Hadron and Nuclear Physics in Germany: Status and Perspectives

Preface

The Komitee für Hadronen- und Kernphysik (KHuK) was initiated in 2000 by the Bundesministerium für Bildung und Forschung (BMBF) to represent the community of German physicists working in hadron and nuclear physics. This initiative was taken on by the Fachausschuß 'Hadronen und Kerne' of the Deutsche Physikalische Gesellschaft (DPG), and later that year elections were carried out within the community to determine the KHuK members. In addition to the eight elected board members, four *ex officio* persons serve on the committee. As one of its main tasks - among several others - the committee has been charged with outlining a long-term strategy for strong and balanced programs of research in hadron and nuclear physics in order to ensure and strengthen the future of these fields in Germany. In response, the committee has worked out a written statement on the current status as well as on the future perspectives of the field, which is part of this document.

Current members of the committee (E: elected member) are:

- Gisela Anton (Universität Erlangen) - E
- Peter Braun-Munzinger (GSI Darmstadt/TU Darmstadt) - E; Vice Chairman KHuK
- Heinz Clement (Universität Tübingen) - E
- Amand Faessler (Universität Tübingen) - DFG
- Hartwig Freiesleben (Technische Universität Dresden) - E
- Friedrich Klein (Universität Bonn) - E
- Volker Metag (Universität Giessen) - Chairman BMBF GA 'Hadronen- und Kernphysik'
- Ulrich Mosel (Universität Giessen) - E
- Andreas Schäfer (Universität Regensburg) - Chairman DPG FA 'Hadronen und Kerne'
- Hans Ströher (FZ Jülich/Universität Köln) - E; Chairman KHuK
- Thomas Walcher (Universität Mainz) - NUPECC
- Jochen Wambach (TU Darmstadt) - E

The committee has held three one-day topical meetings at GSI (Darmstadt) during the previous year (2001) covering the following areas:

- Nuclear Structure, Astrophysics, Fundamental Symmetries
- Hadron Physics with Hadronic Probes and Heavy Ion Physics
- Hadron Physics with Electromagnetic Probes

These meetings were intended to summarize the current status of the subfields and to discuss future scenarios, key issues, challenges and opportunities. All the meetings were attended by a large number of German as well as foreign participants.

The committee met twice in Mainz in early 2002 in order to prepare a written statement based on these meetings and subsequent discussions. A draft version was presented to the community at the DPG 'Nuclear Physics Spring Meeting' in Münster in March 2002. An additional KHuK-meeting in July 2002 was held to prepare the final version of the document.

Definition of the Field

Hadron and nuclear physics aim at the understanding of nuclei and their constituents. Protons, neutrons and all other hadrons are composed of quarks and gluons, which are the fundamental degrees of freedom of the strong interaction. Quantum Chromodynamics (QCD) is accepted as the correct theory for describing their mutual interaction. Due to its large coupling constant and strong non-linearity at low momentum transfer, this theory leads to a very rich phenomenology which - so far - is only partly understood. Prominent effects are confinement, i.e. the permanent trapping of quarks and gluons inside hadrons, and chiral symmetry breaking, which plays a key role for the generation of mass of ordinary matter. QCD offers the best opportunity to relate complex, non-perturbative properties of quantum field theories to a large variety of experimental facts. The detailed understanding of such properties therefore strongly enhances our knowledge of quantum field theories in general. One specific aim is to find out how quark-gluon and hadronic degrees of freedom are related in detail, which may serve as a paradigm for the generation of complex degrees of freedom from elementary ones. Knowledge of this relation is essential for an understanding of matter under both normal conditions and - experimentally accessible in high energy heavy ion collisions - at extremes of temperature and density.

Nuclei, comprised of protons and neutrons, are predominantly synthesized in stars and make up almost all of the ordinary matter in the universe. The study of their properties continues to provide insight into the complexity of highly correlated, finite quantum many-body systems and the salient features of the mutual interactions of their building blocks. A thorough investigation of the structure of stable nuclei, as well as the limits at which they disintegrate because of a large imbalance in the number of protons and neutrons, extends our knowledge of the dynamics of strongly interacting matter. Nuclear structure investigations and reaction studies also shed light on questions of astrophysical interest, such as the explosive synthesis of elements, the structure of neutron stars and the formation of black holes.

Hadron and nuclear physics thus encompass all aspects of strongly interacting, composite systems.

The Scientific Case: Challenges and Opportunities

Significant progress has been made in recent years in the fields of hadron and nuclear physics.

Basic research in nuclear and hadronic physics has made remarkable advances in the past decade. We are beginning to understand the extremes of nuclear stability and the behavior of hadronic matter under unusual conditions of density and temperature. Progress has also been made in understanding hadron properties and their detailed nature starting from QCD. Achievements in the major areas

- Hadron Physics with Electromagnetic Probes
- Hadron Physics with Hadronic Probes
- Nuclear Structure Physics and Nuclear Astrophysics
- Relativistic Nuclear Collision Physics

will be detailed in four separate chapters that describe the scientific status of the various subfields and elucidate future challenges and opportunities.

Hadron and nuclear physics face exciting challenges.

One major objective is to understand in detail the interplay between the different layers of complexity, ranging from quark-gluon degrees of freedom to hadronic ones, and finally to collective nuclear motion. The study of the medium-modification of hadrons in both cold and hot nuclear matter should for example hold the key to a better understanding of how hadron masses are generated.

In the field of hadron physics we encounter opportunities for progress in answering fundamental questions such as:

- What is the nature of confinement?
- What is the mechanism underlying spontaneous chiral symmetry breaking?
- How do hadron masses arise in view of the small light quark masses?
- What is the many-body dynamics of QCD and what is its phase structure at finite temperature and finite density?
- What are the characteristic structural properties of the many different types of hadrons and which novel states are realized in nature?

Answers to these and other questions and a further improvement in our experimental knowledge of hadronic properties should allow us to establish the connection between QCD and effective hadronic theories.

Research in nuclear physics and nuclear astrophysics will center around fundamental questions such as:

- What are the limits of nuclear existence?
- How are the elements produced in stars and in explosive nucleosynthesis?
- Which many-body dynamics govern the behavior of nuclei close to the limits of stability?
- How can nuclei be used as a tool to study properties of the weak interaction?

For many of the experiments planned to address these questions, high intensity beams of unstable nuclei are a prerequisite.

Spin-offs from hadron and nuclear physics stimulate other fields of physics.

The goal of nuclear and hadronic physics is to understand matter at a fundamental level. Concepts developed to understand nuclear many-body systems have had seminal impact on the description of finite quantum systems such as quantum dots, atomic clusters, helium droplets and trapped ultracold bosonic and fermionic gases. Nuclear science techniques are widely used in material analysis as well as in the modification of materials through irradiation, and have greatly contributed to the development of new scientific tools such as the free electron laser.

