The Universe in the Laboratory
Research at the FAIR particle accelerator facility in Darmstadt
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FAIR – The Universe in the Laboratory

International particle accelerator facility

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The mission of the international FAIR particle accelerator facility in Darmstadt is to unravel unsolved secrets regarding the structure of matter and the evolution of the Universe. To achieve this, researchers at FAIR are striking out in new directions with their experiments. In close cooperation with astronomers, who use telescopes to view the Universe at a distance, the scientists at FAIR will directly create and examine cosmic matter in the laboratory.

In giant planets, stars, and also during stellar explosions and collisions, matter is subject to extreme conditions such as very high temperatures, pressures and densities. FAIR will enable scientists to create such conditions in the laboratory. To do so, they will bombard small samples of matter with ions (electrically charged atoms). These collisions will, for very short periods of time, create the cosmic matter at the tiny impact points.

Come and immerse yourself in research that will be conducted at FAIR. Accompany the particles as they travel through the accelerator tubes and collide with a material target. Discover how the researchers will conduct experiments, and how they will use a wide variety of sophisticated and sometimes gigantic instruments to measure even the smallest of particles.
Accelerating ions for novel experiments

Currently the FAIR particle accelerator facility is under construction, but imagine it in operation! A look into the future.
A small piece of uranium is prepared for use in the laboratory. In a few moments, some of the atoms of this piece of uranium will go on a long tour. Within a few seconds, they will travel more than one million kilometres through tubes and tunnels. The facility’s operators in the main control room work with great concentration as they prepare to send the uranium particles through the FAIR accelerator. Their goal is a new intensity record. Therefore, they intend to accelerate around 500 billion uranium ions to nearly the speed of light — a feat that can’t be achieved anywhere else on Earth.

1 0 seconds, 0 km/s
The small piece of uranium is firmly held in place in a gas-filled chamber. When the operators give the go-ahead, a voltage is applied between the uranium and an electrical contact within the chamber. The voltage is slowly increased until an electric arc suddenly shoots through the gas. As the voltage discharges, it tears atoms out of the piece of uranium. Moreover, the uranium atoms lose electrons from their electron shells, turning into uranium ions in the process. An electric force pulls these ions out of the chamber, magnets steer the ions to the first particle accelerator, the UNILAC.

2 0.00001 seconds, 47,000 km/s
The UNILAC can accelerate all of the chemical elements. One copper cylinder after the other is lined up within the vacuum pipes, which are as tall as a person. The first copper cylinder electrically attracts the ions. They pass through the cylinder in a flash. A voltage has also been created between all the other copper cylinders in order to accelerate the ions more and more. The ions race faster and faster. After traveling 120 metres, the ions reach the end of the accelerator. Fractions of a second after they were launched, the ions are now moving at 47,000 kilometres per second. They have left the UNILAC behind and are on their way to the second accelerator.

3 0.7 seconds, 270,000 km/s
The ions are suddenly diverted from their path, as magnets weighing several tonnes force them into the 216-metre-long circuit of the ring accelerator, SIS18. The ions fly round the ring several 100,000 times. Their speed is boosted further by every lap they take through the facility’s five acceleration structures. The number ‘18’ in the ring accelerator’s designation says something about its maximum magnetic strength. The bigger this number is, the faster the ions can travel without flying out of the curve. In less than a second, the SIS18 has accelerated the uranium ions to a speed of 270,000 kilometres per second. That is around 90 per cent of the speed of light.

4 6.7 seconds, 285,000 km/s
The path suddenly goes downward, 13.5 metres underground. The ions fly into the new FAIR accelerator ring, the SIS100, which is located in a 1.1-kilometre-long ring tunnel. In the SIS100, thanks to stronger, superconducting magnets the particles can be accelerated to even higher velocities than in the SIS18 — to 95 per cent of the speed of light. The beam pipe is completely empty of air, as the quality of the vacuum is 100 times better than even in the SIS18. Such emptiness is vital, because every ion that collides with a molecule of air gets kicked out of the beam and is lost. This has to be prevented, because FAIR aims to accelerate as many particles as possible.

