Proposal for an International Accelerator Facility
for Research with Heavy Ions and Antiprotons

From fundamental building blocks...
...to complex matter
FOREWORD

Why is nature the way it is? How is matter formed? What is the origin of the universe? Throughout its history, humankind has been trying to understand the world at an ever deeper level. The driving force for investigating the world around us stems, on the one hand, from our intellectual curiosity, and, on the other hand, from our desire to use this knowledge to improve the conditions of our everyday lives.

Research in the natural sciences, during the last century in particular, has provided us with an increasingly detailed picture of the world and the structure of matter. At the same time, our steadily deepening insights into nature and matter have sparked the development of new technologies and applications to an unprecedented degree.

And the search goes on. We are continuing to analyze the elementary building blocks of the universe and the fundamental forces that act between them at an increasingly deeper level. At the same time, we have learned, however, that the structure of matter—from the atomic nucleus to the biological world—cannot be interpreted in terms of a simple linear superposition of the basic building blocks. Instead, it is governed by a great complexity that we need to understand.

Particle accelerators have played a key role in these investigations, and they will continue to do so in the future. Just like modern microscopes, they allow us an ever deeper probing into the structure of matter and the evolution of the universe.

In order to embark upon a further major step in this direction, GSI scientists are cooperating closely with universities and research institutes, both in Germany and abroad, in planning an international accelerator center for intense, high-energy ion and antiproton beams.

The scientific aims of the new project complement those of particle physics, which studies the smallest building blocks of matter and the forces acting between them. The major goal of the new facility planned at GSI is to answer the question of how these building blocks and forces lead to the creation of the complex structures of matter that constitute our universe today.

To that end, the planned accelerator complex will bring together scientists from diverse fields that range from nuclear and atomic physics, astrophysics and plasma research all the way to materials research and biophysics, thereby enabling GSI to initiate a broad interdisciplinary and international science program at one central research facility.

Prof. Dr. Walter F. Henning
Scientific Director of GSI
From fundamental building blocks... …to complex matter
<table>
<thead>
<tr>
<th>Page Range</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 – 5</td>
<td>GSI</td>
</tr>
<tr>
<td>6 – 7</td>
<td>The Structure of Matter</td>
</tr>
<tr>
<td>8 – 9</td>
<td>The Evolution of the Universe</td>
</tr>
<tr>
<td>10 – 13</td>
<td>Ion Accelerators – Tools for Research into Matter</td>
</tr>
<tr>
<td>14 – 15</td>
<td>The Properties of the Strong Force</td>
</tr>
<tr>
<td>16 – 17</td>
<td>The Origin of the Chemical Elements</td>
</tr>
<tr>
<td>18 – 19</td>
<td>States of Matter</td>
</tr>
<tr>
<td>20 – 21</td>
<td>Symmetries, Symmetry Violations, Symmetry Breaking</td>
</tr>
<tr>
<td>22 – 23</td>
<td>From Fundamental Research to Application</td>
</tr>
<tr>
<td>24 – 25</td>
<td>Technological Challenges and Innovations</td>
</tr>
<tr>
<td>26 – 27</td>
<td>Architectural Plan</td>
</tr>
<tr>
<td>28 – 29</td>
<td>The International Context</td>
</tr>
<tr>
<td>30 – 31</td>
<td>Glossary</td>
</tr>
<tr>
<td>32</td>
<td>Masthead</td>
</tr>
</tbody>
</table>
GSI TODAY – THE CURRENT SITUATION

GSI already has an excellent, and in many respects unique, accelerator facility for ion beams. It repeatedly enabled researchers to make new, and at times unexpected, discoveries while engaging in fundamental research. In addition, it has led to the development of remarkable applications.

Among the best-known findings are probably the discovery of six new chemical elements with the atomic numbers 107 – 112, and the development of a tumor therapy using ion beams, both of which also caught the attention of the general public. However, GSI can list a much broader range of discoveries that are scientifically just as significant—particularly with regard to nuclear, atomic and plasma physics. Such discoveries have greatly helped GSI to secure a leading international role in ion beam research.

The scientific attraction of the GSI accelerator facility is reflected in the large number of scientists from Germany and abroad who use it. All in all, about 1,000 researchers from universities and laboratories around the world conduct experiments at GSI every year.

Among the users, university research groups play the dominant role. In this way, GSI contributes greatly to the education of young scientists and engineers. Presently, more than 220 doctoral students are involved in research projects at GSI.

The successful research team after the discovery of element 112.

Scientists construct large detector systems in order to study the properties of atomic nuclei.

Some 40 patients per year are treated with the new ion-beam irradiation technique.
GSI TOMORROW – THE VISION

With the proposal for a new international accelerator center, GSI is building on its tradition and expertise with regard to the construction of accelerators and research using ion beams. Moreover, it is moving forward in research directions both established and new.

The planned facility will boost the intensity of the beam by a factor of 100 to 10,000 and increase the beam energy 15-fold. It will offer the opportunity to create ion beams and beams of antimatter, antiprotons, of the highest quality for use in the research program. High-quality beams are characterized by their precisely defined energies and their tiny lateral profiles. These features, together with the higher beam energies and intensities, will require the development of innovative, new detector systems and experimental techniques.

With the new project, GSI aims to provide scientists in Europe and the world with an outstanding accelerator and experimental facility for studying matter at the level of atoms, atomic nuclei, protons and neutrons as the building blocks of nuclei—and part of a wider family called hadrons—and the subnuclear constituents called quarks and gluons.

To achieve this goal, the new accelerator facility will offer a research program that is in many ways unique worldwide, combining a wide spectrum of scientific disciplines. Around 2,000 scientists from a great variety of fields will be able to conduct research at the new facility.
WHAT WE KNOW...

When making our way into the innermost regions of matter, we first meet crystal lattices or molecules before reaching the level of atoms. In the 20th century, physicists were able to prove that atoms are not indivisible, but are instead composed of an extended electron shell and a compact atomic nucleus. The nucleus itself consists of positively charged protons and of neutrons, which carry no charge. Together, these particles are designated as nucleons. They are part of a larger family of particles called hadrons.

Around 30 years ago, we discovered that nucleons and all other hadrons also possess an inner structure. The particles that make up this structure are called quarks, and are today viewed as the fundamental building blocks of matter, along with electrons.

The matter in and around us is therefore structured as a hierarchy of various composite systems covering almost 40 orders of magnitude in size, from galaxies and macroscopic matter that we can touch, all the way to the elementary particles—the quarks and electrons.

