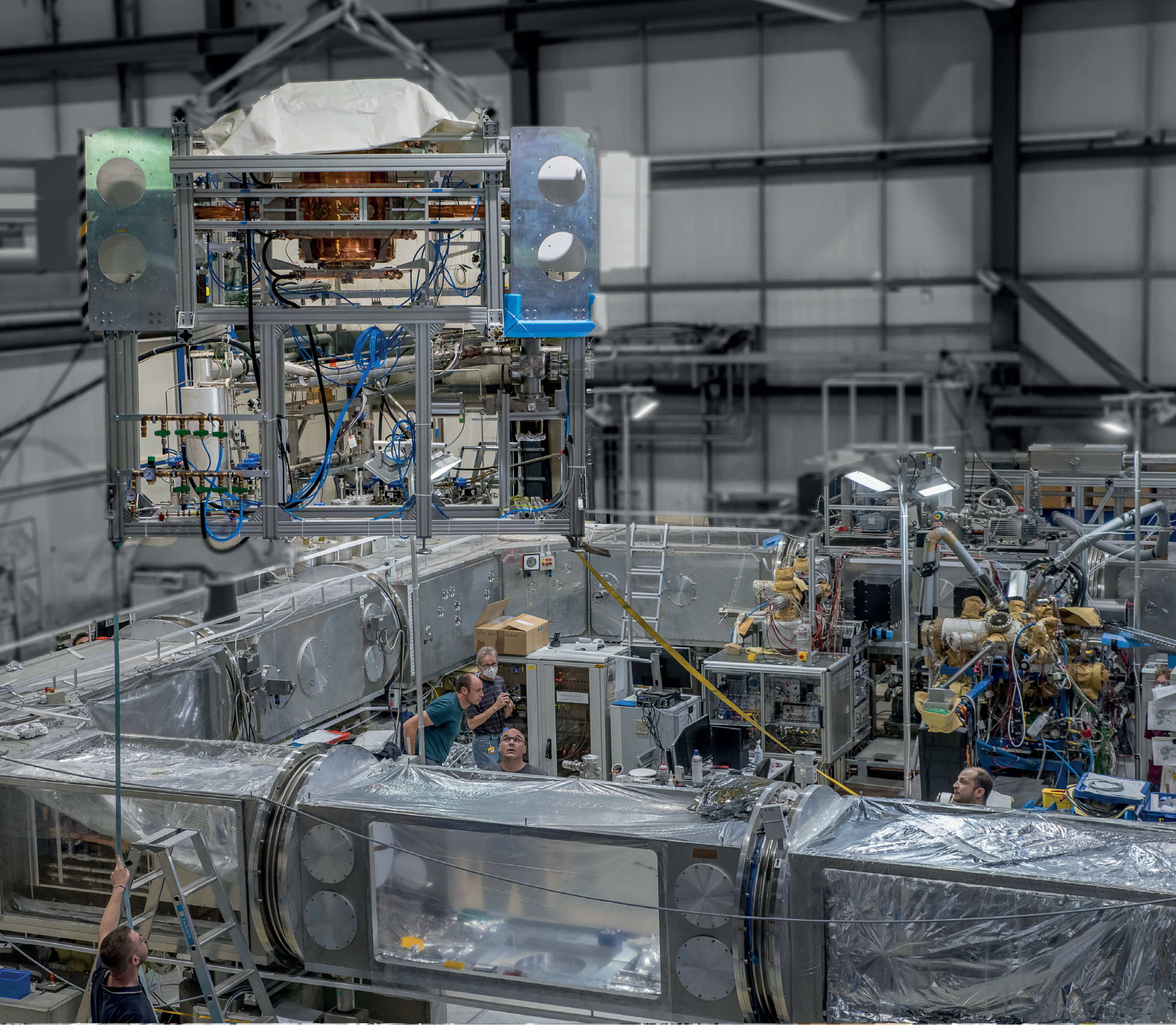
Modern clocks and frequency standards range from ensembles of neutral particles trapped in optical lattice clocks to individual, singly charged ions confined in Paul traps. With a fractional frequency accuracy of 10^{-18}, such clocks enable stringent tests of fundamental symmetries (for example, Lorentz invariance), geodetic measurements and searches for new physics and dark matter.

A further boost of precision is offered by next-generation atomic clocks based on highly charged ions (HCIs). The compact size of HCIs in comparison with atoms makes them less sensitive to external field fluctuations. Although electronic binding energies in HCIs typically amount to several kiloelectronvolts and inter-shell transitions usually appear in the x-ray region, there are also intra-shell fine and hyperfine transitions in the optical and ultraviolet range. Such transitions can be accessible to frequency combs and thus their frequencies can be measured very precisely.

However, insufficiently accurate atomic structure calculations hinder the identification of suitable transitions in HCIs and thus call for alternative methods of searching for such transitions. Recently we have demonstrated how high-precision Penning-trap mass spectrometry directly identifies a suitable clock transition in HCIs by measuring the mass difference between the atomic ground and a metastable state in rhenium $^{187}Re^{29+}$), providing a non-destructive, direct determination of an electronic excitation energy. The result is in agreement with advanced calculations. We use the high-precision Penning-trap mass spectrometer PENTATRAP to measure the cyclotron frequency ratio of the ground state to the metastable state of the ion with a precision of 10^{-11}. With a lifetime of about 130 days, the potential soft-x-ray frequency reference at 4.96×10^{16} hertz (corresponding to a transition energy of 202 electronvolts) has a linewidth of only 5×10^{-8} hertz and one of the highest electronic quality factors (10^{24}) measured experimentally so far. The low uncertainty of our method will enable searches for further soft-x-ray clock transitions in HCIs, which are required for precision studies of fundamental physics.



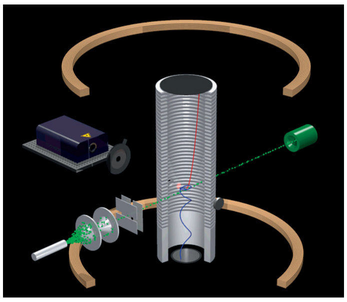
Reference:
R. Schüssler et al., Nature 581, 42-46 (2020), DOI: 10.1038/s41586-020-2221-0



2.2 Atomic and Molecular Dynamics

The Cryogenic Reaction Microscope (CSR-ReMi) is transferred by crane from its nearby pre-assembly area, and guided by the team to its foreseen place in the Cryogenic Storage Ring (CSR), where it is now integrated for final checks before commissioning.

Reaction Microscopes and Absorption Spectrometers



Scheme of a reaction microscope.

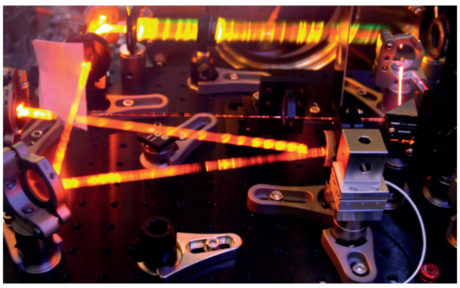
Reaction microscopes – "the bubble chambers of atomic and molecular physics" – have been developed and are continuously improved at MPIK. Ultra-short intense laser pulses or particle beams induce a break-up of simple molecules. The fragment ions and electrons are caught by means of electric and magnetic fields and recorded by large-area time- and position-sensitive detectors. From the reconstructed trajectories of the fragments, their complete momentum vectors, and thus the geometry and dynamics of the molecules before their break-up, can be determined ("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, built and recently integrated. It will be a key instrument for the worldwide unique possibilities to investigate slow and cold ions in the CSR.

Time-resolved attosecond absorption spectroscopy, a complementary technological in-house development, is based on the principle of Fraunhofer: shining a broadband ("white") light source through a medium reveals characteristic dark (absorption) lines in the spectrum. With dedicated vacuum apparatuses, the quantum dynamics of small atoms and molecules are investigated down to attosecond time scales, employing light from the visible to the extreme ultraviolet (XUV) and soft x-ray range, reflecting the coherent excited-state dynamics of the system.

Ultra-short Laser Pulses – the Microcosm in Extremely Slow Motion

How does a quantum system evolve in time and is it possible to visualise 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 fs = 10^{-15} s), while the electrons which mediate the chemical bond are even faster: here, attoseconds (1 as = 10^{-18} s) are the characteristic time scale.

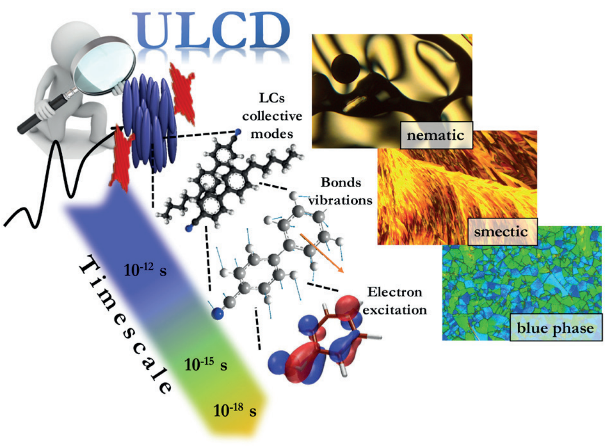
A key tool for time-resolved experiments are ultra-short intense laser pulses which are used to steer the atomic or molecular dynamics with extremely high precision. At MPIK's laser laboratories, phase-controlled laser pulses shorter than 5 femtoseconds at intensities of up to about 10^{16} W/cm^2 are available for experiments. Even shorter pulses of some attoseconds duration are generated by extreme non-linear optics. The resulting coherent high-harmonic radiation in the extreme UV range produces isolated as well as trains of attosecond pulses, which can be precisely timed relative to the broadband infrared to visible pulses of our laser systems, 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 in absorption spectroscopy setups and reaction microscopes, this allows for direct and time-resolved observation (and control) of nuclear and electronic quantum motions in chemical reactions.



Visualised beam path of an experiment for laser control of molecules.

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. Rotation of a molecule triggered by a laser pulse is used to measure the timing of the reaction that takes place in a second laser pulse. Such a "rotational clock" is a general concept applicable to sequential fragmentation processes in other molecules.

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. The broad-band spectrum of ultra-short laser pulses is used to detect the characteristics of the excitation processes within atoms and molecules – while their natural dynamics is disturbed by the intense fields of the laser. The electron pair of a helium atom can be specifically controlled in such a way that the energy levels are shifted for only fractions of the excited-state lifetime. In a molecule such as sulfur hexafluoride, the electronic exchange interaction, a pure quantum effect of a many-electron system, can be precisely controlled with a strong laser pulse on an ultra-fast time scale.



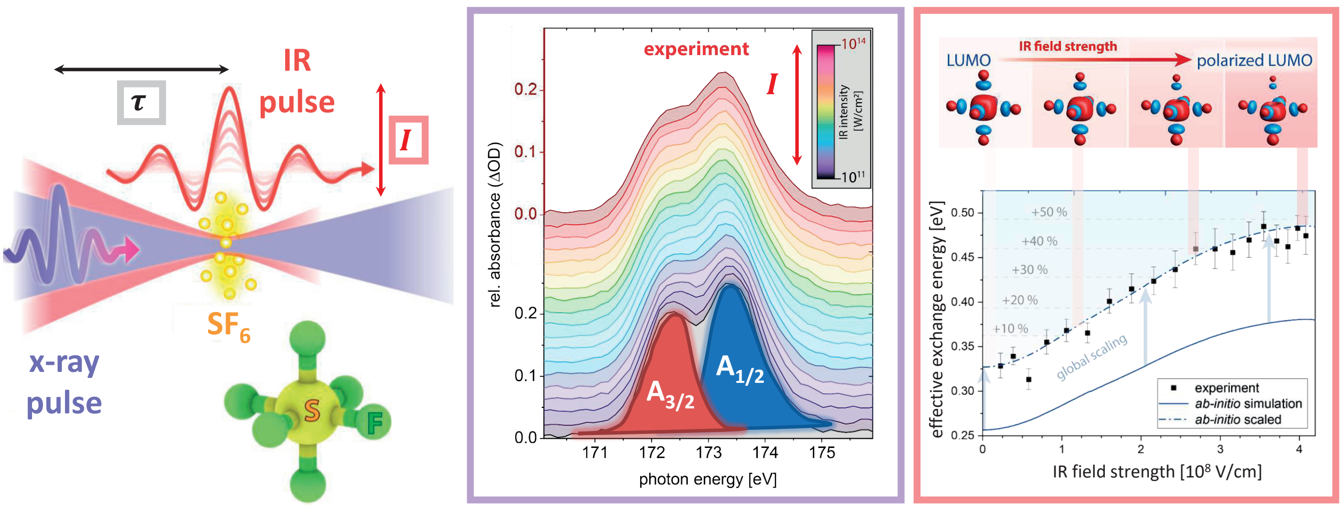
Research on ultra-fast liquid-crystal dynamics.