The operators have achieved this goal thanks to the facility’s ultra-high-performance vacuum system, and the perfectly coordinated control of the accelerator structures and their associated steering magnets. After travelling more than one million kilometres through the accelerator pipes in just a few seconds, the approximately 500 billion uranium ions reach the experimental stations at 95 per cent of the speed of light. That is more than ever before — a new world record!

Well on track

To the experiments
However, the operators are not yet done. They channel the ions with the highest intensities through an extensive system of vacuum pipes to selected experimental stations. There, the ions hit the targets, which are made of a suitable material, with such a great force that exotic states of matter, normally existing only in cosmic objects like stars or star explosions, are created for the first time on Earth. These are identified and studied with the help of detectors the size of buildings.

Storage rings
A great opportunity is offered here by the fact that subatomic particles such as antiprotons (the antimatter version of protons) and rare exotic isotopes created when the accelerated ions hit a target can be captured in large accelerator devices called storage rings. This prevents these valuable and rare particles from being lost to our research. On the contrary, the researchers can conduct experiments with these particles every time they fly past. This is a clever trick, because such repeated use of a particle is indirectly equivalent to a further increase in intensity, without requiring the associated accelerator facilities.
We are all made of stardust. This is because stars and stellar explosions create the chemical elements of which our bodies and all living things are composed. Only the simplest element, hydrogen, was created exclusively during the Big Bang, which also generated much of the next lightest element, helium, as well as significant traces of the lightest metal, lithium. To understand the stars, we first need to understand atomic nuclei. That is precisely what the scientists strive for with the experiments of the NUSTAR collaboration. They want to study the nuclear reactions that occur inside stars. This leads us to the world of exotic isotopes.

**Exotic nuclei and the heavy elements**

The Sun and the other stars shine because the atomic nuclei of light elements continuously fuse to create those of heavier elements. In this way, hydrogen creates all of the elements up to iron, the 26th element in the Periodic Table. This process creates energy in the form of heat and light — the sunlight and starlight we see here on Earth.
Heavier elements such as gold and lead are among the almost 70 elements that are created in stars and stellar explosions. They are generated by complex chains of reactions, which sometimes encompass hundreds of intermediate steps. Supernova explosions and mergers of neutron stars are important producers of these elements. These cataclysmic cosmic events generate many neutrons, which are captured by lighter atomic nuclei. However, the resulting neutron-rich nuclei are unstable and decay. In this process (known as beta decay), one of the neutrons in the nucleus is converted into a proton. The nucleus now contains an additional proton and has thus become the next-heavier element in the periodic system. Neutron capture and decay take place in a multiple and varying interplay of reactions. This process continues until a stable heavy element is created. However, everything happens very quickly. The atoms of all the heavy elements are created in the first few seconds after the stellar explosion.

The neutron-rich nuclei created, which are indispensable for the generation of the heavy elements, are different from the atomic nuclei found on Earth and may have completely different properties. Nevertheless, we would not exist without them.

The aim of the scientists at NUSTAR (Nuclear Structure, Astrophysics and Reactions) is to study the properties of these exotic nuclei. To this end, they are setting up several experimental stations that contain a variety of measuring devices. A key instrument that will be used for all of the experiments is the Super Fragment Separator (Super-FRS).

**Sorting nuclides in the Super-FRS**

The ions of the heaviest elements are shot at a target with a force that breaks them up into fragments on impact; these are the exotic nuclei of interest. However, they are extremely rare. The Super-FRS — a kind of sorting machine for nuclei — will help the scientists find what they are looking for. It is more than 100 metres long. With the help of magnets that weigh several tonnes, the system will sort the exotic nuclei according to their charge and mass. This will enable the scientists to filter out exactly the exotic nuclei they want to study — a feat not achievable anywhere else in the world.