Different binding forces hold the systems together in the various hierarchies. While processes on the macroscopic level are governed by the force of gravitation, the prominent force at the atomic level is the electromagnetic attraction between the negatively charged electrons and the positive atomic nuclei. The atomic nuclei, in turn, are held together by the so-called strong force, which acts
between the quarks within the nucleons and also is responsible for the binding of nucleons in nuclei. In addition, there is the weak force, which is just as important for the creation of matter, since, by the way of radioactive decay, it allows the transformation of nuclei.

...AND WHAT WE WOULD LIKE TO KNOW

Even if we know what the basic building blocks of the universe are, we still have a long way to go until we can describe the complex properties of matter and its various manifestations. One reason for this is that we still know too little about the fundamental forces and their underlying symmetries. This is especially the case with the strong force acting between quarks and between nucleons, a force that still retains many mysteries.

The second reason can be best explained with the expression: The whole is more than the sum of its parts. The various manifestations of matter are the result of a complex interaction between many of its component parts. Since the creation of the universe, this complex interaction has produced various metamorphoses of matter that have brought about increasingly larger and more complex structures.

THE PLANNED FACILITY IS INTENDED TO HELP US SOLVE THE PUZZLE POSED BY THE STRUCTURE OF MATTER.

Unlike electrons, quarks do not exist in nature as isolated particles. Instead, they are always linked to each other in groups of two or three.

► Why do quarks never exist in isolation?

Protons and neutrons contain three quarks each. Strangely enough, however, the mass of the elementary quarks accounts for less than two percent of the mass of the nucleons.

► Why are protons and neutrons so much heavier than their constituents?

There are about 300 different stable nuclei here on earth. The universe, however, is home to a much larger group of unstable atomic nuclei (probably over 6,000) that transform into stable nuclei by means of radioactive decay.

► In what ratios of protons to neutrons can nuclei exist? What new properties do highly unstable nuclei reveal?

The forces that act on the basic building blocks of matter are subject to specific symmetries that fundamentally influence the structure of matter and the development of the universe.

► What fundamental symmetries govern the laws of nature? When, and with what consequences, do violations of such symmetries occur?
WHAT WE ALREADY KNOW...

The composition of matter—the hierarchy of consecutive levels from the microscopic to the macroscopic scale—is closely linked to the sequence of the evolutionary eras that our universe has passed through.

The universe was born in the big bang, and expanded explosively while gradually cooling down from an initial state of extreme energy densities and temperatures. A sequence of metamorphoses brought it to its current state, and will continue to alter our universe in the future.

At the very beginning of the universe, elementary particles were formed from pure radiation fields. Out of a primordial soup consisting of quarks, gluons, photons, and leptons the building blocks of atomic nuclei—neutrons and protons—came into being just fractions of a second after the big bang. Within the first three minutes the lightest atomic nuclei were formed. Neutral atoms came into existence only 300,000 years later. They accumulated into huge gas clouds, from which the first stars were born after about one billion years. Atomic nuclei fused inside the stars to form the chemical elements up to iron. The heaviest elements were generated in violent stellar explosions. These processes still go on today—15 billion years after the big bang—and will continue into the distant future.
The cosmic evolution is directly determined by the laws of physics and by the fundamental symmetries of nature. Our quest for understanding the origin and the development of the universe, and therefore our own existence, is one of the basic motivations for scientific research.

AND WHAT WE WOULD LIKE TO KNOW

Although we know the approximate sequence of events in the cosmic drama, there are still many unanswered fundamental questions concerning the details.

THE NEW FACILITY IS INTENDED TO HELP US ANSWER SOME OF THESE FASCINATING QUESTIONS ABOUT THE EVOLUTION OF THE UNIVERSE.

About a millionth of a second after the big bang, all matter existed as an unimaginably hot, dense primordial soup consisting of quarks, gluons and other elementary particles. Like electrons in a plasma, quarks were able to move about quasi-freely in this quark-gluon plasma. Scientists believe that similar forms of matter might exist in the interior of neutron stars.

Is it possible to use nuclear reactions to recreate and study the transition from nuclear matter to quark-gluon matter?

It wasn’t until a billion years after the big bang that the first complex atomic nuclei and thus the chemical elements were formed at the cores of stars and in stellar explosions. Prior to this, there existed only hydrogen and the lighter elements, up to lithium.

How do heavier nuclei and elements come into being? What is the significance of unstable nuclei in this process?

The moderate temperature and pressure conditions on earth were favorable for the birth of life. The great majority of matter in the universe is subject to extremely high pressures and temperatures—in the earth’s core, for example, or even more dramatically, in the center of larger planets and of the sun.

What is the state of matter under extreme temperatures and pressures?

Astronomical research has demonstrated that the universe now contains only matter, and that no antimatter exists. Scientists’ qualitative explanation for this is that physical laws violate certain fundamental symmetries. However, cases of this symmetry violation found in experiments are not sufficient to quantitatively understand how matter survived in the universe.

Can we discover new information in nature regarding symmetry violations?

We know from the movement of the galaxies that there must be approximately 20 times more mass in the universe than we can directly observe. It has been suggested that this so-called dark matter possibly includes new types of particles bound by the strong interaction, the existence of which we have not yet been able to prove in experiments.

Will it be possible to discover more about these new forms of matter under improved experimental conditions?
WHAT WE ALREADY HAVE AT GSI...

The key research instrument that allows us to look further and further inside matter and into its structure is the particle accelerator. Scientists use it to accelerate electrons, protons or atomic nuclei to very high energies and then make them collide either with each other or with a sample of matter. By analyzing the resulting fragments and new particles, they gain information about the composition and structure of the matter being studied. The higher the energy to which electrons, protons, nuclei or atoms are accelerated, the sharper the microscopic resolution. Time structure, energy sharpness, and spatial focusing of the particle beams are other important parameters for the experimental programs. Depending on the nature of the accelerated particles, different aspects of the matter under observation are studied.

GSI has been operating a worldwide unique facility for ion acceleration for more than 25 years. Ions are atoms from which part of the electron shell has been stripped away. This means ions are electrically charged and can be accelerated to high speeds using electric fields. GSI is capable of accelerating intense ion beams of all elements in the periodic table, from hydrogen, the lightest, to uranium, the heaviest element found in nature.
The accelerator facilities at GSI currently consist of the UNILAC linear accelerator, the SIS heavy-ion synchrotron, and the ESR experimental storage ring. UNILAC is the world’s most versatile linear accelerator for heavy ions and has the highest beam currents. Using the SIS synchrotron and the ESR experimental storage ring, ions of all the elements can be accelerated to a wide range of velocities, up to 90 percent of the velocity of light. Furthermore, it is also possible to collect secondary beams in the ESR storage ring, such as beams of unstable nuclei that have been formed in nuclear reactions of the primary beams. These secondary beams can then be used in experiments.