Experiments at the free-electron laser FLASH in Hamburg demonstrate strongly-driven non-linear interactions of ultra-short extreme-ultraviolet (XUV) laser pulses with atoms and ions. Here, powerful excitation of an electron pair in helium competes with the ultra-fast decay, which temporarily may even lead to population inversion. Resonant transitions in doubly charged neon ions were shifted in energy, and observed by XUV-XUV pump-probe transient absorption spectroscopy. Being specific to characteristic atomic transitions of core-level electrons, in such experiments the nuclear dynamics of atmospherically relevant molecules such as diiodomethane and oxygen can be time resolved.

A new topic is ultra-fast liquid-crystal dynamics focusing on the understanding of such phenomena across LCs as phase transition from isotropic (liquid) to liquid crystal and solid phase. This investigation allows to define the degree of localisation in collective molecular dynamics excited with phase-stable THz pulses

Laser-controlled structural and electronic dynamics in SF_6

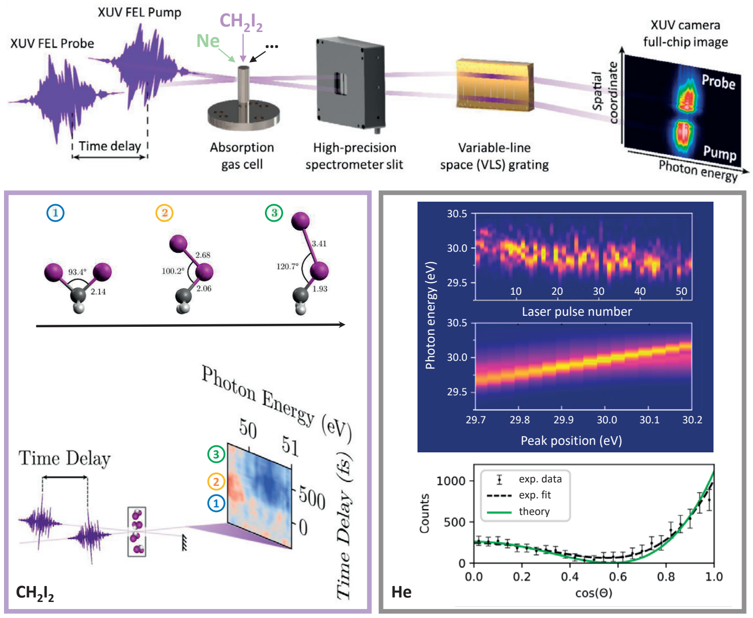
The laser-controlled structural and electronic dynamics of the SF_6 molecule is measured in the vicinity of the sulfur $L_{2,3}$ x-ray absorption edge with attosecond time-resolved absorption spectroscopy. The doublet lineshape of this transition (shown in the centre of the figure) connects a deeply bound (localised) core orbital with the (delocalised) valence orbitals of the molecule. Both quantum-mechanical spin-orbit and exchange interactions of the electrons play a role. Hereby the laser polarizes the valence orbitals of the molecule, which leads to an effective increase of the electronic exchange interaction between the valence and the core electrons in SF_6 [1], which is shown in the figure on the right. Femtosecond time-resolved x-ray absorption spectroscopy is further demonstrated to be sensitive to extremely small-scale molecular vibrations, which are quantified with a precision of only 14 femtometers [2].



References:
[1] P. Rupprecht et al., Phys. Rev. Lett. 128, 153001 (2022), DOI: 10.1103/physrevlett.128.153001
[2] P. Rupprecht et al., arXiv:2207.01290 [physics.chem-ph] (2022), DOI: 10.48550/arXiv.2207.01290

XUV-optical non-linear spectroscopy of small atoms and molecules at FLASH

A new beamline for time-resolved site-specific XUV-pump–XUV-probe transient absorption spectroscopy of atomic and molecular dynamics has been developed and successfully operated at the Free-Electron-Laser FLASH [1]. By measuring the time-delayed transmission through an absorbing neon (Ne) gas, the spectro-temporal profile of the FEL pulses can be quantified in situ [2]. The structural dynamics of diiodomethane (CH_2I_2) has been time resolved along a non-trivial dissociation pathway, both initiated and probed locally, resonant to transitions at the iodine atoms [3]. The apparatus for XUV-optical spectroscopy is now permanently installed behind the reaction microscope (ReMi) at Beamline FL26 at FLASH. This unique combination allows the coincident detection of ions, electrons and photons (spectra) on a single-shot level, enabling new experiments of fundamental AMO science and non-linear light-matter interaction. Sorting the spectral distribution of statistically fluctuating FEL pulses, the resonant photoelectron angular distribution of a two-photon-two-electron transition in helium has been resolved by high-resolution digital tuning within the much larger average FEL bandwidth [4].



References:

[1] T. Ding et al., Faraday Discuss. 228, 519–536 (2021), DOI: 10.1039/d0fd00107d

[2] T. Ding et al., Nature Communications 12, 643 (2021), DOI: 10.1038/s41467-020-20846-1

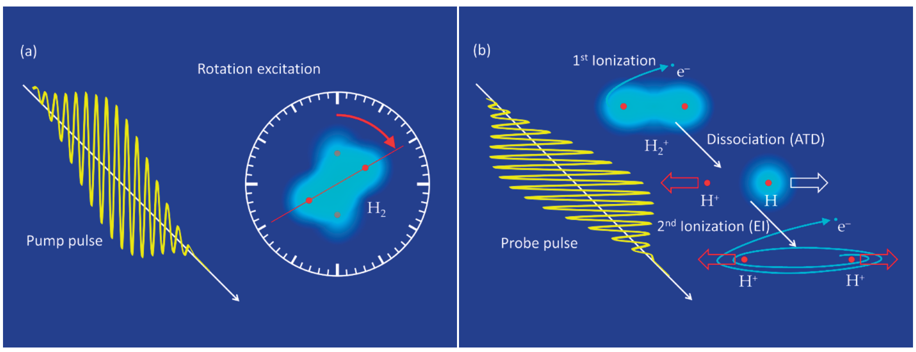
[3] M. Rebholz et al., Phys. Rev. X 11, 031001 (2021), DOI: 10.1103/physrevx.11.031001

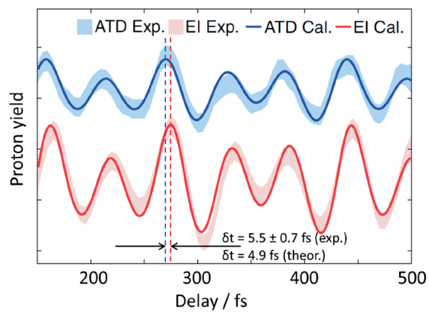
[4] M. Straub et al., Phys. Rev. Lett. 129, 183204 (2022), DOI: 10.1103/physrevlett.129.183204

A molecular "rotational clock" for the observation of fragmentation mechanisms

How does a molecule break apart in an intense laser field, and what are the time scales of processes that contribute? To answer this question and to measure the timing of fragmentation steps for the model system of molecular hydrogen, H_2, the rotation of the molecule was used as an "internal clock".

Essentially two fragmentation pathways contribute, the so-called "above threshold dissociation" (ATD) and "enhanced ionization" (EI). While the underlying mechanisms are reasonably well understood, the temporal sequence and the timing with respect to the first ionization step have not yet been measured. Both processes happen at different internuclear separations and they are both sensitive to the orientation of the molecular axis relative to the direction of the laser electric field – they happen most likely for parallel orientation. In our experiment, a weak femtosecond pump pulse excites the molecular rotation and a stronger probe pulse, which follows with a variable time delay, then ionizes the molecule and triggers the fragmentation (left figures). The two pulses are polarized perpendicular to each other. The experimental yields of ATD and EI events show an almost regular up and down, corresponding to the rotation of the molecule (right figure). In a closer analysis, however, a slight delay of approx. 5.5 fs is observed for EI compared to ATD. Using theoretical model calculations, further details can be extracted and the experimental results are very well reproduced. The "rotational clock" is a general concept that can be applied to fragmentation processes in other molecules as well.



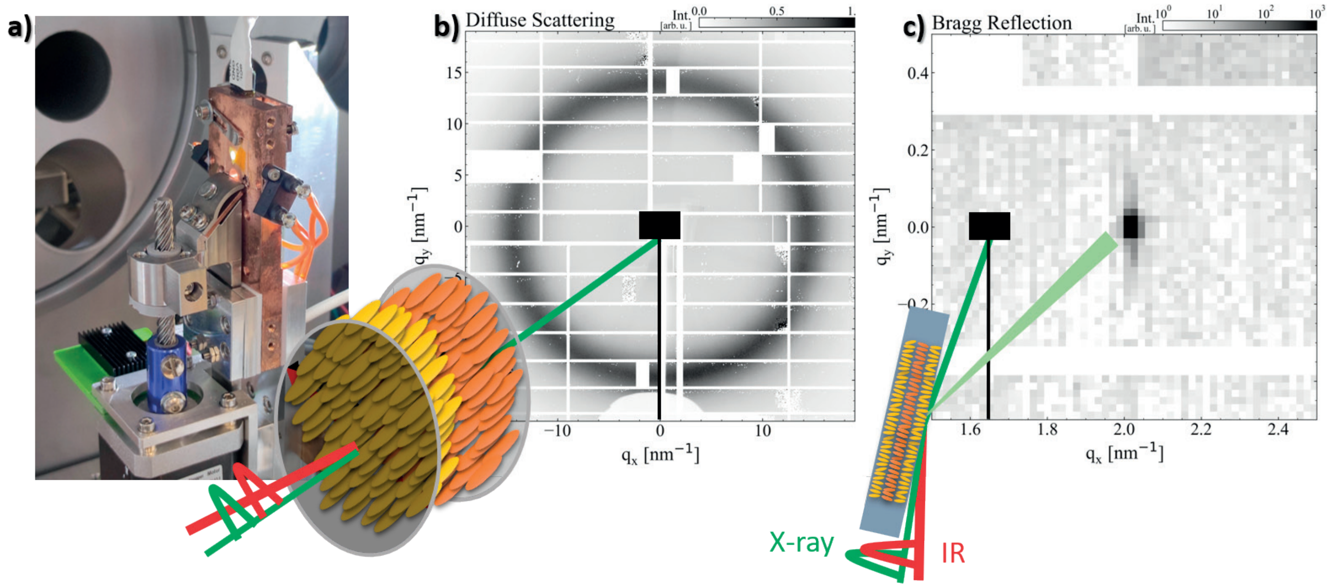


Reference:

Y. Mi et al.; Phys. Rev. Lett. 125, 173201 (2020), DOI: 10.1103/PhysRevLett.125.173201

Looking at liquid crystal dynamics from a hard x-ray point of view

Liquid crystals (LCs) are fluid-like liquids but they exhibit solid-like ordering at the molecular scale. To understand LC molecular dynamics at the picosecond time scale triggered via non-resonant excitation, we performed near-infrared pump (800 nm, 50 fs), hard x-ray diffraction probe (100 fs, 8.9 keV) on free standing films of octylcyanobiphenil (8CB) which presents a layered structure (smectic A) in the range 22 to 34°C. The key idea is to follow the impact on the 8CB x-ray diffraction pattern when low-frequencies collective molecular vibrations are laser-induced, with the aim to look at the short-range interaction among neighbouring molecules. A dedicated holder was built in collaboration with the workshops at the institute (panel a). Two different geometries were used: transmission where the diffuse scattering ring (panel b) is sensitive to intermolecular distances, and Bragg diffraction (panel c) sensitive to the smectic A inter-layer spacing.



Atomic and Molecular Collisions – Billiard Game with Quantum Balls

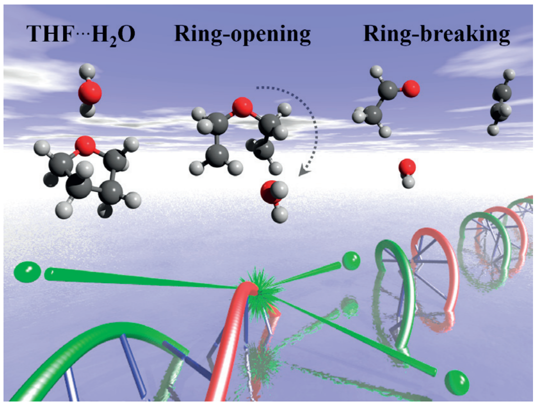
Research on correlated quantum dynamics represents one of the great challenges in contemporary science. Researchers at the MPIK explore quantum dynamics on a fundamental level, starting from a limited number of few interacting particles in atoms and molecules, and extending to more complex finite quantum 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.