Spin-offs from hadron and nuclear physics serve society in many different ways.

Research in nuclear and hadronic physics leads not only to intellectual advances in knowledge, but also promotes the developments of new technologies and advanced facilities. Some more general benefits to society include:

- Education, by creating a scientifically and technologically sophisticated workforce prepared for the ever increasing complexity of our world.
- Development of methods and tools which are of immediate practical use, such as diagnostic medical imaging, radiation cancer therapy with photons, protons, neutrons and heavy ions, age determination of objects of art and in archeology, as well as environmental applications involving dating techniques for climate change and pollution control.
- Development of new techniques, detector and electronic components and software for the use in telecommunication, space exploration, materials research and safety issues.
- Scientific cooperation to foster scientific exchange across political and cultural borders.

New Equipment and Facilities

Hadron and nuclear physics are largely driven by experiment. Successful programs at existing facilities have extended our understanding of the underlying physics and provided the insight to formulate the questions to be addressed in the forthcoming years. Progress in these fields depends critically on advances in instrumentation: accelerators, detectors, data acquisition and analysis systems. Extensions of existing facilities in Germany are currently being realized; the energy upgrade of the Mainz Microtron (MAMI C) to 1.5 GeV and the new injector at COSY for polarized protons and deuterons will open up new possibilities for studying the many-body structure of strongly interacting systems and spin degrees of freedom in hadronic interactions. In order to fully address the fundamental questions of QCD, however, the use of both electromagnetic and hadronic probes over a much wider range of energies and momentum transfers is imperative and will require new facilities.

Equipment for Electromagnetic Probes

Electron facilities currently in operation have demonstrated the potential of the electromagnetic probe to provide high-precision information on the hadron spectrum and structure. It is accepted that the more ambitious goal of relating a much larger range of hadron properties to the underlying elementary degrees of freedom of QCD can only be achieved with a new facility. Its key parameters are dictated by the need to explore exclusive reactions at high momentum transfer. Current plans aim at electron beam energies of at least 25 GeV, a duty factor and luminosity as high as technically possible for both polarized and unpolarized beams, as well as detectors optimized to ensure exclusivity of the reaction in forward kinematics. According to first considerations, these requirements could be met by a superconducting single pass accelerator, customized to fit into existing areas so that cost can be kept within reasonable limits.

Equipment for Hadronic Probes

Antiprotons are an important probe for the study of strongly interacting systems in the non-perturbative regime of QCD. Proton-antiproton ($p\bar{p}$) annihilation as a gluon-rich process appears to be a promising approach to search for gluonic states. High-precision experiments in the charm sector can be performed in $\bar{p}p$ reactions: antiprotons with momenta up to 15 GeV/c can map out much of the charm-anticharm ($c\bar{c}$) system with high precision, provide charmed mesons, and produce strange baryons for hypernuclear studies. Beams with very small momentum spread are required which can only be produced at present by high-energy electron and stochastic cooling techniques, as foreseen in the High Energy Storage Ring (HESR) project at GSI.

Equipment for Nuclear Physics

Radioactive nuclear beams can be produced by two complementary methods: *Isotope Separation Online* (ISOL), exploiting post-acceleration of stopped target fragments, and in-flight fragmentation of high energy heavy ion projectiles.

The ISOL technique is being pursued at REX-ISOLDE and plans exist for a project at the FRM-II (MAFF for Munich Accelerator for Fission Fragments). The GSI project for "An International Accelerator Facility for Beams of Ions and Antiprotons" (see below) encompasses an in-flight facility for the production of exotic nuclei as a major component.

Equipment for Heavy Ion Physics

The ALICE experiment, currently under construction at the CERN/LHC, is designed to investigate quark-gluon matter at ultra-high temperatures and to reach into unexplored areas of QCD at high chromoelectric and chromomagnetic field strengths.

The high baryon density frontier can be studied with heavy ion beams at the planned GSI facility. Heavy ion collisions in this energy regime should give access to the behavior of charmed mesons in a dense medium, and allow dilepton measurements that probe regions of highly compressed baryonic matter.

Computational Facilities

The theoretical description of the complex many-particle systems that are characteristic of nuclear and hadron physics requires substantial computational resources. Examples of such applications are *ab initio* nuclear structure calculations, transport calculations for the description of heavy ion collisions and lattice QCD simulations.

Driven by the computational needs of running and planning experiments, GRID computing based on a large PC network will be installed during the next years. This architecture could also satisfy many of the requirements of theorists. For lattice QCD, however, specialized high performance computers are needed. DESY and GSI have started a joint effort to install such machines with a total computing power of about 25 TFlops (e.g., 15 TFlops at DESY Zeuthen and 10 TFlops at GSI) in the years 2004/05 - similar to efforts in Great Britain, Japan and the USA.

Recommendations

- *We recommend as highest priority the construction of the proposed GSI facility as outlined in the Conceptual Design Report "An International Accelerator Facility for Beams of Ions and Antiprotons".*

  The GSI project proposes to combine experimental possibilities for nuclear structure, hadron structure and heavy ion physics, as well as other areas of physics, and will provide a focal point for the community of hadron and nuclear physics. In addition to the strong synergy effect in accelerator and detection design, the intellectual stimulus arising from close contact between the different subfields is a very attractive prospect.

- *We recommend as next priority exploiting the high potential of hadron physics with electromagnetic probes in the 25 to 50 GeV range.*

  Plans for such a facility should be developed and their realization vigorously pursued within the European context. This research field is complementary to the physics possibilities with the GSI facility and constitutes an integral part of modern hadron and nuclear physics.

- *We recommend a dedicated effort to provide positions for young theorists.*

  Theoretical research plays an essential role in defining the research directions of hadron and nuclear physics. In general, elaborate theoretical analysis is required in the planning phase of an experiment as well as in its data analysis and interpretation. One of the strengths of the hadron and nuclear physics community is the close and mutually beneficial collaboration between theorists and experimenters. To ensure the vitality of theoretical research, new positions for young, promising theorists at universities and research centers are urgently needed.

- *We recommend the realization of dedicated computer facilities in the TFlops range.*

  The GRID computer resources should be opened for projects in theoretical hadron and nuclear physics. The plans of DESY and GSI for dedicated lattice-QCD computers in the 25 TFlops range should be realized.

Hadron Physics with Electromagnetic Probes

Introduction

The proton and neutron are, via the formation of atomic nuclei, the building blocks of the matter of our world. Surprisingly, in view of the highly developed state of the Standard Model of Particle Physics, we have only a poor understanding of the mechanism of their formation and appearance in a rich mass spectrum and of other basic properties like size, magnetic moments, form factors and mutual interaction. The discovery of the systematics in the mass spectrum, along with the observation of cross-section scaling in deep inelastic scattering of leptons, gave evidence that they are, as are all hadrons, composite systems of elementary quarks and gluons, which in turn are acting as the basic degrees of freedom of a fundamental field theory, Quantum Chromodynamics (QCD). Our confidence in the validity of QCD is based almost exclusively on experiments at high energy and large momentum transfers or equivalently short distances, where perturbative methods can be applied. For intermediate and long-distance phenomena, such as nucleon–nucleon forces, its full complexity, including nonlinearity and confinement develops and is a strong obstacle to understanding them at a fundamental level. In this sense the primary goals of hadron physics are to determine the relevant degrees of freedom at all scales and to relate them to the parameters and fundamental fields of QCD. To this aim the phenomenology of the partonic and the hadronic regimes have first to be explored.