**COOLED ION BEAMS**

For many precision experiments, the ion beams, in particular the secondary beams produced in nuclear reactions, have far too low energy sharpness. This means that the velocities of the individual ions in the beam are not uniform, but are distributed around an average. Accelerator physicists have developed various beam manipulation techniques to ensure as far as possible that the ions travel at the same speed. This so-called beam cooling technique is one of the outstanding technological innovations that has been very successfully employed by GSI researchers for generating high-quality beams of heavy ions.

One such method is electron cooling. This process involves superimposing a parallel beam of electrons moving at a precisely defined speed on the ion beam in the storage ring over a distance of a few meters. Each time the circulating ions pass through the electron beam, thousands of collisions occur between the electrons and the ions, causing each ion in the beam to conform to the speed of the electron beam within a fraction of a second. The initially wide velocity distribution of the ions thereby becomes as narrow as that of the electrons. At the same time, the beam profile becomes smaller and sharper. This corresponds to a reduction in the disordered movement of the individual ions in the beam—or, in the words of the accelerator physicists, to a reduction in the beam temperature. This is why they refer to the procedure as beam cooling.

Another process used at GSI is so-called stochastic cooling. Here, a probe is used to measure the speed of a small group of ions in a beam. The correct speed is gradually achieved by successively feeding in correction pulses with the appropriate phase.

Both cooling techniques have been developed and employed with great success for precision measurements with energetic ion beams at GSI over the last few years.
...AND WHAT THE NEW FACILITY IS TO ACHIEVE IN THE FUTURE

The proposed project is for an international accelerator facility of the next generation. It builds on the experience and technological developments already made at the existing GSI facility, and incorporates new technological concepts. At its heart is a superconducting synchrotron double ring facility with five times the circumference of the current SIS. A system of cooler-storage rings for effective beam cooling at high energies and various experimental halls will be connected to the facility.

What advantages does the facility have over the existing equipment, and how does the new project differ in terms of new and specific beam properties?

The large synchrotron will achieve 100 times higher primary-beam intensities than possible today, and the intensity of the secondary beams of unstable nuclei will be up to 10,000 times greater. Furthermore, energies 15 times higher than in the present SIS synchrotron can be attained using the second synchrotron in the double ring facility. Due to the high energies and intensities of the primary beam, it will also be possible to generate intense, cooled antiproton beams at the new facility and so open up new types of experiments.

The existing GSI facility (blue) with the linear accelerator UNILAC, the heavy-ion synchrotron SIS, the fragment separator FRS and the experiment storage ring ESR; and the new project (red) with the double ring synchrotron SIS 100/200, the high-energy storage ring HESR, the collector ring CR, the new experiment storage ring NESR, the superconducting fragment separator Super-FRS and several experimental stations. The UNILAC/SIS complex serves as the injector for the new double ring synchrotron.
The higher the intensity of the ion beams, the higher the probability that rare reactions or reaction products can be observed. By providing the highest beam intensities, the planned facility opens up new possibilities for scientists in studying secondary beams of unstable nuclei. Researchers will have access to a wide range of new nuclei previously unavailable in the laboratory. For example, the nuclei that play a vital role in explosive nucleosynthesis—the synthesis of the heavy elements in supernova explosions—will become available.

Ion and antiproton beams of the utmost energy sharpness are necessary in precision experiments to determine the mass of short-lived, unstable nuclei—or to look for new particles associated with the strong interaction. The beam cooling techniques already in operation at the existing facility—stochastic and electron cooling—will therefore continue to play a central role in the new project. Implementing them will be one of the big technological challenges at the planned facility, since the beam intensities and energies are so much higher.

The new double-ring synchrotron will also allow significantly higher ion energies compared to the present GSI facility. Thereby highly compressed nuclear matter can be produced in nucleus-nucleus collisions and be probed with forefront detectors at unparalleled intensities. In this way, scientists aim to study the state of matter that existed at the birth of the universe. Such extreme forms of matter may also exist at the center of neutron stars. Moreover, it is expected that a maximum production rate of hadrons with strange quarks will be achieved in the energy region covered by the new facility. Furthermore, the energy threshold for the production of hadrons with charm quarks and of antiprotons will be exceeded. As a consequence, scientists will be able to produce intense antiproton beams.

In order to create hot, dense plasmas in bulk matter by ion beam irradiation, it is necessary to generate short, high intensity ion pulses. At the new facility, ion pulses with a power of a thousand billion watts can be generated.

One of the basic arguments in favor of the double ring concept for the new accelerator at GSI is its ability to operate in parallel up to four different scientific programs involving different kinds of ions. This will be achieved by well-coordinated use of the accelerators and storage rings. A particular synergy effect will be created when the entire facility is in use.
Quarks are held together inside the nucleon by binding particles known as gluons. The force acting between quarks demonstrates unusual behavior. It is very small when quarks are positioned close together, increases as the distance between quarks grows, and then remains constant even when quarks move further and further away from each other. The reason for this unusual behavior is that gluons interact with and attract not only quarks, but also each other. In this way, a kind of flexible tube made up of gluons is produced between the quarks, comparable to an elastic band or a spring. The paradox is therefore that two quarks are only free when they are positioned close to one another. Separating them from each other requires huge amounts of energy and results in the production of new quark-antiquark pairs.

Despite intensive searches, no quarks have yet been discovered in isolation in nature. This imprisonment of quarks is known as confinement. One of the greatest intellectual challenges faced by modern physics today is to understand confinement not just as a qualitative phenomenon, but also to comprehend it quantitatively as part of the theory of the strong force. Experiments at the planned new facility will play an important role in this research.
THE ORIGIN OF MASS OF THE MATTER THAT SURROUNDS US

The mass of a compound system is generally made up of the sum of the masses of the individual constituents, except for small corrections due to binding effects, which slightly reduce the total mass. The mass of an atom is therefore determined to a large extent by the mass of the nucleus and the electrons, and that of a nucleus by the sum of the masses of the nucleons.

Less than two percent of the total mass of a nucleon, however, is accounted for by the mass of the quarks. So how can mass arise from more or less massless constituents? The knowledge we have available to us today tells us that the mass comes from the kinetic energy and the interaction energy of constituents of the nucleon. Ultimately, all this energy is equivalent to a mass defined by Einstein's equation $E = mc^2$. The details of this mechanism are, however, not yet fully understood. The theory of the strong force is so complex under the conditions prevailing inside the nucleon that a deeper understanding of the physics involved can only be achieved through further, high-precision experiments. Such experiments will be possible at the planned facility. The fundamental significance of this problem can be demonstrated by the fact that the mass of the nucleons determines the mass of matter around us—more than 99.9 percent of the mass of an atom is found in the nucleons of the atomic nucleus.