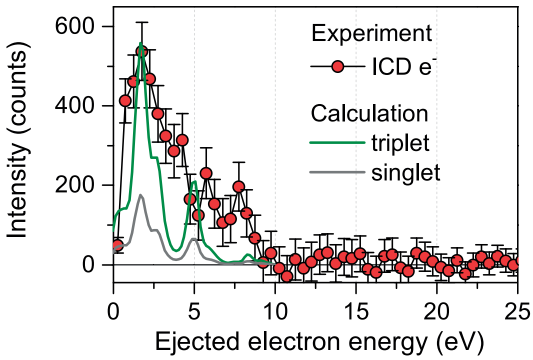
Ultra-cold Dynamics – Investigating Exotic Quantum Gases

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.

Amplification of electron-induced lesions in smallest condensed aggregates of organic molecules

Research on the elementary interactions of energetic radiation with organic and biologically relevant molecules can advance applications in medical treatment like radiation therapy and help to improve its effectiveness. Using multi-particle imaging spectrometers (reaction microscopes) we study the impact of electrons on molecular pairs (dimers) and larger clusters and could find hitherto unrecognised reaction pathways. For the tetrahydrofuran-water dimer (THF···H_2O) indicated in the upper figure we observed efficient molecular ring break for ionization of even the least bound electron where a single tetrahydrofuran monomer would stay intact [1]. We showed that the rearrangement of the water molecule bound to the THF ion releases sufficient vibrational energy to overcome the relevant reaction barriers. Similarly, in ionized methanol dimers new and fast dissociation channels were found. These outpace and, therefore, suppress slow channels occurring in the monomer like the "roaming" of an abstracted H_2 molecule in the vicinity of the methanol [2]. Lastly, we identified an intermolecular energy transfer and a subsequent Coulomb explosion reaction in weakly bound aromatic benzene pairs [3]. This intermolecular Coulombic decay (ICD) can be a blueprint for similar reactions across the hydrogen bonds of DNA base pairs or in folded protein chains. The lower figure shows the spectrum of the emitted ICD electrons. All observations were supported by theory and ab initio molecular dynamics simulations.





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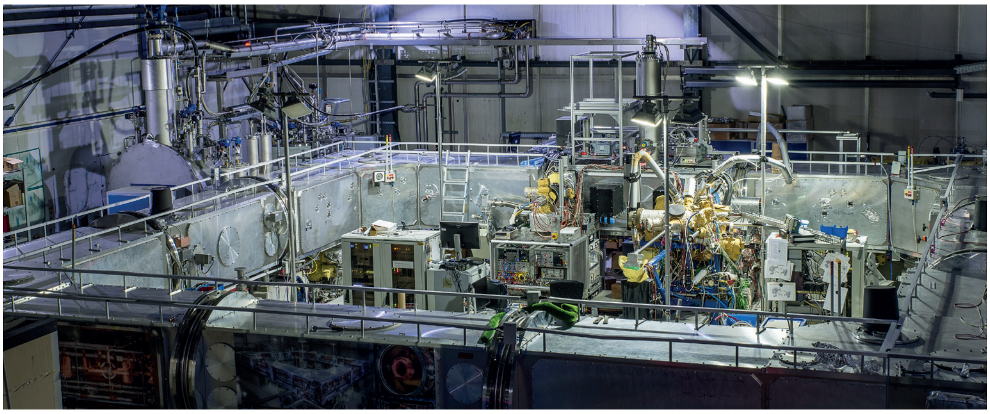
[1] *E. Wang et al., Nat. Comm. 11, 2194 (2020), DOI: 10.1038/s41467-020-15958-7*
[2] *E. Wang et al., Phys. Rev. Lett. 126, 103402 (2021), DOI: 10.1103/PhysRevLett.126.103402*
[3] *X. Ren et al., Nat. Chem. 4, 232 (2022), DOI: 10.1038/s41557-021-00838-4*

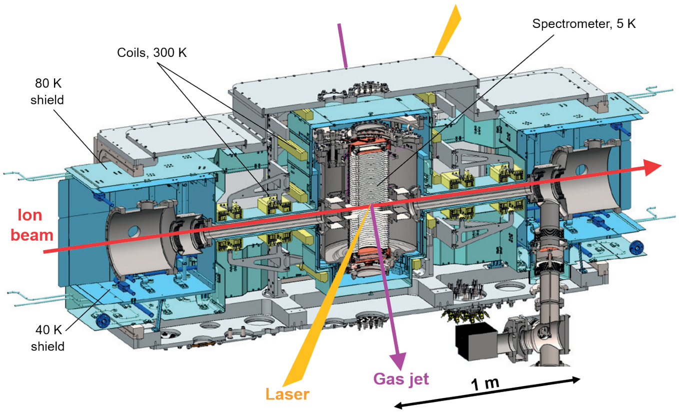
The Cryogenic Storage Ring

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. Besides beam diagnostics, instrumentation comprises particle detectors, a laser system, and the novel reaction microscope. The innovative mechanical concept of the CSR was developed and realised in close cooperation with MPIK's engineering design office and precision mechanics shop.

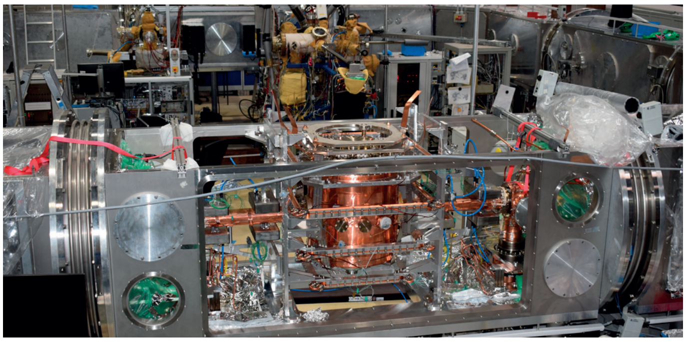


The cryogenic storage ring CSR with the electron cooler.

The CSR-ReMi - a reaction microscope for molecular break-up studies in the CSR



Design of the CSR-ReMi with its main components including projectile and target beams.



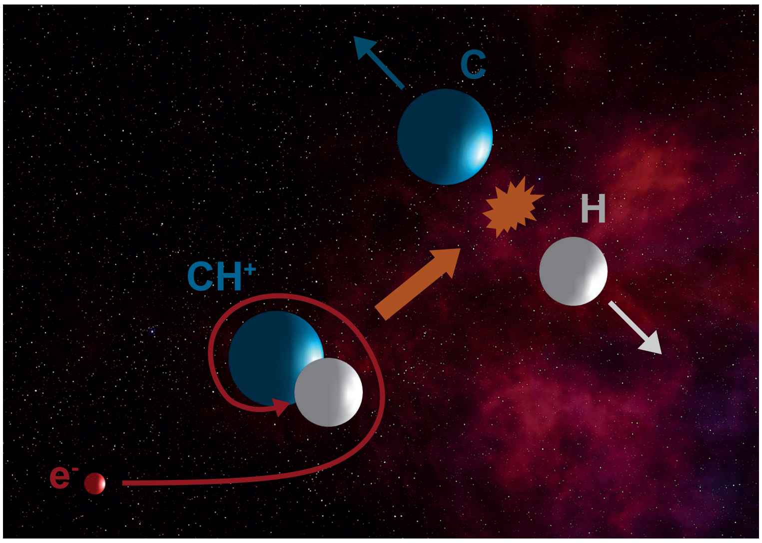
Photograph during CSR-ReMi installation into the storage ring.

Reaction microscopes (ReMi) are combined electron and ion spectrometers for energy and angular resolved detection of fragments emerging from individual collision events. In order to use this powerful technique for experiments with beams of slow and cold molecular ions and clusters inside the electrostatic cryogenic storage ring CSR, we designed a dedicated in-ring spectrometer, the CSR-ReMi. It is the first cryogenic reaction microscope worldwide (see figures).

The implementation of the fully constructed machine into the CSR started in May 2022. After its integration, which is expected to be finalised at the beginning of 2023, first test experiments with stored cold molecular ions are envisaged for spring 2023. Possible experiments include reactions like electron or even proton transfer, photodetachment or collisional ionization, and molecular break-up reactions of any kind.

The CSR-ReMi will significantly widen the spectrum of scientific applications at the CSR infrastructure. As a next step, in combination with a high-power femtosecond laser, time-resolved experiments on state-prepared molecules using established pump-probe techniques are planned. In all cases, the CSR-ReMi will be instrumental to unravel the dynamics of molecular fragmentation and relaxation processes.

Laboratory Astrophysics – the Chemistry of Space



Dissociative recombination of a methylidine ion in interstellar molecular clouds. A free electron traversing through space is attracted and captured by the positively charged CH^+ ion. The energy released in this process blows the molecule apart into a carbon (C) and hydrogen (H) atom.

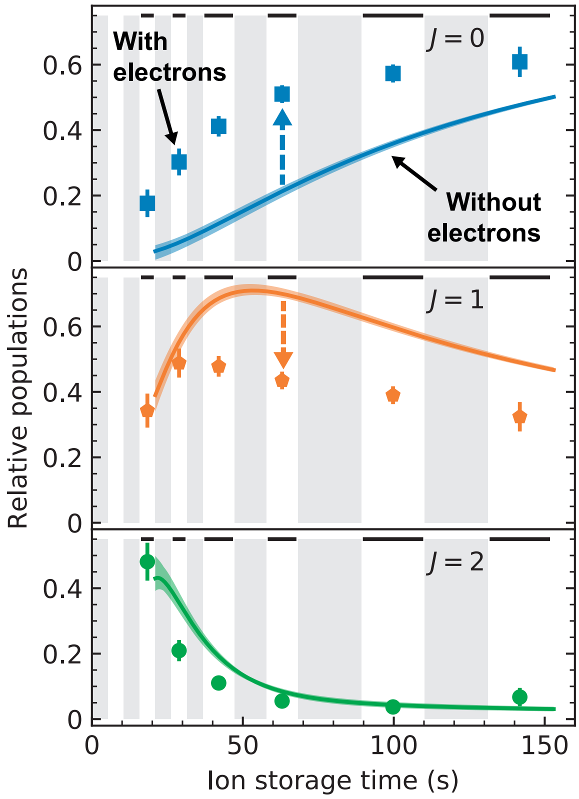
The gas-phase chemistry in interstellar clouds is driven by reactions involving ions and radicals which are created in collisions with photons and cold electrons. Here, the H_3^+ molecular ion plays a key role. The break-up of molecules after capture of an electron, called dissociative recombination, can be studied in detail in the cryogenic storage ring CSR. There, 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 neutral-atom beam setup at the CSR combines ground-state atoms with cold molecular ions, and thus provides access to this largely unexplored class of processes under true interstellar conditions.