**Repeated use of rare nuclides**

Downstream from the Super-FRS will be several measuring stations and storage rings. The storage rings will be able to capture the rare exotic nuclides and store them for hundreds of millions of revolutions. During each revolution, the nuclei can be used in ‘in-ring’ experiments so that they do not have to be re-created afresh. A special beam-cooling system will play a crucial role here, as it will keep the speed of the circulating particles extremely constant. It is the only way that the nuclei can be investigated with high precision.

The scientists’ measurements focus on properties such as the lifetime, shape, and internal structure of the exotic nuclei. These properties are the key to understanding the creation of elements inside stars; in addition, they provide scientists with completely new insights into the structure and behaviour of matter.
Inside a neutron star

The collision of atomic nuclei at high speeds can simulate the conditions inside supermassive objects for a split second.
When a massive star reaches the end of its life, it explodes as a huge supernova, leaving behind an incredibly dense central core—a neutron star. Although it is only the diameter of a city, it weighs around one million times more than the whole Earth! Scientists are planning to use the CBM (Compressed Baryonic Matter) experiment to find out how matter changes at such densities. They want to know, for example, if all of the matter breaks down into its elementary particles—quarks and gluons—to create a ‘quark–gluon’ plasma, as is thought to have existed shortly after the Big Bang.

**States of matter — the different forms of matter**

In everyday life, matter can exist in either solid, liquid or gaseous states. Experience has shown that these states depend on the temperature. Water, for example, is a solid at 0°C and below; it is a liquid between 0 and 100°C, and then boils at 100°C to become a gas at higher temperatures.

However, the state of the matter in question depends not only on the temperature but also on the pressure and thus its density. At an altitude of about 3,000 metres, for example, water boils at 90°C because the air pressure is lower than at sea level. It is thus important to know the state of a substance at a particular temperature and density because this information gives us a deep understanding of its building blocks and the forces acting within its interior.

**Highest densities**

The densities inside a neutron star far exceed anything found here on Earth; we know that the positively charged protons and the negatively charged electrons composing atoms are literally crushed together to form neutral neutrons (thus the name). However, nobody knows what happens right at the star’s core where the density is highest. Do the neutrons dissolve into a kind of super-dense ‘elementary particle soup’ of freely moving quarks and gluons, as predicted by physical models?

This theory can be tested with the CBM experiment, which will create such highly compact matter on a tiny scale. To do this, scientists will make two heavy nuclei collide with high energy so that they are pressed together to form an extremely dense ‘fireball’. It will be too fleeting to be studied directly, but the subsequent explosion can be observed.

**Inside the fireball**

It will create up to 1,000 new particles, most of them very ephemeral. Some of these particles will immediately decay into pairs of electrons and their antiparticles, positrons, while others will split into pairs of muons, a kind of heavy electron. CBM will focus specifically on these particles, because they are direct messengers from the expanding fireball region and are not affected by the strong interaction (the fundamental force holding together the quarks making up the protons and neutrons in nuclei). This will enable scientists to determine how nuclear matter behaves at extremely high densities such as those found in neutron stars.

**BIG DATA**

A high-performance computer centre, Green IT Cube, has been built to efficiently store and evaluate the huge amounts of data that will be generated by the experiments at FAIR. With its 300,000 processor cores, the centre achieves a processing performance of 5.27 billion computer operations per second. The data will be stored in the system’s 100 petabytes of memory. Thanks to a special cooling system, the Green IT Cube is extremely energy- and cost-efficient.
The strong force is the force that binds the elementary building blocks of matter, the quarks, into protons and neutrons, and then the protons and neutrons to nuclei. Despite its key role for the formation of matter, our understanding of the strong force is still far from complete. To study its properties in more detail, scientists have designed the PANDA experiment. Using beams of antiprotons, they want to create new particles that are predicted by theory but not yet observed. Moreover, they want to understand how mass is created by the strong force.

In the world of elementary particles, it is not magic that is needed to make something disappear and be replaced by something completely new: Instead, physicists can use antiparticles — the building blocks of antimatter. Every particle of ‘normal’ matter has its corresponding antiparticle. Although antimatter has the opposite electrical charge to normal matter and also differs in other ways, as far as we know it obeys the same physical laws. This means that we could not distinguish a world of antimatter from one of normal matter with the naked eye. Anti-gold would glisten like real gold and anti-water would ripple like normal water. It would be a kind of mirror world.