The experiment of Hansen, Lyman and Scott in 1950, which gave first evidence for the finite size of atomic nuclei through elastic scattering of electrons, marks the beginning of the fruitful era of electromagnetic probes in the study of hadron structure. Since then this research field has expanded and split into a variety of methods, exploiting advantageous characteristics of electromagnetic probes: the coupling of photons to charges is relatively weak and well understood and provides undistorted information about the hadronic object under study. By choosing the four momentum transfer $\sqrt(Q^2)$ in the scattering of electrons or muons the (transverse) spatial resolution of the exchanged photons, can be controlled at will. Moreover, photons come in characteristic polarization states (longitudinal, linearly or circularly transverse) with specific sensitivities to the distribution of charge, magnetism, spin and convection currents. These polarization states can be set experimentally either by appropriate choice of kinematics (e.g., Rosenbluth separation), by polarized electron beams or coherent bremsstrahlung in crystals. In coincident detection of emitted or produced hadrons, additional observables become accessible through interference.

The development of the acceleration of polarized continuous beams and experimental instrumentation brought these powerful tools to our disposal. High beam intensities and large solid angle detectors overcome the obstacles set by low reaction probabilities in the presence of an intense background. Theoretical methods and concepts which relate hadronic properties to features of QCD or its (presumed) extrapolations to lower energies have been developed with similar thrust. With the availability of unprecedented computing power, great hopes are set on calculations in strong coupling by discretization on the lattice.

Predictions can be confronted with a wealth of well-defined and undistorted data on observables such as excitation strengths, (generalized) polarizabilities, form factors, structure functions, etc. In this way stringent tests of QCD and an understanding of the mechanisms how this complex field theory develops hadronic scales from basic constituents appear attainable to a degree never achieved before.

Status and achievements

Electromagnetic probes are used in a variety of ways and in a wide range of energies – from a few tens of MeV up to several hundred GeV, focussing on different aspects of hadron structure. The physical phenomenology, the key questions, and the experimental and theoretical methods change at an energy of the hadronic system of about 3 GeV, roughly separating the resonance and the continuum regions. A full understanding of hadron structure and QCD means that both regimes can be described in terms of their specific degrees of freedom and that the relation between the hadronic degrees of freedom and the quark-gluon degrees of freedom can be made quantitative and explicit. Experimental and theoretical research in both regimes is thus indispensable to a full understanding of QCD and will be the central tasks of present and future hadron physics.

a) Resonance region

The region below W $\simeq$ 3 GeV is characterized by the appearance of discrete resonant states with definite quantum numbers. It is the classical area of hadron spectroscopy from which the quark model of hadrons and the notion of colour as the strong charge originated. The apparent degrees of freedom are hadronic or effective such as constituent quarks, instantons and vacuum condensates which are believed to be generated from those of elementary quarks and gluons through 'strong QCD' which remains essentially untested up to now. Effective field theories reflecting the symmetries of QCD (e.g., chiral perturbation theory) have been developed with considerable success and provide guidelines for the understanding of the generation of these relevant degrees of freedom.

Naturally, most empirical information exists for the proton and neutron, and somewhat less for the pion, because other states are more elusive to experimental investigation. Several basic experimental observables have been studied quite extensively. Electromagnetic polarizabilities provide an integral measure of the rigidity of hadrons (or of their couplings to excited states) and could be measured through photon scattering from the proton and the neutron (by quasielastic scattering from the deuteron) at MAMI and LEGS.

Elastic electromagnetic form factors belong to the most direct observables for nucleon structure. For the vector coupling of the photon, four such functions are defined, two for proton and neutron, respectively, termed charge and magnetic form factors $G_{E,p}$,$G_{M,p}$,$G_{E,n}$, and $G_{M,n}$. They depend on the square of the four-momentum transferred Q^2 and can be measured in elastic electron scattering. Exploitation of parity violation of spin-dependent scattering gives access to two more and allows for a flavor decomposition of the elastic nucleon response. Physically they are complementary and equally important parametrizations of the electromagnetic hadron structure but, due to differing experimental requirements, our knowledge of them is very unbalanced. While $G_{M,p}$ could be measured over a large range of momentum transfer (up to 30 GeV^2/c^2) with the low duty cycle SLAC accelerator, information about all the others is available only at much lower momentum transfers. $G_{M,n}$ is only reliably accessible through nuclear targets with coincident detection of the recoiling neutron, demanding a good calibration of detection efficiencies. The situation has been improved with new data from ELSA, MAMI and JLab, but not yet to a physically satisfactory level. $G_{E,p}$ was traditionally measured through Rosenbluth decomposition of the elastic electron proton cross section. Beyond Q^2 $\simeq$ 1 GeV^2/c^2 its weight in the cross section rapidly falls off, however, giving rise to large statistical and systematic errors. With recent experimental achievements in performing elastic scattering with a polarized beam and target, the ratio $G_{E,p}/G_{M,p}$ was measured with much better sensitivity and is now known to deviate from the previously accepted proportionality to $G_{M,p}$ in the measured range of momentum transfers up to 6 GeV^2/c^2. This technique was pioneered at MAMI in the measurement of $G_{E,n}$ with polarized ^3He as a neutron target and, with smaller model uncertainty, through observation of the recoil polarization of neutrons in double scattering after quasi-elastic knock-out from deuterons. First results on parity-violating electron scattering from MAMI, Bates and JLab are consistent with a vanishing contribution of strangeness to the nucleon vector matrix element for elastic scattering.

With the combination of targets operated in frozen spin mode, allowing for large detection acceptance, and polarized photons up to several GeV, the helicity-dependent total photon absorption cross sections

$\sigma_{3/2} - \sigma_{1/2}$ was recently measured at MAMI and ELSA and integrated in order to test the GDH integral. The obtained cross section difference $\sigma_{3/2} - \sigma_{1/2}$ oscillates in the photon energy region below 1400 MeV, with minima falling to zero, and keeps around zero above. Apparently, beyond 1400 MeV the sum of all partial cross sections does not depend on the relative spin orientation between the photon and the proton target, characteristic for diffractive production. This observation raises the interest in revealing the spin dependence for individual partial cross sections, including those for the neutron.