THE SEARCH FOR NEW FORMS OF MATTER

All compound particles bound together by the strong interaction are called hadrons. So far, two types of hadrons have been found in experiments: baryons, which consist of three quarks, such as protons and neutrons (the building blocks of the nucleus); and mesons, which consist of two quarks, or a quark and an antiquark to be more precise.

According to the theory of the strong interaction, other combinations are also possible. Examples are hybrid states, made up of two quarks and a gluon, or pure gluon states, also known as glueballs. The existence of these exotic hadrons has been hinted at by various experiments, but we have no unambiguous signatures of the particles as yet. Furthermore, a large variety of multiple quark combinations may also exist.

With its high-energy antiproton and ion beams, the new facility will open the door to unique possibilities in the search for such exotic hadrons. Some of these are also considered to be candidates for part of the so-called dark matter in the universe. Finding proof of their existence would thus have important implications for astrophysics and cosmology.
The chemical elements of the periodic table are the building blocks of matter and the basis of life itself. How did this variety of elements arise? What processes played a role here?

Answering these questions is one of the central concerns of modern nuclear physics and astrophysics, and also one of the main areas of research in the new project.

We know that the chemical elements are formed through nuclear reactions inside stars and in stellar explosions. During this process, known as nucleosynthesis, a multitude of different types of nuclei, or isotopes, is formed. Most of these are unstable and decay into stable nuclei either directly or via several intermediate steps.

### FUSION UP TO IRON

The elements up to iron are produced by fusion reactions inside stars. Beginning with the fusion of hydrogen into helium, larger and larger nuclei are formed. This process releases energy, which is the reason why the sun shines and provides us with heat. Fusion ceases with the element iron. This is because fusion into even larger nuclei would require energy input. As a result, stars begin to burn out when this stage has been reached.

Fusion reactions inside stars (protons: red; neutrons: blue).
DETOURS TO URANIUM

Nuclei heavier than iron are produced at the end of the lives of large stars—so-called red giants—and in violent explosions of stars. All the production paths that occur in such circumstances lead to stable heavy nuclei indirectly via intermediate radioactive nuclei.

The prerequisite for this is the presence of free nucleons, neutrons or protons, that can be captured by the existing light nuclei. Neutrons are released by nuclear reactions in red giants and—in significantly greater numbers—in supernova explosions; protons are released in X-ray binary star systems such as X-ray bursters. Through the capture of these free nucleons, unstable neutron-rich or proton-rich nuclei form and subsequently decay to form the heavier stable isotopes. This is how all the elements up to uranium are formed.

NUCLEOSYNTHESIS IN THE LABORATORY

To date, we have only a qualitative understanding of nucleosynthesis; the detailed processes are to a great extent still unknown. At the proposed new facility, scientists will be able to artificially produce the nuclei that occur as radioactive intermediate products in the formation of stable isotopes. The various processes involved in nucleosynthesis can thus be measured directly in the laboratory, and the intertwined paths of nucleosynthesis traced. This will also permit a better understanding of the abundance of the elements in the universe.

All of these nuclear and astrophysical aspects can be investigated in detail at the new facility. The project thus presents us with a fascinating view of the properties of nuclei and the origin of the elements—and hence of our own existence.
The matter that surrounds us from day to day impresses us with its variety of states and colors. Everyone knows water, for example, as snow and ice at low temperatures, as a refreshing drink at room temperature, or as hot steam in a cooking pot. Through changes in temperature and pressure, water can be brought into these three different states—or phases: solid, liquid, gaseous.

Another state of matter is plasma. This state is reached when we apply such high energies that individual electrons are torn from the electron shell of the atoms that make up matter. A system of free, negatively charged electrons and positive ions is thus created. This electron-ion plasma can exist across a large range of temperatures and densities, and can change into various phases.

HYDROGEN AND ITS VARIOUS FORMS

The adjacent diagram illustrates this for hydrogen, which, depending on pressure and temperature, occurs in the universe in very different states and with various properties: as a cold gas in large hydrogen clouds; a thin, hot plasma in the solar corona; a molecular fluid on the surface of and a metallic liquid inside giant planets; or a high-density fusion plasma in stellar interiors.

To create hot and dense plasmas in the laboratory, scientists at GSI bombard solid materials with high-intensity, pulsed heavy-ion or laser beams. For the first time worldwide, the combination of these two beams is being synergistically used for the analysis of the plasmas created. At the proposed new facility, it will be possible to advance into ranges of plasma temperature and density that approximate the conditions in giant planets, such as Jupiter. Moreover, these studies open up the fascinating possibility of investigating the basic physics aspects of inertial fusion—for many scientists a process that may represent the future energy supply for humanity.
THE MATTER THAT MAKES UP ATOMIC NUCLEI

Nuclear matter—the stuff that makes up atomic nuclei—is more than $10^{14}$ times denser than normal matter. A piece the size of a lump of sugar would weigh about 300 million tons. Just like normal matter, nuclear matter—or more generally hadronic matter (matter consisting of hadrons)—exists in different states. These phases are also defined by temperature and density, on the surface and in the interior of neutron stars, for example. In the laboratory, nuclear matter can be heated and compressed in high-energy, nucleus-nucleus collisions. In reactions of this kind, hadrons that contain so-called “heavy quarks” are also created.

Thus far we have referred to quarks only as one type of particle. However, in all there are six different types of quarks with various charges and masses known as the up, down, strange, charm, bottom, and top quarks. The light quarks are the up and the down quark, which make up the proton and the neutron. Strange quarks might exist in neutron stars, the heavier quarks only existed in the early universe. The heavy quarks can be created in accelerator facilities for a short period of time. The collision energies that can be achieved with the proposed accelerator complex will open up the physics of the medium-heavy strange and charm quarks, large areas of which have yet to be investigated.

First indications of the existence of the quark-gluon plasma were recently discovered in experiments at CERN in which GSI scientists played a major role. Its properties will now be studied more closely at very high temperatures at the RHIC accelerator in the U.S.A. and, beginning in 2006, with the ALICE experiment at the LHC (CERN).

The task of the proposed facility at GSI will be to investigate the possible phase transition to the quark-gluon plasma at high densities. With energies up to 15 times greater than those now available at GSI, the new facility is ideally suited to advancing into this largely unknown area of the phase diagram of hadronic matter. This is precisely the region in which—based on experimental results at CERN and BNL, Brookhaven—nucleus-nucleus collisions can be expected to produce hadronic matter with an increased proportion of strange quarks. The latter are suspected of being a basic component of the dark matter in the universe.