Annihilation — the destruction and creation of particles

What really makes this difference special, however, is that whenever a particle meets its antiparticle, they annihilate each other in a burst of free energy from which other, new particles can arise. This effect will be exploited for the PANDA experiment (Antiproton Annihilation at Darmstadt). Scientists will fire antiprotons at protons in order to create particles that will provide us with deeper insights into the mysterious strong force.

The strong force

The strong force is mediated by particles called gluons, and can be thought of as a kind of ‘rubber band’. It has the unusual property of becoming stronger as the distance between interacting quarks increases. It eventually becomes so strong that it is impossible to separate two quarks, because the amount of energy required to do so is so great that it would immediately create a new quark–antiquark pair. Theories describing the strong force predict a whole range of exotic particles consisting of different combinations of quarks and gluons. However, these particles have never been observed. They include ‘glueballs’, composite particles consisting solely of gluons. In the PANDA experiment, scientists want to use particle–antiparticle annihilation as a ‘trick’ to create such particles, and discover which of them actually exist and what their properties are. This would greatly increase our understanding of the strong force.

How does mass arise?

In this context, scientists also want to find out how particles come to have their mass. A proton, for example, weighs 50 times more than the three quarks composing it. Hence, the mass arises because the strong force (the gluons) binds the quarks together to create the proton. If scientists can improve our knowledge about the strong force with the help of the PANDA experiment, they might also enhance our understanding how matter gets its mass.
The PANDA detector

- weighs as much as 235 elephants: 700 tonnes;
- is as long as a truck with a trailer and as tall as a two-story building: 18 metres long, 6 metres tall, and 6 metres wide;
- can measure 100 million particle tracks per second with a precision of 50 micrometers;
- contains a superconducting magnet that is cooled down to -269°C;
- generates magnetic fields that could lift 480 tonnes of iron.

Particle magic with antimatter
From atoms and planets to cancer treatment

Research at APPA (Atomic, Plasma Physics and Applications) will range from the investigation of fundamental processes in atoms and macroscopic effects in materials or tissues all the way to engineering and medical applications.

Biophysics and materials research

Biophysicists and materials researchers are exploiting the effects of ion beams on living cells and solids.

Carefully targeted beams of ions can be used very effectively to kill difficult-to-reach tumour cells while leaving surrounding healthy unharmed. Researchers at GSI have developed a groundbreaking cancer treatment employing ions that is now being used to treat patients successfully at hospitals in Heidelberg and Marburg in Germany, and Shanghai in China. Biophysicists also plan to use FAIR to develop a further cancer therapy using protons that travel at 98 per cent of the speed of light. Such extremely fast protons could not only destroy tumours but also simultaneously be used to image them via proton radiography. As a result, therapy and diagnostics could be combined into ‘theranostics’. The biophysical research will also focus on other medical applications, such as the treatment of atrial fibrillation.

From outer space...

Astronauts and technical equipment are exposed to cosmic rays coming from outer space as soon as they leave the Earth’s protective atmosphere. Nobody knows what effect this radiation would have on human beings undertaking long missions to destinations such as Mars. Moreover, the radiation could damage the electronic systems of a spaceship spending a long time in space. At FAIR, scientists will generate particle radiation such as that found in space in order to experiment with it. The biophysics and materials research areas include investigating how cells respond to cosmic rays and which materials can best withstand the extreme conditions of the space environment.