Our knowledge of the structure of the ground state partners of the proton and the neutron and the excited states is similarly important, but much poorer. The baryon mass spectrum is clearly organized according to flavor content, spin and parity, indicating that so-called constituent or dressed quarks are relevant degrees of freedom. Significant structure parameters are given by transition amplitudes, which depend on the relative helicities. The $\Delta(1232)$ already shows up in the absorption cross section and can be most directly studied. At various laboratories (MAMI, ELSA, JLab) the ratios of electric and coulomb quadrupole to magnetic dipole amplitude for Δ production (E2/M1 and C2/M1) have been measured through pion production. They parametrize the deformation of the nucleon and/or Δ and provide strong constraints on quark models, for example.

Other resonances need to be explicitly tagged by additional cuts in meson photo- or electro-production, or through their specific polarization-dependent excitation. Along with great improvements in the construction and operation of large solid angle photon detectors, the photoproduction of η–mesons matured to become a valuable tool for spectroscopy. The production of the $S_{11}(1535)$–state, which is negligible in the total cross section, can be efficiently isolated and was studied for the nucleon and light nuclei. This allowed the parametrization of η–production in the MAID-code, which was created for pion production, with great accuracy.

The production of strange mesons is experimentally difficult to measure due to small production cross sections and the necessity for efficient pion rejection. Recent experiments at ELSA have given total and differential production cross sections and demonstrated the potential to discover 'missing resonances' in the baryon spectrum that have not been found in pion-scattering. The same potential to reveal missing resonances is assumed for the isoscalar vector meson ω. New data are just coming from ELSA and JLab and seem to confirm this impression.

b) Partonic regime

The inclusive scattering of charged leptons (equivalent to the absorption of virtual photons) with large energy-momentum transfer to the nucleon target (deeply inelastic scattering, DIS) takes an incoherent snapshot of the partonic structure and probes small (transverse) distances. The many insights delivered from this branch of research can only be shortly summarized here. From structure functions taken in DIS with electron and muon beams we learned that the nucleon is made of spin-1/2 quarks and spin-1 gluons. In the framework of the naive quark parton picture and more refined versions, parton distribution functions (PDFs) depending on the Bjorken variable x and, to a lesser degree, on the momentum transfer, could be derived. Factorization theorems guarantee that these are of universal validity, for example appearing also in neutrino and high energy proton reactions. Integrals of PDFs are generally in accordance with sum rule expectations, but with important surprises. One of these is the observed violation of the Gottfried sum rule, implying that the quark sea is not flavor symmetric ($\bar{d}/\bar{u} \neq 1$). The evolution of structure functions in momentum transfer is consistent with the expectation of perturbative QCD and its analysis provides an independent determination of the strong coupling constant as well as a determination of the gluon distribution in the nucleon. The x-dependence of PDFs is a genuine property of non-perturbative QCD and could only partially be reproduced by lattice QCD calculations so far. Experimental progress opened the door for semi-inclusive DIS (SIDIS), where one or more additional particles have to be detected in coincidence with the scattered lepton as done for example in the HERMES-experiment at DESY. These measurements give access to a hierarchy of flavour separated PDFs and fragmentation functions.

Perhaps the most surprising findings were made for spin-dependent PDFs, as their integrals do not meet naive expectations. According to these results, the nucleon spin is not simply made up of the spin of the quarks, but receives sizeable contributions from other sources such as gluon spins, and quark and gluon orbital angular momenta. The precise decomposition depends on the choice of scheme and gauge in a well-defined manner, allowing (in principle) re-expression of the results for any choice unambiguously. First results again from HERMES in fact indicate a noticeable gluon polarization. Since the errors are large, one can only state that the polarization is positive.

Scientific questions and challenges

Quarks and gluons constitute the elementary degrees of freedom of hadrons, yet in a nontrivial manner. Higher twist corrections in the Q^2–evolution of their momentum distributions, which show up at low momentum transfers, point towards correlations between partons neglected in perturbative QCD. They can be regarded as precursor phenomena for the transition to the regime where hadronic degrees of freedom determine the phenomenology. The resulting intricate dynamical picture can be studied in a clean and well controlled manner with electromagnetic probes.

In theory – apart from continuous improvements in parametrizations of PDFs, calculations of integrals (‘moments’) with non-perturbative QCD techniques, and the analysis and evaluation of higher quark-gluon correlations, the formalism of generalized parton distribution functions (GPDs) may have the strongest impact on future work. GPDs offer a way to connect a variety of hadron properties within a standardized framework. This opens the possibility to connect the development of a comprehensive, consistent description of most hadrons with the mathematically well-defined task of determining the shape and analytic properties of GPDs. Although a lot of work is still necessary to confirm the power of this new tool and to develop a realistic strategy to reach their extraction from observables, experiments are conceived to get precise data on exclusive meson production (EMP) and Deeply Virtual Compton Scattering (DVCS) – two classes of processes which can provide stringent constraints for GPDs.

Baryon models reproduce the main features of the mass spectrum at low excitation energies, but fail to reproduce the high-mass spectrum. An abundance of states is predicted where experiments find only a few leading resonances dominating a particular partial wave. This is the so-called missing resonance problem; it is under debate if the missing resonances are so far unobserved because of inadequate experiments (resonances may decouple from the πN decay mode and thus from formation in πN scattering experiments, e.g.), or if they do not exist at all due to peculiarities of the three-quark dynamics. Different theoretical scenarios for the existence of parity doublets and their pattern of degeneracy with their partners exist for higher-lying states and await experimental tests. While low-lying resonances are already visible in production cross section, the higher-lying ones are broad, weak and overlapping, and their population can only be tagged through combination of missing mass techniques, observation and reconstruction of sequential decay chains including polarization degrees of freedom. In this sense the production of η mesons is of particular selectivity for baryon spectroscopy due to its isoscalarity. Its potential for baryon spectroscopy is, like multiple meson production in general, far from exhausted.

Vector mesons (ρ, ω, ϕ, K^*, etc.), due to their quantum numbers, couple to different matrix elements in the production and decay process of ground state and excited baryons. The particular process of inelastic diffractive production of ω–mesons can serve as a probe for scalar matrix elements of the nucleon due to the fact that the quantum numbers of the photon are taken over by the outgoing ω. Vector mesons also attract interest outside the field of baryon spectroscopy. They maintain their full mass of typically 2/3 of that of a baryon in the vacuum, with an enhanced susceptibility for mass reduction in a hadronic medium. For a study of mass shifts, a good knowledge of the mechanisms for their photoproduction on the nucleon and from nuclei is crucial.

Experiment

Early experiments using electromagnetic probes were either inclusive or could maintain exclusivity only in special kinematically overdetermined reactions, e.g., elastic scattering. The advent of cw accelerators and the construction and operation of large-acceptance detectors brought a new quality into this research field, as they allow for the selective and exclusive study also of complex multi–particle final states. This was a great step in the reconstruction of higher-lying resonances or heavier mesons which decay into multi–particle states. It is a prerequisite if we want to know more about the electromagnetic structure of ground state baryons other than the proton and neutron, and even more for their excitations (N^*, Δ^*, Σ^*, etc.). Experiments of this type have just started delivering data on photo- and electroproduction of mesons with quantum numbers different from the pion, namely η, η', K and ω, from which additional and complementary information about resonance production can be drawn.