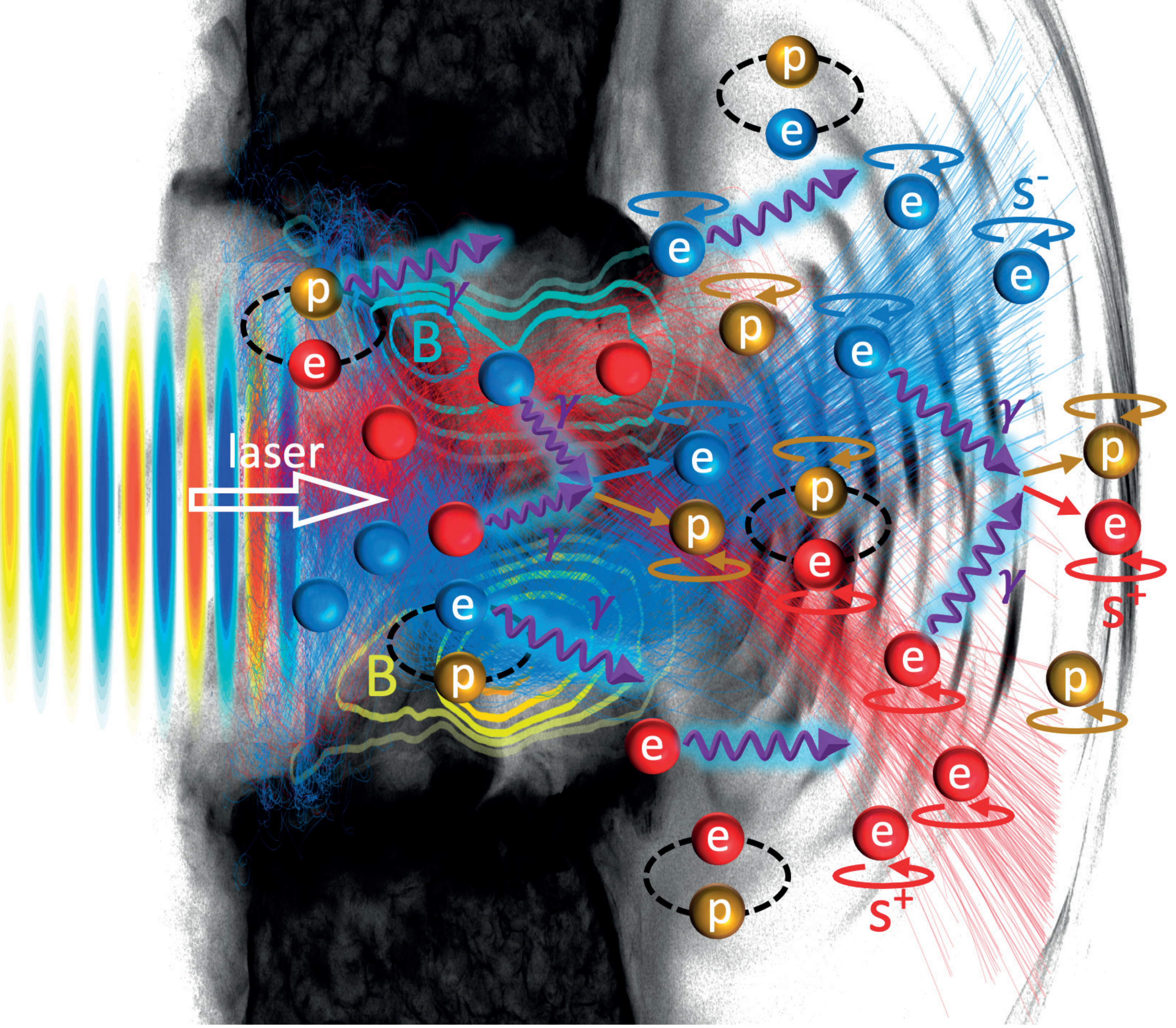
Laser spectroscopic measurements on molecular ions in the CSR using the electron cooler give new insight into quantum transitions modified by collisions with surrounding electrons under space-like conditions.

Laser probing of the rotational cooling of molecular ions by electron collisions

A lone molecule free in cold space will cool down by slowing down its rotation – it will spontaneously lose its rotational energy in quantum transitions, typically only once in many seconds. This process can be accelerated, slowed down, or even inverted by collisions with surrounding particles. In an experiment at the cryogenic storage ring (CSR), the rate of rotational state transitions due to encounters between molecules and electrons was measured by bringing isolated charged molecules in contact with electrons under controlled conditions at about 26 K. Thus, they could make this rate – only known by complex calculations so far – high enough to be quantitatively determined in an experiment at last. To this end the occupation of rotational energy levels in methylidine ions (CH^+) was probed by laser spectroscopy during up to 10 minutes of storage in CSR. The time evolution of the CH^+ rotational population has been acquired without the electron interactions, i. e., involving only radiative cooling in the low radiation field of CSR. This was then compared to the case with electron interactions to yield the pure electron-induced rate. The result represents the first experimentally derived rates for electron-induced rotational molecular transitions, while the derived values match well the so far unverified theoretical calculations. The electron-induced rates of rotational level changes are crucial in analysing, e. g., the faint signals of molecules in space detected by radio telescopes, or in predicting level-dependent chemical reactivity in dilute cold plasmas.



Reference:
Á. Kálosi et al., Phys. Rev. Lett. 128, 183402 (2022), DOI: 10.1103/PhysRevLett.128.183402



2.3 Matter in Extreme Fields

Extremely intense laser pulses impinging on matter: Electrons are accelerated resulting in gamma photons, magnetic fields, radiative reaction and lepton pairs being generated. Important information on the internal dynamics and generated electromagnetic fields is gained from the ejected lepton polarizations.

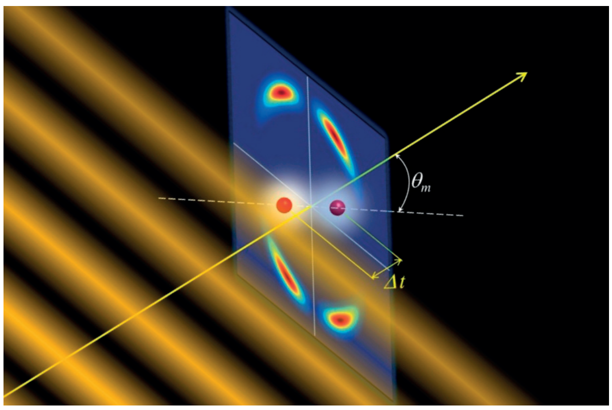
Matter in Strong Laser Fields – at the Frontiers of Feasibility

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 these partly will be reached experimentally only in the near future. This requires the search for solutions of the many-body time-dependent Schrödinger and Dirac equations involving often also quantum electrodynamics and nuclear physics.

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. However, the accurate description of the sub-barrier dynamics can significantly modify this simple picture. Recent studies have identified a new pathway of strong-laser-field-induced ionization of an atom which takes place via recollisions under the tunnelling barrier. The interference of the direct and the under-the-barrier recolliding quantum orbits is shown to induce a measurable shift of the peak of the photoelectron momentum distribution which can be associated with a time delay. Based on a simple model without critical approximations, we showed that other conflicting approaches for the tunnelling time delay, as e. g., the backpropagation method, can be reconciled with our sub-barrier recollision theory. We also investigated the role of quantum features in the direct vicinity of the tunnelling exit and explained why not all experiments could find a non-vanishing tunnelling time.

The non-dipole description of the sub-barrier dynamics is also very important because it yields a non-zero momentum of the electron along the laser propagation direction at the tunnel exit. This modifies the photon momentum sharing in strong-field ionization as confirmed by recent experiments of Reinhard Dörner. Further studies revealed the counterintuitive nature of the Coulomb field of the atomic core for the non-dipole sub-barrier dynamics. Despite its attractive nature, the sub-barrier Coulomb field increases the photoelectron non-dipole momentum shift along the laser propagation direction. The scaling of the effect concerning the principal quantum number and angular momentum of the bound state indicate that the signature of Coulomb-induced sub-barrier effects can be identified in the asymptotic photoelectron momentum distribution via a comparative study of the field-dependent longitudinal momentum shift for different atomic species.

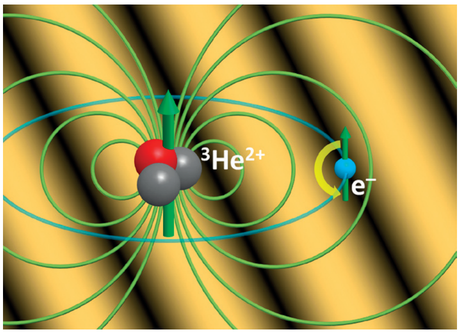
In addition, the non-dipole strong-field ionization time delay in a molecule due to the finiteness of the light speed manifests itself in the longitudinal momentum distribution, featuring double-slit interference (see figure), which efficiently encodes the molecular structure and laser parameters. The delay depends essentially on the tunnelling exit distribution rather than the molecular bond length – with corresponding consequences for the interference patterns.



Ionization of a diatomic molecule in an intense laser field tilted by an angle θ_m *to the laser beam. The light wave (yellow) hits the two atoms of the molecule with time delay* (Δt)*. The molecule acts as double-slit creating the interference structure in the photoelectron distribution (blue).*

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.

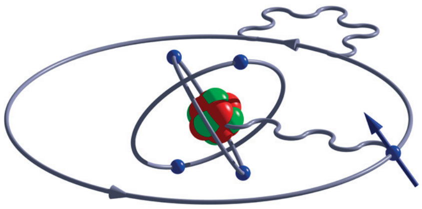


Schematic view of the $^3He^+$ ion's external and internal magnetic interactions. Background: microwave radiation.

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. Here, a first-principle derivation of the underlying equations has been put forward.

Very strong fields also prevail in the vicinity of heavy nuclei. 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 binding energy or magnetic moment of electrons. On the one hand, comparison with precision experiments permits validation of QED predictions, while on the other hand theory helps to determine magnetic dipole moments like for $^3He^{2+}$ or natural constants like the electron mass: its value became by an order of magnitude more accurate.

Precision theory of ionic quantum dynamics



In a highly charged ion, besides the mutual relativistic interaction of electrons (in blue), QED effects such as the self-interaction of electrons via quantum fluctuations of the photon field (wave line) have to be taken into account, together with effects arising from nuclear structure.

We predict the properties of highly charged ions (HCI) to high precision. One purpose of our large-scale modelling is to support or guide local experiments with trapped and stored ions. In an experiment with the PENTATRAP Penning-trap setup, a long-lived, excited electronic state in a Re ion has been determined measuring the mass difference of the ion in its ground and excited states and using Einstein's $E = mc^2$ formula [1]. Our atomic theory helped to identify the corresponding levels and provided the lifetime of the metastable state. Such a non-destructive determination of a transition energy is anticipated to help the discovery of HCI transitions suitable for constructing future atomic clocks. Similar experiments, together with our calculations, yielded the Q value of the β-decay of ^{187}Re, relevant for the determination of the neutrino mass [2].

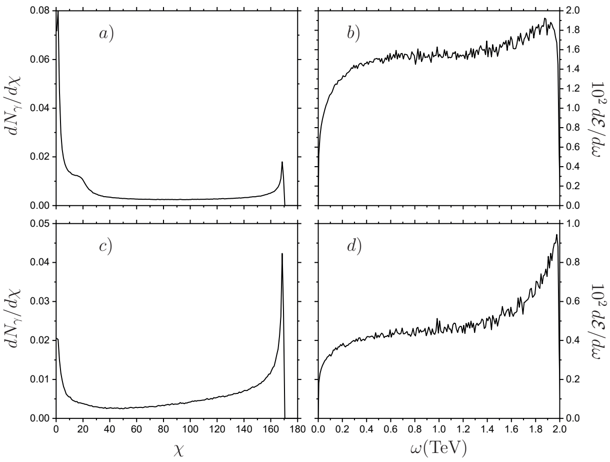
Another property which can be measured to high accuracy is the magnetic moment of the electron bound in HCI. We have put forward the use of this quantity in new physics searches [3]. This idea was implemented in an experiment performed with the ALPHATRAP setup, in which the difference between the magnetic moments of two Ne isotopes was measured with a remarkable precision [4]. The combination of theory and experiment provided a novel way of proving the existence of a hypothetical fifth force. Furthermore, our theory also enables to extract the magnetic properties of ^{3}He from high-precision experimental data, relevant for the calibration of new nuclear magnetic resonance probes [5].

Besides HCI, anions are also excellent systems for benchmarking precision atomic theory. Long-lived metastable states of the Si ion were studied at the cryogenic storage ring by selective photodetachment. The measured lifetimes of the extremely weekly bound excited states are in a very good agreement with our predictions [6].