The illustration shows the phase diagram of hadronic matter as predicted by theory. It plots the temperature in units of one million electronvolt against the density in units of normal nuclear density $\rho_0$. At very high temperatures and densities, physicists expect that the quarks and their bonding particles, the gluons—normally locked up inside the nucleons—become liberated from their confinement and move as free particles in a so-called quark-gluon plasma. A phase transition in the opposite direction, from quark-gluon matter into hadronic matter, occurred in the early universe. Today, quark-gluon matter might still exist in the interior of neutron stars.
Symmetries play a central role in the states of matter. On a simple level, we can see this in the geometric—and often beautiful—structure of crystals or a snowflake. Symmetries in the elementary framework of the laws of nature are less visible, but they are of fundamental importance. Do elementary processes go on unchanged when they are mirrored, when particles are interchanged with antiparticles, or when time is reversed as in a film running backwards?

Take mirror symmetry, for example. A pirouette turned to the right can just as well be turned to the left, e.g., mirrored. It was therefore surprising to discover that in beta decay, which is caused by the weak force, mirror symmetry is violated: the process that constitutes a mirrored version of beta decay does not occur in nature. Although such symmetry violations seem of little importance for our everyday lives, they have been crucial for the existence and composition of matter in the cosmos since the beginning of the universe.

The search for symmetry violations in nature is therefore a central concern of modern physical research. They can be studied with great precision in the microcosm of atoms, of atomic nuclei or of quarks, without disturbances from complex external influences. It is sometimes a matter of only the smallest deviations from the expected symmetry. Their detection not only entails a radical change in the worldview of physics but can also have enormous consequences for our ideas of the evolution of the universe.

Any action in everyday life, such as turning a pirouette, can also occur as its mirror image. In the microscopic world, however, processes exist that violate mirror symmetry. The beta decay of the isotope cobalt-60 is shown as an example. This unstable nucleus possesses a spin, indicated by the yellow arrow. In the experiment, one finds that for the given direction of the spin, the electron is always emitted upwards. The mirrored process—electron emission in an upward direction with reversed spin orientation—is not observed. Mirror symmetry is thus violated.
OUR EXISTENCE – RESULT OF A SYMMETRY VIOLATION IN NATURE

A striking example of the importance of symmetry violations is provided by processes in which the combination of mirror symmetry and the symmetry of particle-antiparticle exchanges is violated. The existence of this type of symmetry violation is essential for our own existence, since without it the matter and antimatter that were produced symmetrically in the big bang would have completely annihilated each other into radiation. No matter would then remain, and the universe would be filled with nothing but electromagnetic radiation. Nevertheless, the amount of matter that exists in the universe cannot be explained quantitatively by the few cases of this type of symmetry violation that have been found thus far. At the new facility, physicists therefore want to look for other examples, particularly among hadrons with *strange* and *charm* quarks.

Another topic is the search for processes in which a violation of the time-reversal symmetry occurs. Their detection would be most remarkable also from a philosophical point of view, as time would thus already have a defined direction in the universe at the level of elementary processes. The proposed facility offers scientists very sensitive tests of time-reversal symmetry by means of precise measurements of the beta decay of exotic nuclei or the search for electric dipole moments in certain atoms and nuclei.

THE MASS OF HADRONS – GENERATED BY SPONTANEOUS SYMMETRY BREAKING

In addition to symmetries and symmetry violations, certain spontaneous symmetry breaking phenomena have had a crucial influence on the evolution of the universe and the properties of matter. A vivid example of this type of spontaneous symmetry breaking is the phase transition from paramagnetic iron to the ferromagnetic state, in which an arbitrarily aligned magnetization sets in below a critical temperature. The full rotational symmetry originally present in the paramagnetic state is thus spontaneously broken.

Physicists assume that the phase transition from the quark-gluon plasma to the hadrons was also accompanied by a spontaneous symmetry breaking. According to their view, in the early phase of the universe, the “chiral” symmetry was satisfied for the light *up* and *down* quarks, which make up almost all of the matter in existence. This means that the handedness (Greek: chirality) of an *up* or *down* quark, which is defined by its momentum and spin, is preserved in the presence of the strong force.

If this symmetry were also satisfied in our world today, it would have to be reflected in the masses of the hadrons made up of light quarks. In particular, certain pairs of hadrons known as “chiral partners” should have equal masses. But this is not what we observe. The explanation physicists give for this is that the chiral symmetry was spontaneously broken in the transition from the quark-gluon plasma to the hadronic phase.

Further considerations lead us to conclude that in dense nuclear matter this symmetry should be partially restored, especially at the temperatures and densities that occur in high-energy collisions of two atomic nuclei.

With energetic ion and antiproton beams, the new facility opens up a broad field of research for probing the phenomenon of chiral symmetry and thus for coming closer to the secret of how quark-composed particles, which make up our world, obtain their masses.

---

In a hypothetical chiral world—one that satisfies chiral symmetry—certain pairs of hadrons known as chiral partners should have equal masses. The spontaneous breaking of chiral symmetry in our world leads to a mass shift and splitting that finally determines the observed hadron masses. Scientists believe that chiral symmetry is partly restored at high temperatures and densities. Experiments at the new facility will probe this phenomenon.
In the past, research with heavy ions has led to diverse applications and technological innovations in other fields. Impressive examples of this are techniques for hardening materials or for creating microstructures and micro-objects. Others include the development of testing equipment for electronic components in satellite and aerospace engineering, and work in radiobiology and accelerator engineering directed towards developing a new tumor treatment using ion beams.

The ion beam treatment developed at GSI is currently being tested in clinical studies with extremely promising results. And the next step toward general patient care and commercial exploitation of the new technologies developed for such an application is already in sight. Based on the pilot project at GSI, the first center for ion beam therapy in Europe will be built in the coming years at the University Clinic of Heidelberg in cooperation with industrial partners.

A large number of the applications that have emerged from research with ion beams have required long development times—over 20 years in the case of cancer therapy with ion beams—and were not initially obvious. Thus, it is extremely difficult to foresee concrete applications that will arise from the scientific and technical achievements brought about by the new facility. As in the past, however, we expect new developments, some of which will lead to specific applications. From today’s point of view, it is possible to discern several areas for such applications.

NEW PROBES AND TECHNIQUES FOR SOLID STATE PHYSICS AND MATERIALS RESEARCH

Radioactive atoms are being used very successfully as probes to study processes and the properties of materials. The proposed facility will enable the use of new radioactive probes for such studies and, when necessary, make them available as isotopically pure secondary beams. The high energy of the secondary beams also results in new...
possibilities in other areas. One can implant the probes through thick walls—in high-pressure cells, for example—and in this way study material properties under extreme conditions.

TEST EQUIPMENT FOR SATELLITES OR SPACECRAFT COMPONENTS

During their missions, satellites and spacecraft are exposed to cosmic radiation, especially high-energy protons, helium nuclei and other heavy ions up to and including iron. This can lead to the corruption of information or permanent damage in electronic chips and, in extreme cases, jeopardize the entire mission. Accelerator systems make it possible to simulate cosmic radiation. The new facility allows us to examine not only individual components but also whole systems, including satellites or spacecraft components, and to do so throughout the relevant energy range of cosmic radiation.