Another interesting issue is the scalar excitation of baryons as opposed to vector coupling in photon absorption. This is particularly useful for obtaining information about the Roper resonance $P_{11}(1440)$, the nature of which is still an open question, and also for higher lying P_{11} and P_{31} states. Scalar excitation strengths are accessible via the measurement of inelastic production of vector mesons at forward angles. This process proceeds predominantly diffractively through 0^+–exchange at low four-momentum transfer $\sqrt{t}$; therefore, a high photon energy is mandatory.

At higher energies the HERMES experiment is in the very favorable situation of having already collected an impressive body of semi-inclusive electroproduction data at 27.5 GeV energy with and without polarized beams and targets. These data have already led to a number of novel experimental observations and extensions of earlier ones. The interest in exclusive channels like DVCS and hard exclusive meson production has led to a number of pioneering results. The need for an increase in luminosity and a cleaner separation of specific final states has become a central issue. HERMES will soon add a recoil detector to improve on the reaction exclusivity. Nevertheless, clear limits remain for these types of studies, which can only be overcome by a new accelerator and spectrometer setup that is optimized for exclusive reactions. The HERMES experiment will pursue the studies of the spin structure of the nucleon by concentrating on the transversity, which is another example of an observable sensitive to a basic aspect of hadronic structure and whose significance has only been recognized recently. The transversity structure function $h_1(x,Q^2)$ can only be extracted from semi-inclusive data taken with a transversely polarized target. It is a so-called twist-2 structure function, at the same level as the well known 'quark momentum' distribution $F_1(x,Q^2)$ or the net helicity distribution $g_1(x,Q^2)$. Its study gives new and independent insight into the spin structure of the nucleon and also into processes of non perturbative origin which flip helicity and which are chirally odd.

The transversity will also be measured in the COMPASS experiment at the CERN muon beam. This is relevant since it is the scale-breaking dependence on Q^2 of $h_1(x,Q^2)$ that makes it different from $g_1(x,Q^2)$. The higher energies of almost a factor ten are not only of importance to gain in Q^2–lever arm but also to study some not-so-well understood specifics of semi-inclusive processes related to the separation of the hadrons from the fragmentation of the hit quarks (which are of interest) and of the leftover 'diquark' (which are not interesting in this context). The other central issue of the COMPASS muon program is the measurement of the gluon polarization of the nucleon. Here the higher energies are essential to pass the charm threshold and also for the ability to probe the polarization of gluons carrying only small momentum fractions down to about 5 percent. In order to proceed further in accuracy in the determination of $\Delta G(x,Q^2)$, the use of new polarized facilities at center of mass energies $\sqrt{s}$ ranging from 20 to 100 GeV is being discussed. The use of the polarized beam of the TESLA north arm has been proposed ($\sqrt{s}$=23 GeV) and appeared as an appendix to the TESLA technical design report. In the U.S. an earlier European discussion about a polarized electron-nucleon collider has been taken up and is now pursued energetically at BNL.

Theory

In recent years several very promising developments have greatly enlarged the potential of QCD to describe hadronic properties. These provide fascinating theoretical problems for the years to come. Some of the challenges are:

- The analytic properties of GPDs have to be understood in greater detail, ever wider classes of processes have to be expressed in terms of GPDs, factorization proofs have to be extended, and higher-twist as well as higher-order corrections have to be calculated.
- HERMES has demonstrated that semi-inclusive and exclusive angular correlations give access to many new distribution and fragmentation functions. These have been systematically classified within QCD but only partially analyzed. For some of these the physical content is already understood, resulting in various model-based cross-relations, but for most of them the intuitive physical meaning remains to be worked out.
- Lattice calculations that reach the precision of experiments are needed. The calculation of quantities which cannot be measured will help to gain insight into the physics comprised by QCD. There is a realistic expectation that such calculations will soon be achieved.

In order to meet these challenges one needs competitive computer resources for lattice QCD calculations. A center for QCD studies (as practised, for example, in Durham (UK) and at BNL (USA)), would be very helpful to make the great professionalism achieved in this field available to individual university groups to combine the know-how necessary for further progress.

Present Facilities

In accordance with the high potential of electromagnetic probes for the study of hadron structure, several facilities delivering electron, photon or muon beams are operational with a broad spectrum of characteristics. The superconducting linac of TU Darmstadt (S–DALINAC) provides a continuous-wave beam of electrons, which makes it particularly suited for nuclear structure physics experiments and other non-hadronic research areas like FEL.

MAMI B of the university of Mainz produces a high-intensity continuous wave electron beam up to about 855 MeV. With these specifications, along with its instrumentation in high resolution magnetic spectroscopy, it is excellently suited for coincidence experiments in nuclear and hadron physics with charged particles in the final state. Its high intensity allows for measurements of electroproduction and form factors where luminosity is of importance. The electron beam can be polarized to a high degree and at intensities sufficient for parity violation measurements. Among many experiments performed there, those on the electric form factor of the neutron, the measurement of the GDH integrand in the energy range below 800 MeV, many single- and double-pion production cross sections, and the study of short range correlations of nucleons in nuclei may be recalled here.

The upgrade by a fourth microtron stage (MAMI C) is underway, partially funded by the DFG in the frame of a Sonderforschungsbereich. From 2005 on it will deliver an energy of about 1500 MeV corresponding to an invariant γp–energy $W \simeq 1.85$ GeV in experiments with tagged photons. Thus, states of the second resonance region can be excited and the thresholds for the production of heavier mesons such as ω, ρ, η' and associated strangeness in $K\Lambda$ are exceeded. The instrumentation will be extended by the Crystal Ball detector, with good capabilities in photon spectroscopy. As for MAMI B, the high current of MAMI C allows for experiments where higher luminosity is a prerequisite (electroproduction at larger angles, form factors of nucleons and mesons, parity violation, etc.).

The electron stretcher ring ELSA of the university of Bonn delivers an electron beam of lower intensity (several tens of nA), but a higher maximum energy of 3.5 GeV. γp-cm-energies of 2.65 GeV can be reached in experiments with tagged photons. For photon experiments, as well as for electroproduction with momentum transfers below 0.5 GeV, the available current does not limit the practical luminosity. Beam polarization has so far been achieved for energies up to 3 GeV. Experiments were made on the neutron magnetic form factor, the $N\Delta$-transition, photoproduction of associated strangeness and vector mesons and, recently, on the spin dependent total absorption cross section difference $\sigma_{3/2} - \sigma_{1/2}$ and the GDH sum rule. With the 4π spectrometer Crystal Barrel, in combination with additional detectors, like TAPS, experiments on the spectroscopy of baryons via multi-meson production have been started.