References:
[1] R. X. Schüssler, H. Bekker, M. Braß et al., Nature 581, 42 (2020), DOI: 10.1038/s41586-020-2221-0
[2] P. E. Filianin, C. Lyu, M. Door et al., Phys. Rev. Lett. 127, 072502 (2021), DOI: 10.1103/PhysRevLett.127.072502
[3] V. Debierre, C. H. Keitel, and Z. Harman, Phys. Lett. B 807, 135527 (2020), DOI: 10.1016/j.physletb.2020.135527
[4] T. Sailer, V. Debierre, Z. Harman et al., Nature 606, 479 (2022), DOI: 10.1038/s41586-022-04807-w
[5] A. Schneider, B. Sikora, S. Dickopf et al., Nature 606, 878 (2022), DOI: 10.1038/s41586-022-04761-7
[6] D. Müll, F. Grussie, K. Blaum et al., Phys. Rev. A 104, 032811 (2021), DOI: 10.1103/PhysRevA.104.032811

Testing strong-field QED close to the fully non-perturbative regime using aligned crystals

Strong-field QED is the theory of quantum processes occurring in the presence of intense background electromagnetic fields. The scale of the field strength is determined by the so-called critical field of QED $F_{cr} = m^2c^3/\hbar|e|$, which is of the order of 10^{16} V/cm (10^{13} G) in the electric (magnetic) case. The interaction between the background field and the electrons/positrons has then to be taken into account exactly in the calculations, whereas the interaction between electrons/positrons and photons can be commonly treated perturbatively. However, the Ritus-Narozhny conjecture states that if electrons/positrons experience field strengths of the order of $F_{cr}/\alpha^{3/2} \approx 1600\ F_{cr}$ in their rest frame, with $\alpha \approx 1/137$ being the fine-structure constant, their effective coupling with photons becomes of the order of unity. In this respect, QED would become a strongly coupled theory. We have shown that channelling radiation by ultra-relativistic electrons with energies of the order of a few TeV on thin tungsten crystals allows one to test the predictions of QED close to this fully non-perturbative regime by measuring the angularly resolved single-photon intensity spectrum. The proposed setup features the unique characteristics that essentially all electrons undergo at most a single photon emission and experience at the moment of emission and in the angular region of interest the maximum allowed value of the field strength, which at 2 TeV exceeds F_{cr} by more than two orders of magnitude in their rest frame (see figure, where θ_c is the critical channelling angle, i. e., the maximum angle between the initial electrons' momentum and the crystal atoms lines such that the electrons remain channelled).

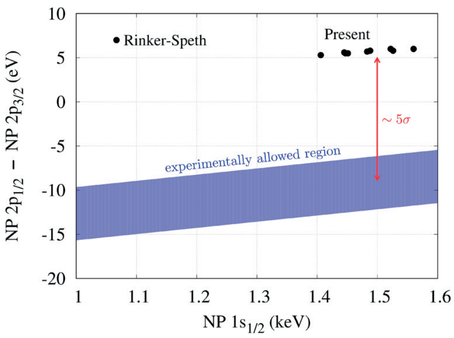


Left panels: Emitted photon number distributions as functions of the electron quantum non-linearity parameter χ (i. e., the crystal electric field in the rest frame of the electrons in units of F_{cr}) at the moment of emission, accounting for all emitted photons (a) and for the photons emitted with an angle larger than $\theta_c/2$ with respect to the z axis (c). Right panels: Average energy emitted per unit of photon energy, accounting for all emitted photons (b) and for the photons emitted with an angle larger than $\theta_c/2$ with respect to the z axis (d).

Reference:
A. Di Piazza, T. N. Wistisen, M. Tamburini, U. I. Uggerhøj, PRL 124, 044801 (2020), DOI: 10.1103/PhysRevLett.124.044801

Muonic fine-structure anomaly

In terms of the Standard Model, a muon is the second-generation lepton, identical to an electron except for its mass, and the interaction with other charged particles can be described by QED. Being captured by a nucleus, it forms a muonic atom, where the Bohr radius of muonic orbitals is 207 times smaller than that in electronic atoms, which causes high importance of QED effects and enhanced sensitivity to nuclear structure. A combination of the theoretical predictions for the energy levels and experiments measuring the muonic atomic spectra enabled the determination of nuclear parameters like charge radii, electric quadrupole and magnetic dipole moments. However, for over 40 years there has been a disagreement between theory and experiment, called muonic fine-structure anomaly.



Theoretical values (dots) of the nuclear polarization correction for muonic zirconium in relation to the experimentally allowed range for Δ2p as a function of the same contribution for 1s state.

Accessing the nuclear parameters is only possible with a thorough inclusion of the nuclear theory. In this respect, the most challenging effect to describe is the intricate interplay between muonic and internal nuclear degrees of freedom, which is known as nuclear polarization (NP) effect. First, the effects of nuclear excitations on atomic properties were described in a field-theoretical framework. Then, the nuclear ground state has been obtained from the Skyrme-Hartree-Fock procedure. Finally, complete nuclear excitation spectra are computed by means of the random-phase approximation and incorporated into calculations of the nuclear-polarization corrections to energy levels of muonic atoms [1]. The calculation uncertainty has been estimated by analysing the nuclear model dependence. The obtained results were applied to the long-standing problem of the fine-structure anomalies in heavy muonic atoms. We have considered muonic zirconium, tin and lead atoms. Our results [1] show that in all cases the nuclear polarization effect is unlikely to be responsible for the anomaly, contrary to what has been believed for over 40 years. Our recent rigorous predictions for self-energy corrections evaluated the leading-order QED predictions. Finally, excluding the long-suggested QED solutions to the puzzle [2], stimulates the search for other explanations, including physics beyond the Standard Model.

References:
[1] I. A. Valuev, G. Colò, X. Roca-Maza, C. H. Keitel, and N. S. Oreshkina, Phys. Rev. Lett. 128, 203001 (2022), DOI: 10.1103/PhysRevLett.128.203001
[2] N. S. Oreshkina, Phys. Rev. Research 4, L042040 (2022), DOI: 10.1103/PhysRevResearch.4.L042040

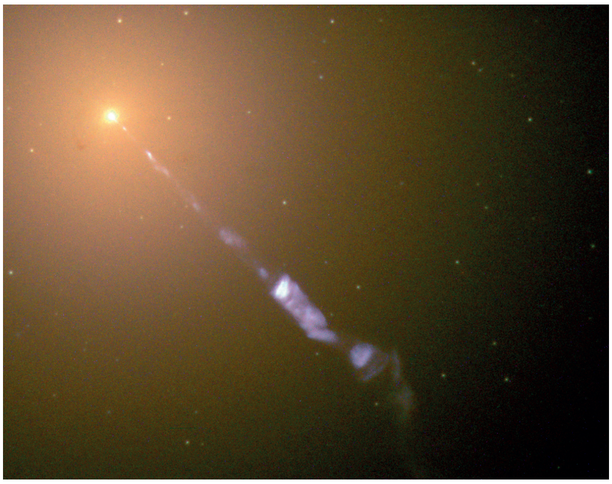
The theoretical calculations also help to determine nuclear properties from the measured data, and to set new limits for new physics and dark matter. A further motivation of such studies is that measurements of the magnetic moments of highly charged ions are anticipated to yield a new independent value of the fine-structure constant, i. e., the fundamental constant defining the strength of any kind of electromagnetic interactions in the Universe.

A long-standing problem of fine-structure anomalies in muonic atoms is revisited by considering level splittings in various muonic atoms. The results for μ-^{208}Pb suggest that the resolution to the anomalies is likely to be rooted in some previously unaccounted-for contributions or even more exotic explanations, including physics beyond the Standard Model.

Our relativistic atomic structure calculations have also contributed to the resolution of a conundrum that has puzzled astrophysicists for four decades. The intensity of two important, strong x-ray lines of a certain highly charged iron ion in astrophysical data and in laboratory experiments did not agree with predictions, obscuring the interpretation of astronomical observations. A recent EBIT measurement at the high-brilliance PETRA III synchrotron facility (see p. 30) finally agrees with our large-scale calculations and with other modern theoretical results.

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

With increasing intensities of laser systems, 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 to possibly preventing the generation of extremely strong laser pulses and we have put forward means to prevent those via suitably chosen focus areas. In particular, various concepts have been developed to generate polarized intense lepton and gigaelectronvolt (GeV) gamma beams. They are based on spin-dependent radiative reaction and are likely to find applications in high-energy, solid-state and astrophysics. As another example, the relativistic spin dynamics of electrons in extreme fields accompanying strong-field QED processes provides a new avenue for in-situ probing the plasma dynamic characteristics in ultra-strong laser fields. The ejected electron spin provides a new degree of freedom to extract information on the structure and magnitude of different components of the transient plasma fields, as well as to test the instability character in the plasma.



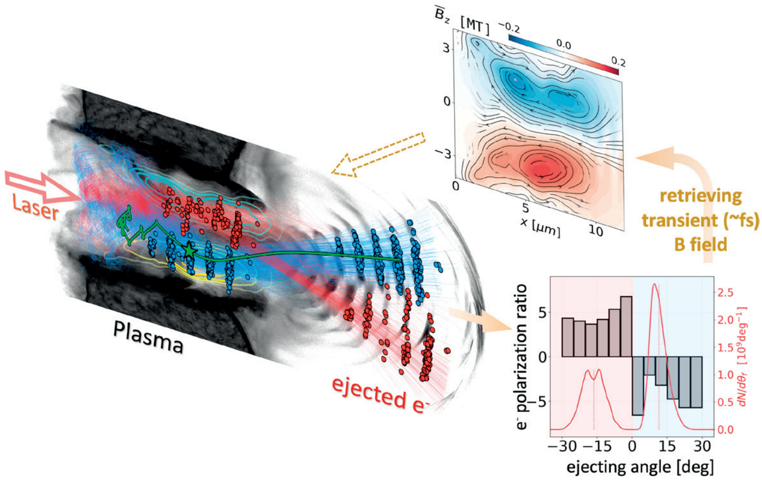
Black hole-powered jet of electrons and sub-atomic particles streams from the centre of galaxy M87 (Hubble).

Already to date, highly intense laser fields enable the acceleration of particles to energies up to the order of 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 ultra-relativistic lepton beams consisting of electrons and positrons in equal amounts as well as gamma rays. Most recently, an international team lead by MPIK researches has put forward a novel theoretical concept by showing that a pulsed, ultra-relativistic electron beam crossing a sequence of thin aluminium foils both self-focuses, therefore increasing its density, and efficiently yields a collimated gamma-ray pulse with more photons per unit volume than electrons in a solid. Such extremely dense beams enable physics studies of matterless photon-photon interactions ranging from matter-antimatter creation, light-by-light scattering, and searches of possible new physics in the interaction of photons with yet undiscovered particles, to laboratory astrophysics studies. Here, dense neutral relativistic jets of electron-positron pairs are generated from the intense gamma-ray pulse. In turn, these electron-positron jets enable unprecedented studies of the collective processes that are thought to shape high-energy astrophysical environments such as gamma-ray bursts and blazar jets, thus providing insights into these exotic systems.

Plasma self-diagnostics based on particles' polarization information

Ultra-relativistic plasma is an extreme state associated with violent gamma-photon emission, radiation reaction, and radiative spin polarization effects. Such an energetic and overdense plasma state drastically evolves at a time scale as short as a few femtoseconds, which disables conventional diagnostic methods relying on the external optical probe or changed particle radiography. Recently, we proposed a novel idea to utilise the polarization information of spontaneously ejected electrons or gamma-ray photons to retrieve the in-situ plasma dynamics.

By employing the unsymmetric electrons' spin-polarization signal, a non-trivial transient self-generated plasma magnetic island structure accompanied with current vortexes could be identified, see figure [1]. The result manifests that the spin signal offers a new degree of freedom to retrieve the structure and magnitude of the transient plasma magnetic fields. On the other side, the angular polarization pattern of emitted gamma photons could facilitate to decipher the electrons' in-situ acceleration status inside the plasma channel. In particular, the acceleration or deceleration status can be detected via the photons' polarization [2]. Also plasma instabilities can be characterised via the outgoing electrons' polarization state [3].



Left: spin-polarized electrons are ejected from the plasma irradiated by an intense laser pulse. Lower: angular distribution of e^- spin-polarization. Upper: identified transient self-generated plasma magnetic fields.

The results open the door for efficient plasma diagnostics based on spin polarization, which inherently exists in ultra-relativistic plasma phenomena, e. g. in cosmic ray radiation, stellar object evolution, and laser/plasma interaction.