RADIOBIOLOGICAL RISK ASSESSMENTS FOR MANNED SPACE MISSIONS

In manned space missions, astronauts are exposed to high levels of radiation, and this will particularly be the case in the planned extended-duration flights to Mars. Little is thus far known about the radiobiological effect of the high-energy components of cosmic radiation. Even when the particle fluxes at these high energies decrease drastically, secondary reactions in the walls of the spacecraft and particle showers resulting from them can add significantly to the overall exposure. With the beam energies available at the proposed facility, these effects can be studied, and the risks they pose to astronauts assessed.

STUDIES ON THE CREATION OF FUSION PLASMAS THROUGH INERTIAL CONFINEMENT

The high-intensity ion pulses delivered by the new accelerator complex enable scientists to create hot, dense plasmas. In addition to its significance for basic research, this phenomenon also carries a long-term interest for its possible applications. For example, this research could indicate new ways of achieving the fusion of hydrogen into helium in the laboratory and for harnessing this process so as to supply energy in the distant future. Together with the high-energy/high-power laser PHELIX currently installed at GSI, the proposed accelerator facility creates ideal experimental conditions for research into the basic physics aspects of inertial confinement fusion.
Advances in particle and nuclear physics have always been linked to innovations in accelerator technology and detector design. Similarly, the new project also involves a number of ambitious developments. These include the following:

- **Superconducting magnets with rapidly variable fields**
  
  Strong magnetic fields are used to keep the ions in the accelerator and storage rings on their paths. For technical and cost reasons, it is advisable to use superconducting magnets to create strong magnetic fields. This technique will therefore be used in the new project as well. In the synchrotron rings, however, not only strong fields but also rapidly variable fields are required. Generating such rapidly varying fields with superconducting magnets represents a special technological challenge. In order to attain the required specifications, new designs for magnets that can be rapidly pulsed are currently being pursued in cooperation with partners from the U.S.A., Europe and Russia.

- **Separator for secondary beams of unstable nuclei**
  
  One important research goal of the new facility is the creation and investigation of unstable nuclei with the perspective of gaining information about nucleosynthesis in the universe. These unstable nuclei must first be created in nuclear reactions and then be separated from the multitude of other nuclei that are likewise produced. To attain this goal, scientists envisage using a large separator stretching over 100 meters. Equipped with superconducting magnets, it will ensure a highly efficient isotopically pure separation of the desired nuclei.
**System of cooler-storage rings**

When it comes to making precision measurements with secondary beams, unstable nuclei or antiprotons, the scientists first direct these beams into storage rings. There, the energy sharpness and the beam diameter can be improved even further for precision experiments by means of various beam-cooling processes. This strategy is already being used very successfully in the existing SIS/ESR system at GSI. The new facility will have a complex system of matched storage rings and beam-cooling systems that create optimum conditions for these studies. In particular cooling of very high energetic ion beams is one of the great technological challenges at the new facility.

**Large detectors with high data rates**

In high-energy nucleus-nucleus collisions, the nuclei break up into many fragments and a multitude of new particles is produced. By measuring these particles and their velocities as precisely as possible, scientists can draw conclusions concerning the properties of the nuclear matter that is heated up and compressed in the nucleus-nucleus collision. To collect the necessary data, physicists build large, highly segmented detectors in which the particles leave traces along their trajectories. This makes it possible to identify them and measure their energies.

The experiments planned at the proposed new facility must be designed in a manner that makes it possible to register up to a thousand particles produced from one single nucleus-nucleus collision. Moreover, it must be possible to measure such events at intervals of one-millionth of a second. The high data speeds involved here exceed the current capabilities of data processing and represent a special challenge for experts working in the field of information technology.
The new accelerator complex will be constructed to the east of the existing GSI facility. The fact that the project will use the existing accelerator as an injector influenced the decision to build the new facility here. The architectural plan also incorporates the need to conform to radiation protection requirements and optimize costs for the buildings and technical facilities. All these considerations have led to the following concept:

The large double ring with a circumference of just under 1,100 meters will be laid out underground in a ring tunnel at a depth of 24 meters. Construction of the tunnel can be carried out very cost-effectively using the shield driving process. The underground arrangement also results in considerable cost savings when it comes to the shielding measures for radiation protection. Another important advantage of the plan is that it preserves part of the forest currently covering the region associated with the double ring.

All of the other buildings will be arranged south of the large ring tunnel. Due to the large areas involved, an above-ground solution is more economical here. Construction of the above-ground buildings will require clearing of approximately 14 hectares of forest that will be replanted in another area as a compensation.
ENVIRONMENT AND SAFETY

Environmental and safety aspects have the very highest priority when it comes to both the operation of the existing GSI accelerators and plans for the new facility.

When in operation an accelerator produces radiation. Therefore, scientists are prohibited from being present in the accelerator tunnel or at the experimental stations. Beyond that, extensive shielding measures prevent radiation from reaching the outside.

For example, in the double ring SIS100/200, such protection is guaranteed by a thick concrete tube and the underground arrangement. The radiation level on the surface will be small compared with the natural level of background radiation that is always present in the environment.

Furthermore, plans call for the use of thick shields of concrete in the design of the above-ground areas of the facility—as is the case at the existing GSI facility. These will reduce the radiation below the natural level of background.

Finally, all plans and guidelines for the shielding measures are being worked out by safety experts at GSI and then reviewed by independent outside specialists. During the later, operational phase, a monitoring system will continuously check the radiation level inside and outside of the facility site—as is the case now at GSI.

Could anything dangerous happen if something at the facility malfunctioned? No, because the accelerator would immediately shut down and beam operation would be interrupted. No more radiation could be produced, and existing radiation in the accelerator would quickly fall to insignificant levels. More importantly, no radiation could reach the environment. Unlike a reactor, an accelerator contains no radioactive inventory at all. For that reason, neither the existing GSI accelerators nor the new project represent any danger to the environment.
THE PROPOSED PROJECT...

...is based on intensive discussions regarding the long-term prospects of physics research using ion and antiproton beams—a discussion conducted with the users of GSI, in particular the universities, and with the international communities involved in the study of nuclear physics, hadron physics, and atomic and plasma physics.

...is oriented toward the long-term recommendations of European and international expert committees—such as the Nuclear Physics Working Group of the OECD Megascience Forum and the Nuclear Physics European Collaboration Committee (NuPECC)—regarding future large-scale facilities for nuclear and hadron physics.