GRAAL at the European Synchrotron Radiation Facilitiy (ERSF) /Grenoble is a real photon experiment exploiting the backscattering of laser light on the circulating electron beam. This allows for a peaked energy spectrum of the photon beam up to 1.7 GeV, unfortunately at the price of a comparatively low intensity. On the other hand, the good control of all degrees of photon polarization returns competitivity in experiments on meson production within the energy and luminosity limits.

The LEPS experiment at SPring8 in Japan produces a photon beam of up to 2.4 GeV in the same way and is presently obtaining first results. The dedicated detector is run with a minimum bias trigger to compensate for the similarly low luminosity.

The Continuous Electron Beam Accelerator Facility (CEBAF) of the Thomas Jefferson National Accelerator Facility (TJNAF) in Newport News (USA) is the biggest installation in the U.S. specifically devoted to hadron physics with electromagnetic probes. With a beam energy of up to 6 GeV and a upgrade plan to 12 GeV for 2008, high current polarized beam and beam splitting for simultaneous operation of experiments in different halls, it provides excellent conditions for a wide spectrum of experiments with real and virtual photons.

HERMES uses the circulating 27.5 GeV positron/electron beam of the HERA ring at DESY (Hamburg) for the study of inclusive and semi-inclusive processes. It has delivered a lot of new data on flavor-separated spin structure functions, and given first evidence for the gluon contribution to the nucleon spin and the significance for transverse structure functions. It has also demonstrated the feasibility of semi-exclusive experiments. HERMES will remain operational until 2006.

COMPASS is a long-term experiment at the CERN M2 beam line using a muon beam with a high beam polarization of about 80% as well as a hadron beam. While the luminosity for muons is inferior to that reached at HERMES, the high energy of about 200 GeV is a significant advantage for the studies of cross sections of partonic sub-processes like photon-gluon fusion into charmed mesons, which is being used for the measurement of the polarized gluon structure function ΔG.

New Equipment

The study of QCD at all scales is the primary goal for the future of the field of hadron structure research with electromagnetic probes. For that, one of the central issues is the availability of suitable equipment for accelerators, targets and spectrometers. A variety of experiments are presently running or scheduled that fully exploit their respective accelerators. However, at the high energy - high luminosity frontier, limits are reached that cannot be overcome with the existing facilities. In particular, the study of semi-inclusive and exclusive processes over a sufficiently wide range of momentum and energy transfers with a statistical accuracy and resolution to allow for precision studies needs new facilities.

Several scenarios for a new generation of such precision experiments to study QCD have been and are being studied in Europe and the United States. Collider and fixed–target options are considered to be fully complementary, since the former cover a wider kinematic range and the latter provide considerably greater luminosities.

In Europe the project of a fixed target option, providing luminosities in excess of $10^{35}\mathrm{cm}^{-2}\mathrm{s}$ even with polarized targets, has been studied in some detail. Here a basic and critical parameter is the duty factor, since multi-particle final states have to be studied in coincidence. Duty factors of a few percent are the minimum request and 10% would already be quite satisfactory. Another relevant parameter is the maximum beam energy of such a facility; it determines the kinematical range of energy and momentum transfers that can be studied. A beam energy of 25 GeV is now considered as the minimum, and 50 GeV would be very satisfactory for an in-depth study of hard exclusive reactions in the so-called valence region and above.

Semi-inclusive studies of the sea region at small parton momentum fractions and precision studies of spin-flavor separated structure function components ($\Delta G(x,Q^2)$, $h_1(x,Q^2)$) and their sum-rule integrals require higher energies. One possibility to obtain these are electron-nucleon colliders, such as the EIC (now studied at Brookhaven), the other being fixed target experiments with beam energies at 250 GeV and above as they will be used in future linear colliders. While e-N colliders appear to be limited in luminosity to about $10^{33}\mathrm{cm}^{-2}\mathrm{s}$, the use of linear collider beams in fixed target mode would suffer from the low duty cycle, typ. below 1% .

At present, there seems to be a preference in Europe for a fixed target facility with a 10% duty cycle delivering a variable energy between 25 and 50 GeV, possibly 100 GeV using a technology which has been developed for linear colliders. This has been formally expressed in a declaration of European scientists on the occasion of a workshop in Ferrara (Italy) in 2002 (www.fe.infn.it/qcd-n02/). With the use of existing or projected infrastructure, a cost effective instrument could be built for the fascinating goal of physics to investigate how hadrons in particular and the matter of our universe in general are made up of the fundamental quark and gluon fields.

Hadron Physics with Hadronic Probes

Hadron physics addresses questions concerning the properties of all particles which are subject to strong interactions. These include familiar ones like the proton, neutron and pion, as well as exotic objects such as glueballs and dibaryons. In fact, particles like the photon, which do not interact strongly in first approximation, also acquire a hadronic component due to quantum fluctuations and are therefore objects of research within hadron physics. The same is even true for the physical vacuum, which has a complex strongly-interacting QCD structure. The aim of hadron physics is to clarify the structure of all these states, to understand the microscopic processes which determine them, and to explore the dynamics of hadronic interactions. To reach these ambitious goals, information from many different experiments involving different probes will have to be combined. This chapter deals purely with hadron-induced interactions, with lepton-hadron scattering being discussed separately.

Experiments with hadronic probes have two specific advantages: (i) many different reaction mechanisms are involved which, for example, allow the production of essentially all existing resonances; and (ii) the cross sections are large, which means that one has sufficiently high counting rates even for exotic reaction channels.

Status and achievements

Experiment

To a large extent, progress in the field of hadron physics with hadronic probes has been driven by dramatic technical improvements, which have made certain experiments feasible – or at least easier. These developments include, for example: (i) the generation of electron and/or stochastically cooled ion and antiproton beams; (ii) the production of spin-polarized beams and targets; and (iii) the use of internal beam-target interactions.

Elastic proton-proton scattering has been studied with high precision for momenta up to 3.3 GeV/c. Exploiting the new technique of internal experiments at cooler rings (e.g., at COSY-Jülich) and making use of both unpolarized and polarized beams and targets, the properties of proton-proton elastic scattering at intermediate energies can now be characterized precisely through energy-dependent phase-shifts. Spin observables have turned out to be particularly sensitive constraints.

Parity violation in proton-proton elastic scattering has been measured at TRIUMF (Vancouver) using longitudinally polarized beams and the weak meson-nucleon coupling constants have thus been constrained. This provides a unique window into the interplay between the weak and strong interactions among and within hadrons.

Recently, appreciable numbers of doubly-strange ($\Lambda\Lambda$) nuclei have been produced at BNL. Such experiments will help to investigate the interaction between two Λ particles and determine whether corresponding six-quark structures (H-particle) exist.