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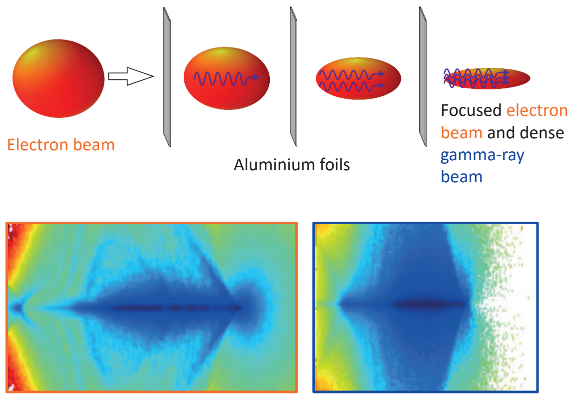
[1] Z. Gong, K. Z. Hatsagortsyan, C. H. Keitel, Phys. Rev. Lett. 127, 165002 (2021), DOI: 10.1103/PhysRevLett.127.165002
[2] Z. Gong, K. Z. Hatsagortsyan, C. H. Keitel, Phys. Rev. Res. 4, L022024 (2022), DOI: 10.1103/PhysRevResearch.4.L022024
[3] Z. Gong, K. Z. Hatsagortsyan, C. H. Keitel, Phys. Rev. Lett. in press (2022), arXiv:2212.03303 [physics.plasm-ph]

Generation of extremely dense gamma-ray pulses in beam-beam and beam-multifoil collisions

The generation of high-energy, dense and collimated photon beams is of great interest both to fundamental and applied research. With experimental implementation ongoing at the FACET-II accelerator facility at Stanford, under our division's leadership in [1] it was demonstrated with fully 3D simulations that a pulsed, ultra-relativistic electron beam crossing a sequence of thin aluminium foils both self-focuses and efficiently yields a collimated gamma-ray pulse with more photons per unit volume than electrons in a solid [1]. After passage of 20 foils, more than 30% of the electron beam energy is converted to gamma rays. This occurs because the strong electromagnetic field accompanying the ultra-relativistic electron beam is "back-reflected" as the beam crosses the foil surface. Similarly to an electromagnetic wave colliding with a mirror, at the foil surface the total electric field acting on the beam is nearly zero, while the total magnetic field is nearly doubled. This strong azimutal magnetic field focuses the electron beam radially and triggers collimated high-energy photon emission. Efficient high-energy photon production with the possibility of precision studies of strong-field QED has also been demonstrated in beam-beam interaction [2].



Schematic setup (upper panel) and density distribution of the generated gamma-ray pulse (blue frame) and of the focused electron beam (orange frame) after the electron beam has crossed 16 consecutive aluminium foils.

Extremely dense beams enable physics studies of matterless photon-photon interactions such as light-by-light scattering and searches of possible new physics in the interaction of photons with yet undiscovered particles [3]. Dense gamma-ray beams also pave the way to matter-antimatter creation from light, as well as relativistic laboratory astrophysics studies. Here, dense neutral relativistic jets of electron-positron pairs are generated from the dense gamma-ray pulse.

References:
[1] A. Sampath et al., Phys. Rev Lett. 126 (2021), DOI: 10.1103/PhysRevLett.126.064801
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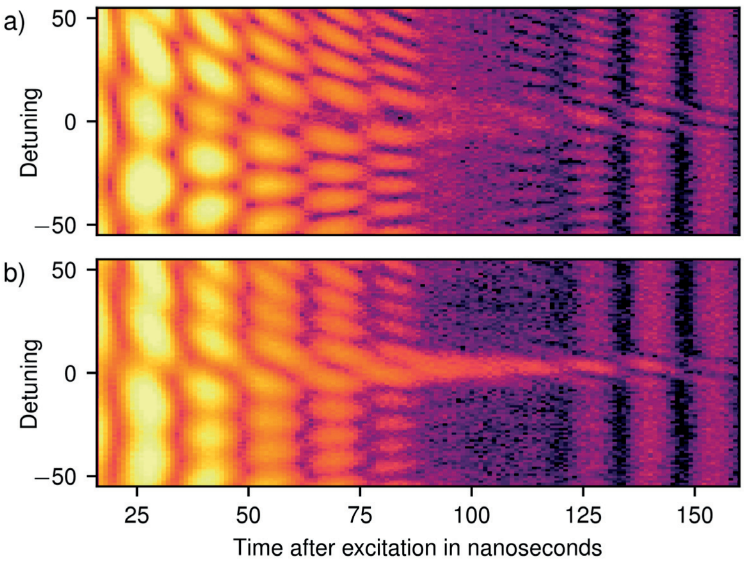
Extreme Light-Matter Interaction – Precisely Controlling and Probing Nuclear Transitions



Observed x-ray interference structures encoding the nuclear dynamics, as function of time after excitation and detuning between control field and target nuclei. (a) Measurement data for the case of enhanced emission, (b) for the case of enhanced excitation.

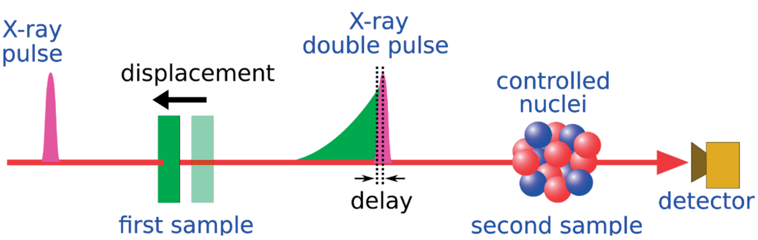
Quantum optics with x-ray light emerged in the last years as a new field. Of particular interest are certain atomic nuclei that only interact with x-rays with an extremely well-defined photon energy, due to an effect discovered by Rudolf Mößbauer at the precursor institute of MPIK in 1958. Spectroscopy – 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.

Using suitably shaped x-ray light, nuclear excitations have been coherently controlled for the first time – with a temporal control stability of a few zeptoseconds. This forms the basis for new experimental approaches for the engineering of complex nuclear quantum states and for the exploration of time-dependent phenomena with nuclei.

In parallel, an ab-initio theory has been developed for thin-film x-ray cavities with Mössbauer nuclei, a key platform for exploring nuclear quantum dynamics. With this theory, the as-yet open inverse problem of directly determining cavity structures providing a desired quantum optical functionality has been tackled.

Coherent x-ray optical control of nuclear quantum dynamics

Modern experiments on quantum dynamics can control the quantum processes of electrons in atoms to a large extent by means of laser fields, often based on coherence and interference phenomena. However, towards energies of hard x-rays, the intrinsic broadening of electronic resonances due to competing electronic processes limits the lifetimes of superpositions of atomic states, thereby rendering such control challenging. Resonances in Mössbauer nuclei are distinct from electronic x-ray resonances by their exceptionally narrow line widths, owing to the recoilless absorption and emission of photons. The narrow width has the advantage of desirably long coherence lifetimes, but on the other hand severely limits the possibility to strongly drive or control nuclear x-ray transitions even at modern x-ray sources. This raises the question, if the nuclear dynamics can coherently be controlled with suitably shaped x-ray fields. In Ref. [1], we have demonstrated such control at the European Synchrotron ESRF (Grenoble, France) in cooperation with researchers from DESY (Hamburg) and the Helmholtz Institute/Friedrich Schiller University (Jena). In the experiment, a sample enriched with the iron isotope ^{57}Fe was irradiated with short x-ray pulses from the synchrotron and, due to the energy sharpness, release this excitation comparably slow in form of a second x-ray pulse (figure).



Schematic setup for the coherent control of nuclear dynamics.

For the control, the sample is displaced quickly by a small distance, thereby inducing tiny delays between the two x-ray pulses, with a stability of only few zeptoseconds. We then used this double-pulse to control the dynamics of a second nuclear target. This target is excited to a coherent superposition of ground and excited state by the first pulse. The second pulse continues this nuclear dynamics, controlled by the mutual pulse delay. By varying this delay, the dynamics could be switched between further excitation of the nuclei and de-excitation of the nuclei, thereby demonstrating the control of the quantum-mechanical state of the nuclei (cf. figure above). These results open the toolbox of coherent control, which has been successfully established in optical spectroscopy, to atomic nuclei – providing new possibilities and perspectives, e. g. by preparing nuclei in particular quantum states towards more precise tests of fundamental physics and more accurate clocks, see also [2].

References:

[1] K. P. Heeg et al., Nature 590, 401–404 (2021), DOI: 10.1038/s41586-021-03276-x

[2] D. Lentrodt and J. Evers, Phys. Rev. X 10, 011008 (2020), DOI: 10.1103/PhysRevX.10.011008

Infra-structure

3

3.1 Scientific and Technical Infrastructure

Aerial view of the institute's campus in fall. In the background the city of Heidelberg.

Campus

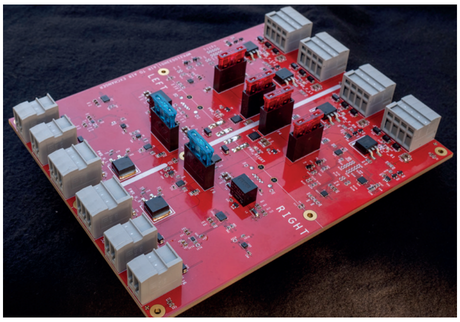
The institute campus is situated in the forest 200 m above the city of Heidelberg. The main buildings are the Walther Bothe and the Wolfgang Gentner Laboratories providing office and laboratory space. The library building with a lecture hall and a seminar room suitable for small conferences lies at the 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 7000 processor cores are available for processing batch jobs. Data is stored on hard disks with a total capacity of over 17 Petabytes. For fast access, most of the data space is organised 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 servers.

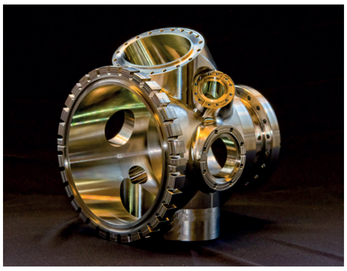
Electronics



Fan control board for the air-to-air heat exchanger for the proposed SWGO electronics cabinet.

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 precise 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

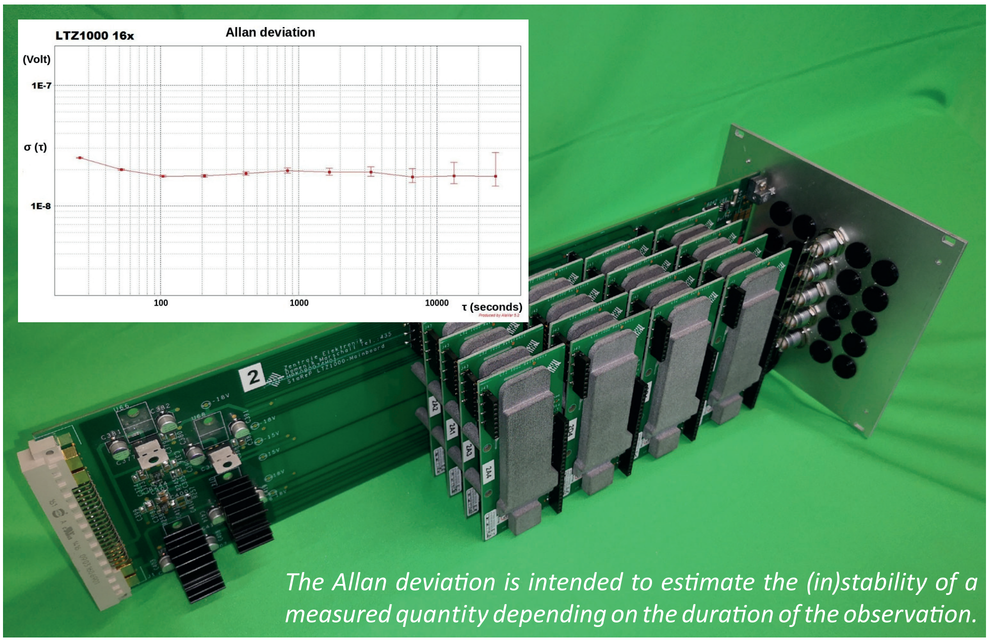


Vacuum chamber, designed and built in the institute's engineering design office and precision mechanics shop.

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 specialised 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.

The STAREP voltage reference cluster



The Allan deviation is intended to estimate the (in)stability of a measured quantity depending on the duration of the observation.