...is worldwide unique in its overall concept but has overlaps and interconnections with projects elsewhere in selected areas. For example, it overlaps in the field of radioactive nuclear beams with large-scale projects in the U.S.A. (RIA project, in planning) and Japan (RIBF project, under construction), but also goes beyond these projects, since new research possibilities are opened up for three additional major areas of work: hadron physics with antiprotons; nuclear matter physics with high-energy ions; and plasma physics with intense ion and laser beams.

...makes it possible to maintain Europe’s strong position in nuclear and hadron physics and in atomic and plasma physics for the future—and to expand it.

...significantly contributes to a top-flight education of the next generation of scientists and engineers in cooperation with the universities.

The research goals of the new facility and its role in the international context were extensively discussed in various workshops with the respective scientific communities.
SCHEDULE

Approximately eight years have been planned for the realization of the project. The construction period is divided into the following partially overlapping phases:

<table>
<thead>
<tr>
<th>Phase</th>
<th>Time [years]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Development</td>
<td>01, 02, 03</td>
</tr>
<tr>
<td>Design of comp.</td>
<td>04, 05, 06</td>
</tr>
<tr>
<td>Construction</td>
<td>07, 08, 09</td>
</tr>
<tr>
<td>Commissioning</td>
<td>10</td>
</tr>
</tbody>
</table>

COSTS

The estimated costs for the project can be broken down as follows:

- Building and infrastructure: 225 Mio. €
- Accelerator: 265 Mio. €
- Experimental stations and detectors: 185 Mio. €

Total: 675 Mio. €

NATIONAL AND INTERNATIONAL COOPERATION

The size and scope of the project and the total costs suggest that the new project be realized in international cooperation. The new accelerator complex will therefore be planned and constructed with substantial participation of national and international partners. As in the past, university groups will play a central role in these collaborations. The involvement of personnel and/or funds from external partners is also being considered for the later operation of the facility.

Close cooperations have already been formed during the design phase—e.g., with European, Russian, and American institutes in the development of the superconducting magnets or the beam cooling. The planning and construction of the detectors and the creation of the research program is also taking place within the framework of national and international collaborations with groups from universities and other research centers. Such cooperative efforts arise from GSI’s long-standing tradition of international collaboration, and the fact that the institute has pursued its research program with the participation of many users from abroad ever since its establishment.

GSI scientists meet regularly with the external collaboration partners to discuss the progress made in the research and development work for the new facility.
GLOSSARY

Accelerator: Facilities that use electric fields to accelerate charged particles (e.g., electrons, protons or their antiparticles, or heavy ions) to very high energies. Accelerator experiments are used in physics to analyze the structure of matter and to study elementary particles and their interactions. A distinction is made between linear and ring accelerators, depending on their shape.

AGS: Alternating Gradient Synchrotron at the Brookhaven National Laboratory, U.S.A.

Antimatter: Matter composed of antiparticles.

Antiparticles: Every type of particle has a corresponding partner (antiparticle) of the same particle family with equal mass but otherwise opposite properties, e.g., opposite electric charge. If a particle collides with its antiparticle, they annihilate to form photons or other particles.

Atom: Atoms consist of positively charged atomic nuclei surrounded by an electron cloud. The number of negatively charged electrons is the same as the number of positively charged protons in the atomic nucleus, making the atom as a whole neutral.

Baryons: Particles consisting of 3 quarks that are subject to the strong force. The best-known baryons are the protons and neutrons that make up the atomic nuclei.

Beam cooling: A process for increasing the energy sharpness and reducing the diameter of the ion and antiproton beams. Two methods of beam cooling will be exploited at the new facility: stochastic cooling by means of high-frequency radiation, and electron cooling, in which an electron beam with high energy sharpness is superimposed on the particle beam.

Beta decay: Transformation of a neutron into a proton (or vice versa) with the emission of an electron (positron) and an antineutrino (neutrino). A sequence of beta decays transforms unstable, neutron-rich (proton-rich) atomic nuclei into stable nuclei.

Big Bang: Origin of the universe. State of extremely high energy density from which the universe evolved by expansion and simultaneous cooling.

BNL: Brookhaven National Laboratory, U.S.A.

CERN: European Laboratory for Particle Physics in Geneva, Switzerland

Chiral symmetry: In general: Invariance of properties when going from right-handed to left-handed systems, e.g., macromolecules; here: conservation of the handedness of (massless) quarks under the strong force.

Dark matter: Matter in the universe that does not radiate and can therefore not be viewed directly. Its existence is assumed on the basis of gravitational effects. It is believed that most of the universe’s mass is made of dark matter.

Detector: Complex instrument composed of various individual components that is used to detect particles by recording their tracks and measuring their energy and other properties.

Exchange particles: In the Standard Model, these are special particles which mediate the forces between particles. The exchange particles are the photon for the electromagnetic force, the gluons for the strong force, and the W and Z bosons for the weak force.

Electric dipole: A system composed of two charges of the same strength but of opposite polarity, located a small distance from each other.

Electronvolt (eV): The common unit of energy in atomic, nuclear and particle physics. One eV is the kinetic energy gained by an electron if it is accelerated by a potential difference of 1 volt. The new facility will accelerate protons to 60 GeV (1 gigaelectronvolt = 1 billion electronvolt) and heavy ions such as uranium to 25 GeV per nucleon.

Elementary particle: Smallest building blocks of matter that cannot be further decomposed. In the Standard Model, these are the quarks and the leptons.

ESR: Experimental Storage Ring at GSI.

Glueballs: Particles that are composed predominantly of gluons. The existence of these particles is predicted because gluons interact with each other, allowing them to form bound systems. Although experiments have found indications of the existence of glueballs, no conclusive signatures have yet been discovered.

Gluons: Exchange particles of the strong force. There are eight different gluons, which transfer the force between the quarks. They are electrically neutral and possess no mass.

Hadrons: Compound particles that are held together by the strong interaction. There are two basic types of hadrons: baryons, which are composed of three quarks, and mesons, which are composed of a quark and an antiquark.

Handedness: Relative alignment of a particle’s direction of motion and its intrinsic angular momentum (spin). The direction of motion and spin of zero-mass particles can only be parallel (right-handed) or antiparallel (left-handed) to each other.

Heavy ions: Ions in which the mass number of the atomic nucleus is large.

Hybrids: Particles composed of quark-antiquark pairs and gluons.

Invariance: When physical quantities are constant or physical processes do not change under a given symmetry operation, for example, in spatial reflection or when particles are replaced by their antiparticles.

Ions: Atoms in which the number of negatively charged electrons in the shell is not the same as the number of positively charged protons in the atomic nucleus, resulting in a net electric charge. Ions can be created, e.g., by a discharge in a gas when individual electrons are torn from electron shells. Their net electric charge enables ions to be accelerated to high energies in accelerators.