Meson production in nucleon-nucleon collisions, spanning the mass range from pions to ϕ mesons and including strange mesons via associated production, has been investigated over a considerable energy range, starting from very close to the corresponding thresholds. In the pion case, double polarization experiments close to threshold have been performed at IUCF (Bloomington, USA) to separate the contributions from different angular momentum states without invoking model assumptions. By careful analysis of final-state meson-baryon and baryon-baryon interactions, it is possible to determine basic properties, such as the scattering length and effective range, for systems that are not directly accessible. Polarization experiments,however, are needed in order to fully exploit this technique.

Approximate symmetries of nature, such as charge independence and charge symmetry, which are violated by the mass difference between up and down quarks and by electromagnetic effects, have been investigated in strong interaction experiments. Examples include elastic neutron-proton scattering using polarized beams, and neutral meson production, which allows one to study meson mixings (e.g., π^0/η and a_0/f_0) induced by such symmetry violations.

The study of rare and forbidden decays of mesons (for example, some of the decays of the η) has recently been resumed in pion beam experiments. This will be intensified at proton accelerators with the help of large acceptance photon detectors, such as WASA at TSL (Uppsala, Sweden). The great interest in these decays stems from the fact that, besides testing C- and CP- invariance and chiral perturbation theory, they will be useful for placing limits on several proposed modifications of the Standard Model and on manifestations of *New Physics*.

Experiments at LEAR (CERN) have demonstrated that particles with gluonic degrees of freedom are copiously produced in proton-antiproton annihilation. In particular, these measurements have revealed gluonic strength in the hadron mass spectrum at around 1500 MeV/c^2. Because of mixing with neighbouring scalar $q\bar{q}$ mesons, a pure glueball state could not, however, be unambiguously identified. Hybrid mesons with exotic quantum numbers in the light quark sector have been observed at BNL (Brookhaven, USA) and LEAR. Hybrid states with charmed quarks, which are predicted by lattice QCD, have not yet been found.

High resolution studies of charmonium states at Fermilab have provided very precise data that will lead to a better understanding of several still not-well-understood aspects of QCD. At the same time, these investigations revealed a number of puzzles. Several charmonium states, which are predicted to exist, have not been found or have yet to be confirmed. In particular, the states above the $D\overline{D}$ threshold are unknown. Information about their excitation energy is essential for determining the quark confinement potential.

The investigation of exotic atoms is being used to obtain a precise value of the charged pion mass. In particular, the X-ray spectroscopy of pionic hydrogen offers the opportunity to study the influence of the strong interaction on the pion-nucleon system – the simplest strongly interacting system apart from $\pi\pi$ – at zero energy.

Proton-nucleus experiments have demonstrated their potential in the investigation of changes of hadron properties due to the nuclear environment. In a sense, such reactions are ‘half-way’ to the corresponding nucleus-nucleus collisions that, in addition, create high temperatures and densities, and so this research is intimately connected with that of heavy-ion physics. Dilepton production in hadronic reactions is not subject to the strong final-state interaction and will thus enable one to disclose medium modifications of mesons – in particular, vector mesons.

Theory

Physics with hadronic probes covers an enormous range in energy and reaction types, and quite diverse theoretical tools have to be used for different fields of research.

1. At very low momentum transfers (up to scales of order 0.2 GeV^2) *chiral perturbation theory* is the effective field theory of low-energy strong interaction physics that encompasses the symmetries and degrees of freedom of nonperturbative QCD in this regime. It is successfully employed, e.g., for describing meson-meson and meson-baryon reactions. This effective field theory also provides many links between quark condensates, quark masses and hadronic observables.

2. In the resonance region, *meson exchange models* are used, which have primarily phenomenological input and are not linked to QCD as closely as chiral perturbation theory. On the other hand they can be applied to a larger energy range and can be used to study resonances in different environments. First attempts are under way to understand quantitatively the link between chiral perturbation theory and meson exchange models – not only to provide an additional justification for the meson exchange phenomenology, but also to allow a consistent understanding of hadronic reactions from their threshold up to the few GeV regime. The extension of chiral perturbation theory by dispersion-theoretical methods should also be mentioned as promising development.

3. Various *constituent quark* or *diquark* concepts are used to derive relations between the effective parameters of different hadrons. QCD provides information that is highly relevant for such models, such as: (i) the scale of 0.2-0.3 fm for what one might call the 'radius' of a constituent quark; and (ii) the structure of the gluon and virtual quark cloud surrounding a valence quark (re-summed to arbitrary high orders in α_s). Existing constituent quark models use this information to varying degrees. The range of reactions to which such models are applied is large, ranging from low to extremely high energies.

4. In all cases in which *QCD* is applicable it provides an undisputable basis for our theoretical understanding, although the range of applicability is still under discussion. A typical high energy example is dijet production in hadron-hadron collisions, which offers, e.g., direct access to the gluon structure of the hadrons involved. In this case (re-summed) QCD-perturbation theory is justified and also the so-called power corrections (which desribe, e.g., correlations between several fields inside of a hadron) are well defined. While the present accuracy of theoretical calculations is, in some respects, still insufficient, there is no doubt that by calculating higher and higher terms it can be systematically improved. A medium energy example is the decay of heavy-quark states studied,for instance, at BaBar or BELLE. In recent years the factorization proofs for such decays have been substantially extended, QCD-perturbation theory has been pushed to next-to-leading-order (NLO) and, in some cases, even to next-to-next-to-leading-order (NNLO) power corrections were estimated, and the knowledge of the relevant wave functions and couplings has substantially improved. Still, some classes of decay channels are not well under control. Lattice QCD is applied to determine, e.g., so-called Bag-parameters and decay constants. The precision of such calculations is expected to increase substantially over the next years. At low energies lattice QCD provides satisfactory *ab initio* predictions for quantities such as f_π or the nucleon-ρ-mass-ratio, which in addition improve consistently with developments in the formal lattice techniques as well as the computational investment. Generally speaking, lattice QCD, which is *the* standard technique for predicting hadron properties from QCD, has developed rapidly in recent years, both conceptually (chiral fermions, numerical renormalization techniques, lattice perturbation theory, etc.) and in terms of available computer resources. It is, therefore, expected that lattice QCD will play a leading role in the 'percolation-process', which should combine the different theoretical concepts and approaches discussed here into one comprehensive picture of hadron physics. It was recently recognized that chiral perturbation theory promises to substantially improve the extrapolation of lattice data to physical quark masses, which demonstrates nicely the ongoing amalgamation

of the different approaches. It should, however, be stressed again that the applicability of lattice QCD, just as of perturbative QCD techniques, is limited to certain classes of quantities, if not so much in principle then clearly in practice for the computer resources available in the forseeable future.

The extension of lattice QCD to finite densities is still in its infancy. While the situation for small chemical potential μ, where an expansion in μ is possible, is rather well under control, exploratory calculations for the range of μ of experimental interest still suffer from substantial systematic uncertainties.