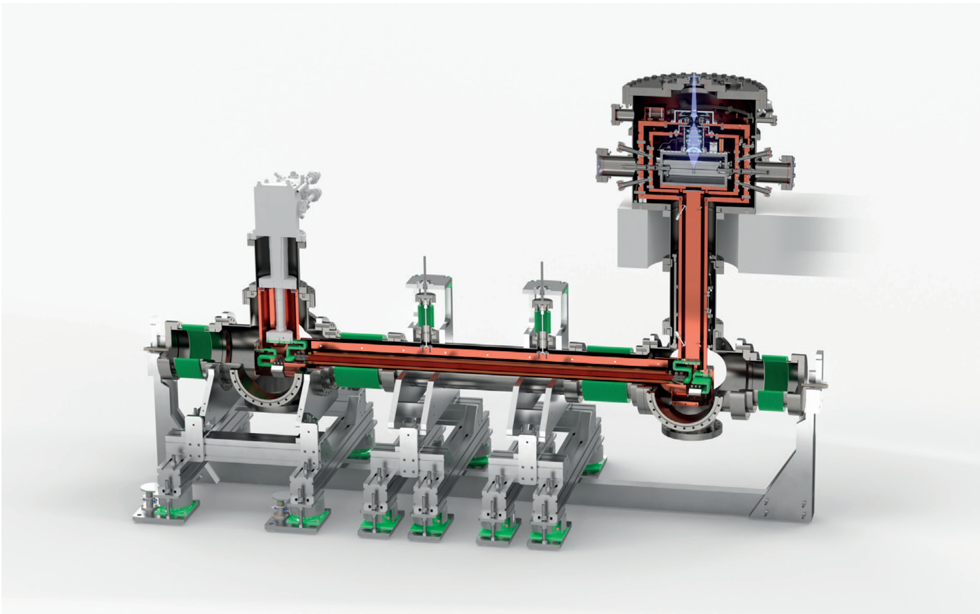
Ion traps offer many opportunities to measure fundamental physics properties of matter. The Penning ion traps at MPIK allow for highest precision measurements of atomic and nuclear states and masses by observing the frequencies of ion motion in strong magnetic fields. Loading, unloading and placement of the ions inside the trap is controlled by several electrical potentials. In order to allow for highest precision measurements, those voltages have to be precise and very stable in time because any voltage variation dilutes the frequency measurements.

In the current STAREP (STAble REference for Penning traps) system, all channel potentials are derived from a central reference voltage source that is based on very stable commercial reference ICs (Linear Technologies LTZ1000). In addition, the ICs are electrically and thermally decoupled from the ambient by dedicated pcb layout techniques and 3D-printed housings. To further reduce the voltage noise, sixteen LTZ1000 are combined to make up a STAREP voltage reference module. With this setup, voltage variations of less than 30 nanovolts over measurement intervals ranging from 10 seconds to about 10 000 seconds can be achieved as illustrated by the measurement of the so-called Allan deviation. The achieved stability is very close to the stability of the best standard available, the Josephson voltage standard.

CryPTEx 2: cryogenic Paul trap experiment

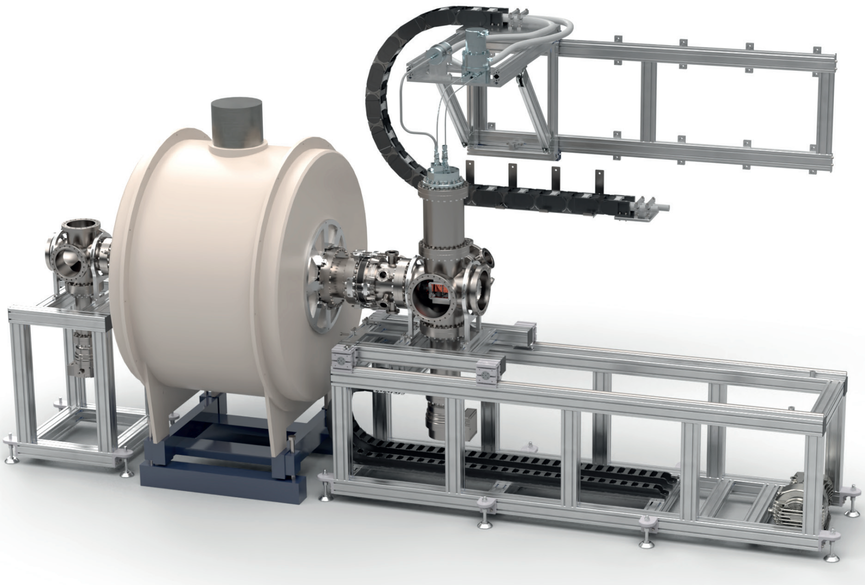
A novel, quasi-monolithic and superconducting radio-frequency trap made of high-purity niobium for the storage and laser spectroscopy of highly charged ions was designed in close collaboration between scientists and the engineering design office and built in the central precision mechanics shop. After the niobium ingot resonator was assembled and aligned, it was electron-beam welded at several points. Optomechanics were also developed and manufactured for the detection of the stored ions.

Complementary to this worldwide unique concept, a vibration-decoupled, cryogenic feed line made of high-purity copper was designed and manufactured. A second, improved version of the entire experiment is currently being manufactured as part of a BMBF-funded project in engineering design and precision mechanics.



ELCOTRAP: an experiment to explore novel methods for cooling single ions

The continuously advancing precision of Penning trap experiments requires increasingly sophisticated techniques for cooling ions. A novel cooling technique, where highly charged ions are cooled down to sub-millikelvin temperatures by coupling them to a cold electron plasma, is expected to further increase precision. The ELCOTRAP (Electron Cooling Trap) experiment was designed to realise this technique. The experiment chamber in the centre of a superconducting magnet is cooled to 4 K, with special attention paid to the best possible thermal conductivity while minimising mechanical vibrations. By designing special bearings and suspensions, the experimental chamber can be pulled out sideways within a few minutes, thus enabling fast iteration cycles. For this purpose, the engineering design office constructed, among other things, a mechanical joint that can be opened without tools and that establishes optimal conductivity during operation by thermal contraction. Using FEM simulations, the cryogenic structure was optimised for the necessary mechanical stiffness. Subsequently, the entire structure was manufactured and pre-assembled in the central precision mechanics shop.



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 MPIK 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" events.

Open Day celebrating the 20th anniversary of the inauguration of the H.E.S.S. telescopes

In 2002, the first of now five telescopes of the High Energy Stereoscopic System H.E.S.S. was inaugurated on Farm Goellschau, about 120 km south-west of Windhoek in Namibia.

To date, H.E.S.S. is the largest and most sensitive telescope array exploring the Universe at the highest energies of the electromagnetic spectrum. In the last 20 years, the H.E.S.S. Collaboration has published over 250 articles in high-impact scientific journals and contributed to close to 1 000 student thesis projects; the Collaboration and its members have been awarded many prestigious prizes, and independent surveys ranked H.E.S.S. among the most influential observatories worldwide.

In order to celebrate these achievements, the H.E.S.S. Collaboration hosted an Open Day for the public on the H.E.S.S. site in Namibia, organised by the Collaboration and MPIK. On Sunday, October 23rd, over 500 guests came to the remote location to have a look at this unique research facility. Besides numerous tours to the telescopes given by members of the H.E.S.S. Collaboration, several activities and showcases had been prepared to highlight the science of H.E.S.S.

Visitors could experience a show in a portable planetarium provided by the University of Namibia, UNAM, where the southern sky was presented. A poster presentation of over 50 newly designed posters explained the H.E.S.S. telescopes, their function and scientific discoveries. Younger guests were invited to test their skills in eliminating unwanted signals from their gamma-ray counterparts in a specifically designed video game. Two technicians from MPIK, who have been supporting the construction and maintenance of the telescopes for the last 20 years, provided an extensive display of tools that have been used in construction of the telescopes as well as crucial parts as a hands-on experience.

As the site of the telescopes is only accessible by an hour-long drive from Namibia's capital Windhoek, free public transportation was organised. As a result, several school classes were among the visitors, as well as many local residents from Windhoek and nearby villages, allowing them a glimpse into Namibias forefront research facility and the importance of gamma-ray astronomy. As tour organisers were notified of the event beforehand, a number of tourists from all over the world attended the Open Day as well.

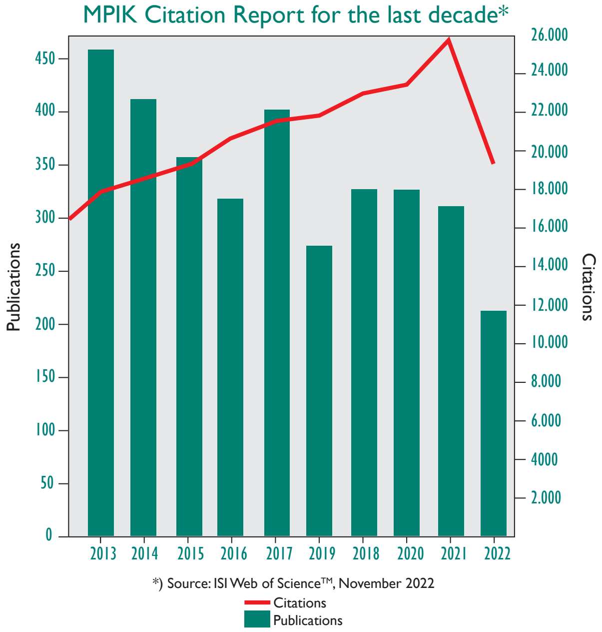
Publication statistics

The publication output of the MPIK is documented via the Max Planck wide publication repository PuRe (https://pubman.mpdl.mpg.de/), which presently contains about 9 100 datasets related to the MPIK. 1 010 entries have been added in the years 2020-2022, of which 429 contain the full text and 392 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 2020-2022, overall 52 papers were regarded as being of interest for the general public and therefore accompanied by a press release. Two papers by MPIK scientists were among the finalists for "Breakthrough of the Year 2021"

The following table lists the most favoured journals during the years 2020 to 2022 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.

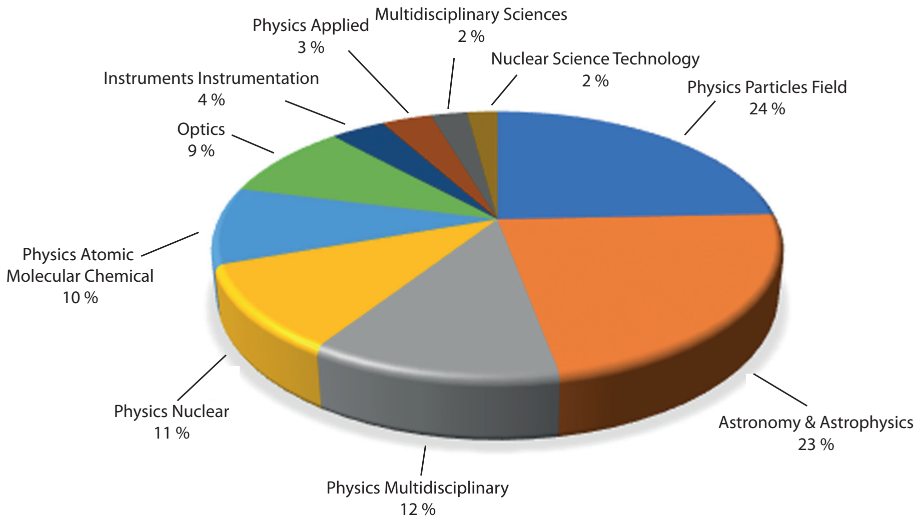
Journal	**Papers**
Physical Review D	92
Physical Review Letters	88
Journal of High Energy Physics	76
Physical Review C	46
Physical Review A	45
European Physical Journal C	42
Astrophysical Journal	34
Astronomy & Astrophysics	27
Physical Review Research	25
Journal of Cosmology and Astroparticle Physics	24
Nature	13
Nature Physics	9
Nature Communications	5
Nature Astronomy	4
Science	4
Nature Chemistry	1