...to the interior of the Earth

The experiments will also enable materials scientists to find out more about the interior of the Earth. We know that minerals subjected to the high pressures and temperatures found in the Earth’s interior can be greatly altered by the radiation emitted by naturally occurring uranium. FAIR will enable the scientists to investigate experimentally what influence the radiation has on minerals. Researchers can simulate such geological processes by bombarding minerals in high-pressure cells with high-energy ions.
**Atomic physics**

Besides the desire to discover and elucidate new phenomena, a typical trait of physicists is to call our existing notions into question. The scientists at FAIR will put an important fundamental theory of physics to the test: quantum electrodynamics (QED). This theory describes all the phenomena related to magnetism and electricity, including the behaviour of electrons in the electron shells of atoms. QED has been tested with a higher level of precision than any other theory to date. However, it is not certain whether this theory is also valid for extremely strong electric and magnetic fields. Such fields dominate the volume inside a uranium atom that is close to the nucleus (because the 92 protons in the nucleus together exert an extremely powerful positive charge). However, these fields cannot normally be studied because they are shielded by the surrounding shells of the 92 negatively charged electrons. At FAIR, scientists will be able to strip away virtually all the electrons to produce highly charged positive ions. The scientists will inject these ions into storage rings, where they will be able to use them for high-precision measurements of the behaviour of the remaining electrons in ultra-strong electric and magnetic fields. These measurements will test the validity of fundamental theories such as QED and Einstein’s special theory of relativity. Atomic physicists also want to use FAIR to help solve one of the biggest mysteries of physics — whether matter and antimatter behave in the same way. In other words, they hope to determine if a fundamental symmetry of the Universe always holds — that antimatter is an exact mirror image of matter. If not, it could help explain why there is very much more matter in the Universe today than antimatter. The scientists plan to do this by generating antihydrogen and antihelium and find out how they differ from ‘conventional’ hydrogen and helium.

**Plasma physics**

Most of the matter we encounter in our everyday lives is either a solid, a liquid or a gas. However, Earth is an exception compared with the rest of the Universe. In fact, 99 per cent of the visible matter in the Universe is a mixture of free ions and electrons. Scientists refer to this state as plasma. It is created, for example, whenever matter is very hot, so that the atomic nuclei can no longer hold on to electrons in their electron shells. Stars such as the Sun consist of plasma; on Earth, plasma can be found in lightning bolts and candle flames. At FAIR, researchers will create especially dense plasmas like those inside planets and stars. The findings of plasma research are also interesting for many practical applications. For example, plasmas play a role in the processing of materials, the cleaning of surfaces, and the production of microscopic electronic components. Laser-generated plasmas are also creating promising new technologies for future particle accelerators.
Researchers at FAIR

About 3,000 scientists from more than 50 countries work at the new FAIR particle accelerator on diverse projects — from the development of accelerators and their components to the wide range of experiments themselves. The scientific work conducted at FAIR typically involves international teams employing cutting-edge technologies to explore complex issues. Many of these scientists are talented young people, PhD students as well as postdoctoral researchers, who receive a structured education at the Helmholtz Graduate School HGS-HI-Re for FAIR. Through this programme, FAIR is making a strong impact on society, because the young men and women who graduate will have bright career prospects in not only the field of science but also the business world.

“How do heavy ions influence the properties of carbon materials?” Katharina Kupka, physicist specialising in materials science, is doing research on carbon stripper foils for the FAIR accelerator.

Grzegorz Kalicy, who is an experimental physicist, is using highly polished quartz rods to develop the DIRC detector system for the PANDA experiment.

“How can we measure the particles in a storage ring without destroying them in the process?” Shahab Sanjari, an accelerator physicist, has developed a resonant Schottky pickup for the experimental storage ring (ESR). The pickup can be used to determine the lifetime and the mass of an individual particle.
“How can ion beams be used to treat cardiac diseases?” Anna Constantinescu, a physicist, is using high-energy particles to research innovative medical treatments.

“What does the nuclear structure of exotic, rare, and unstable oxygen atoms look like?” The doctoral candidate Leyla Atar is a nuclear physicist. As part of the NUSTAR experiment collaboration, she is examining neutron-rich oxygen isotopes created in heavy-ion collisions.

“How can we build supercomputers that are simple to maintain, inexpensive, fast, and robust?” Dominic Eschweiler, computer scientist, is developing system software for a trigger in the CBM experiment.

Sofija Antic, a PhD student who is a theoretical physicist, is developing a model of the equation-of-state for extremely compressed matter.