Isotopes: Atomic nuclei with the same number of protons—thus of the same chemical element—but different numbers of neutrons.

Leptons: Along with the quarks, the leptons form the basic building blocks of matter. There are three pairs of leptons, each pair consists of an electrically charged particle and a neutrino: electron and electron neutrino, muon and muon neutrino, tau and tau neutrino.

LHC: Large Hadron Collider. An accelerator for protons and atomic nuclei being built in an existing tunnel at CERN.

Linear accelerator: Long vacuum tube, in which electrically charged particles are bunched and accelerated by magnetic and electric fields. The linear accelerator used at GSI since 1975 is known as UNILAC (Universal Linear Accelerator) because it can accelerate all types of ions, from protons to uranium.

Matter: The matter of the earth and all visible matter in the universe consists primarily of protons, neutrons and electrons, which together make up all existing atoms.

Meson: Unstable particle composed of a quark and an antiquark and subject to the strong interaction. The meson with the smallest mass is the pion.

Neutrino: Neutral, nearly massless elementary particle belonging to the lepton group. There are three types, the electron, muon and tau neutrinos.
Neutron star: A compact star (diameter about 10 km) that is primarily composed of neutrons. Such stars are the product of supernova explosions. It is believed that matter in the interior of neutron stars contains large numbers of strange quarks. Due to the high densities prevalent in the centers of neutron stars, matter might also be in the state of a quark-gluon plasma.

Neutron: Uncharged particle composed of three quarks. Together with protons, neutrons form atomic nuclei.

Nuclear fusion: Fusion of two atomic nuclei to form a single, larger nucleus.

Nucleon: Collective term for the building blocks of the atomic nucleus. There are two types of nucleons: protons with a positive electrical charge and neutrons which are electrically neutral.

Nucleosynthesis: The creation of atomic nuclei in nuclear reactions. In the universe, such reactions occur in the interior of stars and during stellar explosions.

Phases: Different physical states of matter, such as ice, water and steam. It is possible to go from one physical state to another by adding or taking away energy. The various phases can be represented in a phase diagram in which temperature is shown in relation to the system’s density.

Photon: Exchange particle of the electromagnetic force. The photon has no mass and is electrically neutral. All electromagnetic radiation is composed of photons.

Plasma: Physical state of matter composed of free ions and electrons. It is created from normal matter by adding energy.

Positron: Antiparticle of the electron.

Proton: Positively charged particle made of three quarks. Atomic nuclei are composed of protons and neutrons.

Quarks: Along with the leptons, quarks form the basic building blocks of matter. There are three different families of quarks: up and down, charm and strange, and top and bottom. Quarks can appear in pairs (quark and antiquark) or as triple combinations of quarks or antiquarks.

Quark-gluon plasma: Physical state of nuclear matter at high temperatures and/or densities. In this state, quarks and gluons which normally are confined in the interior of hadrons roam freely. The first indications that the quark-gluon plasma exists were obtained in experiments with high-energy nucleus-nucleus collisions conducted at CERN, to which scientists from GSI contributed decisively.

RHIC: Relativistic Heavy-Ion Collider. Accelerator at the Brookhaven National Laboratory, U.S.A., in which atomic nuclei collide with each other at the highest energies currently attainable worldwide.

rp-process: Creation of proton-rich atomic nuclei by way of rapid proton capture.

r-process: Succession of nuclear reactions in which neutrons are rapidly captured by atomic nuclei to create nuclei that are particularly rich in neutrons. In a series of beta decays, the resulting atomic nuclei gradually turn into stable atomic nuclei. All elements heavier than iron were created by the multiple repetition of this process.

SIS: Heavy-ion synchrotron (German: Schwerionen-Synchrotron) at GSI. The SIS has a magnetic bending power of 18 Tesla meter (Tm). This quantity, which is the product of the magnetic field strength and the radius of the accelerator ring, determines the maximum energy at which ions can circulate in the ring. The planned double ring synchrotron SIS 100/200 has a much higher magnetic bending power of 100 and 200 Tm, respectively.

Spin: Intrinsic angular momentum of elementary particles which appear to rotate around their axes like tiny gyroscopes. The spin can only take on certain quantized values.

Spontaneous symmetry breaking: Although a physical law exhibits a certain symmetry, the ground state of a given system subject to this law does not. An example of this phenomenon is the phase transition from paramagnetic iron into the ferromagnetic ground state. In the process, the atomic spins are aligned and a magnetization axis is defined. The rotational symmetry of the paramagnetic state is thus spontaneously broken. Physicists believe that the phase transition from quark-gluon matter to hadronic matter was accompanied by a spontaneous symmetry breaking, which has major consequences for the hadron masses.

s-process: Creation of neutron-rich atomic nuclei by means of slow neutron capture.

SPS: Super Proton Synchrotron at CERN.

Standard Model: Comprehensive model for the description of all elementary processes in particle physics.

Storage ring: Facility in which particles accelerated to a high energy circulate for several hours for use in experiments.

Strong interaction: One of the four fundamental forces. It binds quarks to each other and is transferred by the gluons.

Superconductivity: The property of certain materials which can transmit electric currents without any losses at low temperatures. The new accelerator uses superconducting magnets that operate at temperatures close to absolute zero.

Supernova: The violent end of a star in a huge explosion that releases large quantities of energy and is thought as a site to produce the heavy elements beyond iron.

Symmetry: The property that physical laws do not change during certain symmetry operations, for example, in spatial reflection or when particles are replaced by their antiparticles. As a consequence, for any natural process that is subject to a given symmetry, (e.g., mirror symmetry), the process that results from the corresponding symmetry operation (e.g., the mirrored process) can also occur in nature.

Symmetry violation: when physical laws or processes do not conserve a given symmetry.

Synchrotron: A ring accelerator in which the particles are kept on a predetermined path by increasing the magnetic field strength synchronously with the increase in particle energy.

Weak interaction: One of the four fundamental forces. It causes, for example, a down quark to transform into an up quark, a process which occurs in the beta decay of a neutron or of atomic nuclei.

UNILAC: Universal Linear Accelerator at GSI.

X-ray binary star systems (X-ray bursters): cosmic objects consisting of two stars in a very close orbit about each other. One of the stars is a normal, massive star; the other is an extremely compact star—in many cases a neutron star. The compact star drains off gas from the extended atmosphere of its companion. The gas falls towards the compact star at a high speed and is thereby heated up to very high temperatures, so hot that it emits X-rays. In some X-ray binaries, the accreted hydrogen-rich matter periodically undergoes brief episodes of explosive nuclear burning on the surface of the compact star, thereby producing bursts of X-ray emission. During these thermonuclear episodes, the rp process that leads to the formation of heavier neutron-deficient nuclei can occur.