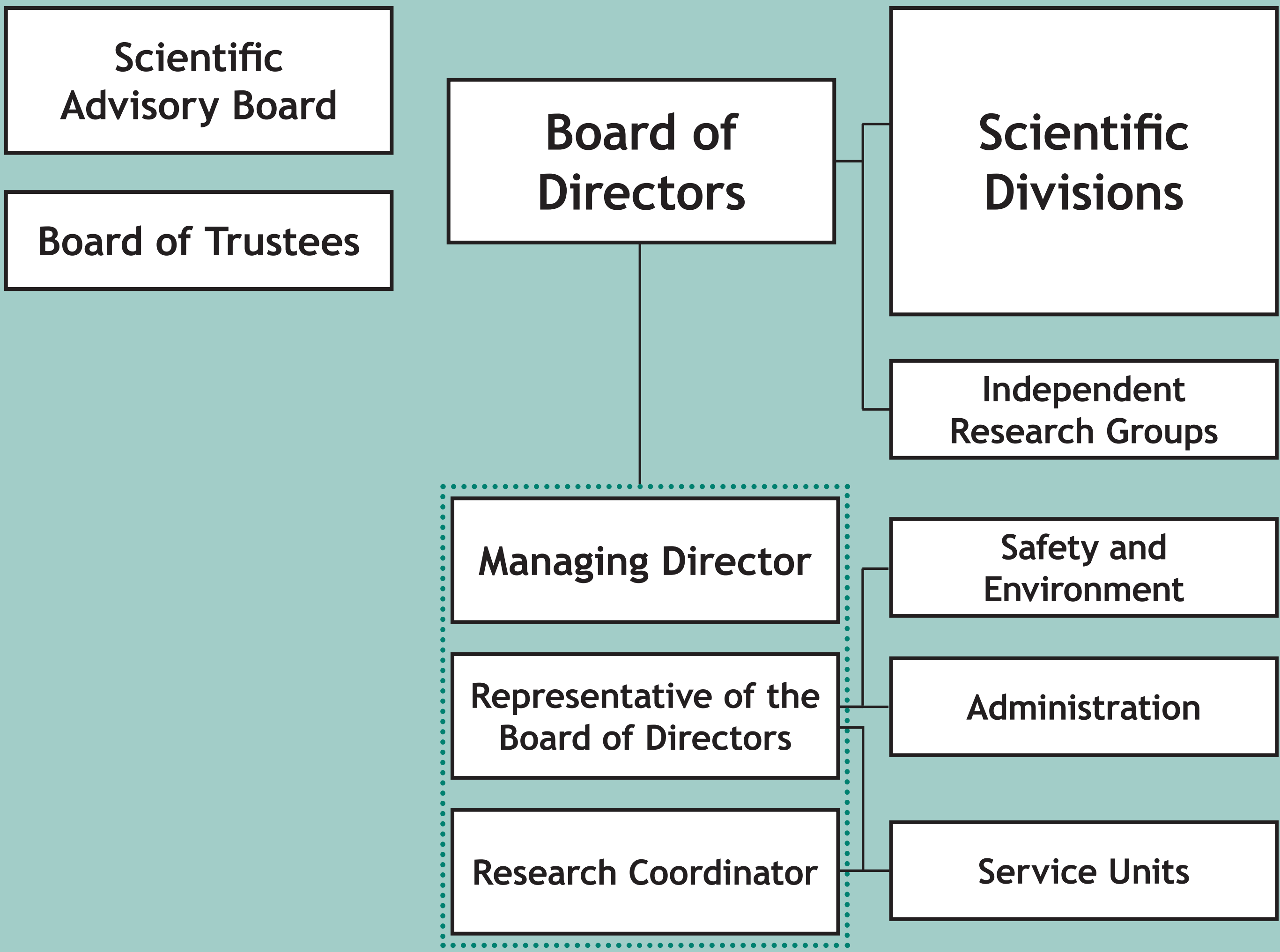


The data for 2022 are still incomplete; the full numbers will be available in spring 2023.

	2020	**2021**	**2022**
Bachelor theses	13	9	9
Master theses	14	12	13
Dissertations	24	19	11
Habilitations	1	1	1

Distribution of the publications corresponding to the Web of Science™ categories





3.2 PERSONNEL

Organisational diagram of the institute.

Distinctions to MPIK Members

Prof. Dr. Klaus Blaum: Lise Meitner Prize of the European Physical Society and Otto-Hahn-Preis der Stadt Frankfurt am Main, der GDCh und der DPG and Member of the Heidelberger Akademie der Wissenschaften
Prof. Dr. Dr. h.c. Manfred Lindner: Fellow of the American Association for the Advancement of Science (AAAS)
Prof. Dr. Heinrich Völk: Honorary Doctorate of the Sibirian Branch of the Russian Academy of Sciences
Prof. Dr. Eberhard Grün: Ehrendoktorwürde der Universität Stuttgart
Prof. Achim Schwenk: Advanced Grant of the European Research Council (ERC)
Apl. Prof. Dr. Andreas Wolf: Dieter-Möhl-Medal 2021 of CERN
Apl. Prof. Dr. José R. Crespo López-Urrutia: Fellow of the American Physical Society
Dr. Jonas Karthein: Wilhelm und Else Heraeus-Dissertationspreis 2020 and Dissertationspreis der DPG
Dr. Peter Micke: Dissertationspreis der DPG
Dr. Frederik Depta: Best Paper Award des Exzellenzclusters „Quantum Universe"
Zheng Gong: Matter at Extremes Young Investigator Award
Stefan Dickopf: Otto-Haxel-Preis der Fakultät für Physik und Astronomie für die beste experimentelle Masterarbeit
Jason Mather: Kammersieger im Leistungswettbewerb des deutschen Handwerks and Azubipreis der MPG 2020
Maximilian Bruder, Vincent Gahn and Lukas Heckmann: Urkunden für sehr gute bzw. gute Leistungen in der Gesellenprüfung
Maximilian Bruder: 1. Kammersieger und 2. Landessiger im Leistungswettbewerb des deutschen Handwerks 2022
Lukas Heckmann: 2. Kammersieger im Leistungswettbewerb des deutschen Handwerks 2022

Appointments of MPIK Scientists

PD Dr. Antonino Di Piazza: Full professor, University of Rochester (NY) and distinguished scientist, Laboratory for Laser Energetics
Dr. Yuanbin Wu: Full professor at Nankai University, China
PD Dr. Adriana Pálffy-Buß: W2-Professur für Theoretische Quanteninformation und Quantenoptik, Universität Würzburg
Dr. Yun Jiang: Associate Professor, Sun Yat-sen University, China
Dr. Giorgio Busoni: Assistant Professor, Australian National University
PD Dr. José R. Crespo López-Urrutia: außerplanmäßiger Professor, Universität Heidelberg
Dr. Anne Harth: Professur für Computational Optics, Hochschule Aalen
Dr. Tommi Alanne: Lecturer, University of Liverpool, UK
Dr. Oliver Fischer: Lecturer, University of Liverpool, UK

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Prof. Achim Schwenk

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Dr. Christian Buck
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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 Heidelberg University.

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)

	2020	**2021**	**2022**
PhD students	41	42	44
female	11	10	12
from foreign countries	26	27	26
funded by IMPRS-QD	10	7	10
graduations	6	8	10

IMPRS-PTFS: Precision Tests of Fundamental Symmetries
Spokespersons: Manfred Lindner and Klaus Blaum
Coordinator: Werner Rodejohann
Institutions: MPIK, Heidelberg University

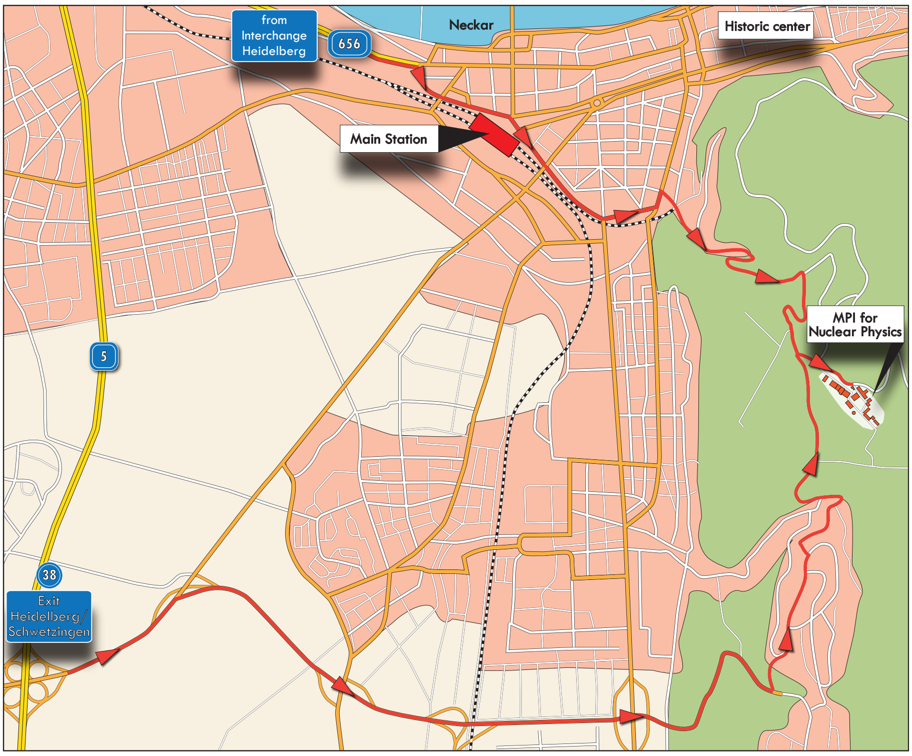
	2020	**2021**	**2022**
PhD students	20	21	22
female	6	6	10
from foreign countries	6	7	5
funded by IMPRS-PTFS	8	7	11
graduations	6	2	5

IMPRS-HD: Astronomy and Cosmic Physics @ MPIA
During the reporting period, 14 PhD students (of which 7 female, 9 from foreign countries, 0 funded by IMPRS-HD, 6 graduations) were working at the MPIK.

Electronic Annex

The electronic annex provides lists of 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 direction Heidelberg; at the end of the Autobahn turn right (direction „Zentrum, Altstadt, Schloss“) and at the main station turn right again, stay on the four-lane road (underbridge), at the traffic light half left, then straight ahead, take third exit in the roundabout ('left'), at the next traffic light turn right into Steigerweg, and follow the direction signs „Max-Planck-Institut für Kernphysik“ about 2.5 km uphill.

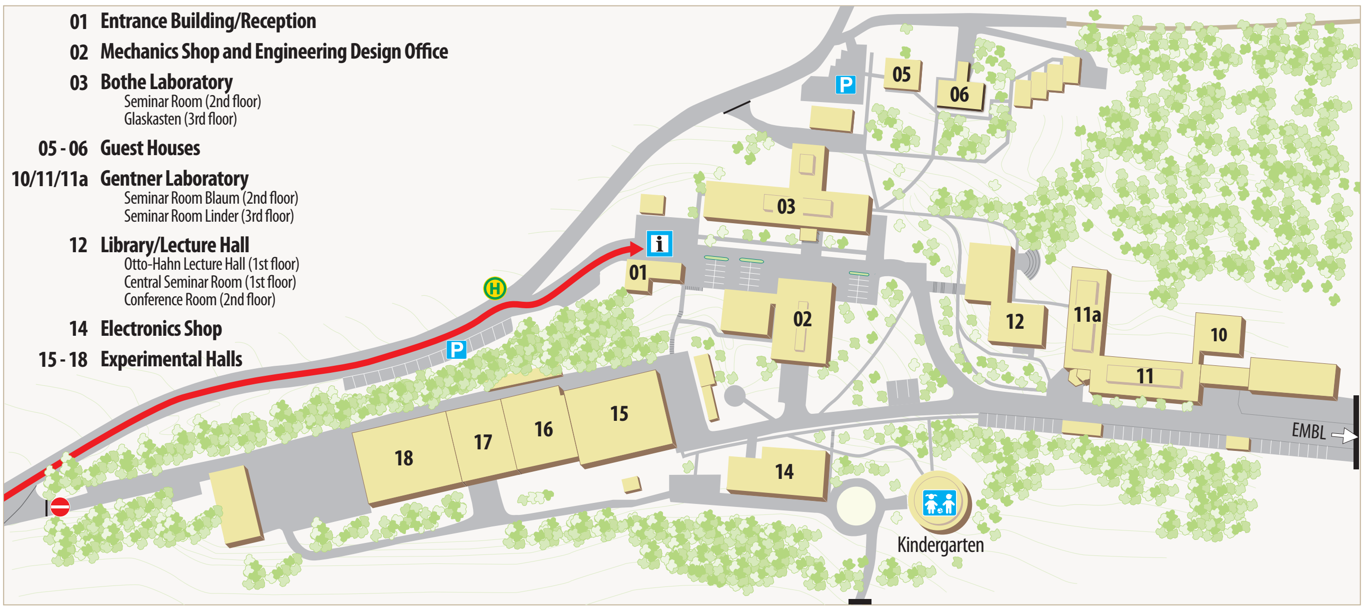
From the south leave A5 at the exit Heidelberg/Schwetzingen, turn on B535 direction Heidelberg/Leimen, then right direction Leimen and keep straight ahead for about 4.5 km (at last uphill) to the Aral station, there turn left to Boxberg and follow the direction signs „Max-Planck-Institut für Kernphysik“.

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 bus 39 direction Königstuhl until the stop „MPI Kernphysik“ or bus 39A until the stop „Bierhelderhof/Ehrenfriedhof“ (about 15 min). Alternatively with S1, S2, S5 to Heidelberg Weststadt/Südstadt, then walk (3 min) to Alois-Link-Platz and take bus 39 or 39A.

By plane: Airport Frankfurt/Main; take either an express train (ICE, IC) at Flughafen Fernbahnhof via Mannheim or the Lufthansa Airport Bus to Heidelberg. Continue with a taxi.

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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