Scientific questions and challenges

As a result of the above-mentioned and many additional developments, a detailed understanding of hadron physics is emerging, but we still lack many important pieces.

While we have a rather detailed understanding of the internal structure of, e.g., the nucleon and the $\bar{b}b$ states (although some simple issues like the role of gluons for the nucleon spin structure are not yet understood), we know substantially less (although still quite a bit) about the photon, the pion, the rho, the Δ and the charmonium states, but our knowledge fades rapidly for the other hadrons.

The reaction mechanisms of nucleons are quite well understood below the resonance region and a lot is known for high energies. Many questions concerning for example hadronic reactions close to thresholds, have yet to be addressed.

Similarly, the light-quark condensate in the vacuum is quite accurately known, but already the value of the gluon condensate is hotly debated and the values of the higher condensates are still a topic of speculations. The μ- and T-dependence of these condensates is correspondingly uncertain.

Nevertheless, with continued experimental and theoretical progress, the answers to many open fundamental problems are within reach in the next decade. Some of them, which can be addressed with hadronic probes, are:

- What are the microscopic mechanisms of confinement and chiral symmetry breaking? The answer to this question would also explain how most of the mass of normal matter is generated. It requires a detailed understanding of the quark-gluon structure of the vacuum. In order to answer it, input from many sources is needed, including the medium modifications of hadrons within nuclei as studied in hadron-nucleus collisions.

- What are the properties of the kaon-nucleon or hyperon-nucleon interaction at low energy and how do they compare to the nucleon-nucleon interaction? The answer to this question is of significant importance for understanding the stability and damping-mechanisms of the remnants of supernova explosions of type II, for example.

- Do glueballs and hybrids exist and what are their properties? The crucial aspect of this question is how quark-gluon Fock states mix to form hadronic states, which provides a paradigm for how complex degrees of freedom emerge from fundamental ones.

- What are the properties of the nucleon-nucleon interaction at very high energy? To answer this question the role of soft gluons has to be much better understood. This is also a prerequisite for the correct interpretation of RHIC and LHC heavy ion experiments.

All these questions have their origin in the specific properties of the strong interaction and represent a major intellectual challenge in our attempt to unravel the nature of the strong force and the structure of multi-particle systems bound by this interaction.

Questions such as those listed above have to be addressed with different experimental approaches:

- Spin polarization physics. At low energy it is used for separating the production mechanisms from final-state interaction physics; this is one of the most promising approaches for extracting information on reaction channels difficult to prepare otherwise (c.f. item 2). At high energies is allows to study the internal spin structure of hadrons.
- Precision studies of production and decays of pseudo-Goldstone bosons. These provide direct constraints on input parameters to chiral perturbation theory and therefore constraints on quark masses and condensates.
- Identification of gluonic excitations predicted by QCD like glueballs and charmed hybrids in the mass range of 3-5 GeV/c^2, where the density of normal meson states is low. The combined study of baryon and meson excitations *and* the pertinent background allows for a sensitive systematical search for such exotic states (c.f.item 3).
- High precision charmonium spectroscopy: measurement of mass, width and decay branches of charmonium states. The link to the theoretical understanding is provided by lattice QCD calculations.
- Search for modifications of meson properties in the nuclear medium, in particular the study of charmed D-mesons and J/ψ mesons in nuclei. (c.f. item 1).

In the near future ongoing experiments will allow progress in the directions summarized in the first two items. For the others, experiments with hadron beams in the 10 GeV energy range – in particular with antiprotons – are a promising approach.

New equipment

A major advance in the study of non-perturbative QCD phenomena is expected from the proposed upgrade of the GSI facility. The HESR project, which is an integral part of this proposal, offers the possibility to address many of the open problems listed above. The structure of hadrons and their interactions with the nuclear medium can be studied using cooled antiproton beams of unprecedented quality and intensity in the momentum range from 1.5 - 15 GeV/c that are stored in the High Energy Storage Ring (HESR). To reach the projected peak luminosity of $2{\cdot}10^{32} cm^{-2}s^{-1}$, an ambitious concept of high energy electron cooling and stochastic cooling is envisioned. A $\overline{p}$- beam momentum spread of the order of 10^{-5} to 10^{-4} is required for high resolution charmonium spectroscopy.

In contrast to e^+e^- colliders, this allows an investigation of all $c\overline{c}$ states, independent of their spin, with a resolution limited only by the beam. Compared to other beams, antiprotons have the advantage of large production cross sections for glueballs and hybrid states, which are expected to be of the same order as for mesons. In $p\overline{p}$ collisions, massive particles can be produced nearly at rest, so that they can be 'implanted' in nuclei for the study of in-medium properties. A high recoil momentum would kick the produced particles out of the nucleus, making a study of in-medium properties impossible.

With increasing luminosity of the HESR facility, further possibilities will emerge such as D-meson decay spectroscopy, search for CP violation in the charm and strangeness sector, extraction of generalized parton distributions from $p\overline{p}$ scattering, and fundamental symmetry tests with stopped antiprotons.

For the major part of the physics program a general purpose detector that allows the detection and identification of neutral and charged particles over the relevant angular and energy range will be used. The inner part of the detector can be modified for experiments with strange hypernuclei or for the special needs of CP violation studies.

In comparison to other facilities planned worldwide, the physics program at the HESR is highly competitive and largely complementary, and goes far beyond the earlier SUPER-LEAR concept. The Japanese High Intensity Hadron Facility is focused on kaon and neutrino beams. The search for gluonic excitations at the HESR is complementary to the corresponding program at the proposed 12 GeV upgrade at Jefferson Lab, which is limited to light quark hybrids because of the accelerator energy. There is partial overlap with research at e^+e^- colliders like BES and the D-meson physics program proposed for CLEOc where, however, studies of in medium properties cannot be performed. The HESR project will thus play a pioneering and unique role in the experimental exploration of non-perturbative QCD and the structure of hadronic matter.

The aim of physics with hadronic probes is primarily the investigation of non-perturbative QCD. Therefore, one of the most important theoretical tools is lattice QCD. Recently, the international competition for the fastest computers, which in fact will be those developed for lattice QCD, has substantially intensified. At present, the most advanced projects are QCDOC (Japan, UK and USA) and apeNEXT (France,Germany and Italy). Both projects aim at modular computers with a performance/price of 1 TFlops (peak)/0.5 MEuro, with delivery starting at the beginning of 2004. These new computers, in combination with the conceptual progress of recent years, promise to bring lattice QCD to a qualitatively new level.

Nuclear Structure Physics and Nuclear Astrophysics

Atomic nuclei are small, finite fermionic systems which, due to the strong nucleon-nucleon interaction, are highly correlated and hence very complex. The field of nuclear structure deals with the ground-state properties and the excitation spectrum and encompasses a broad range of research activities. These include nuclear structure studies in the strict sense, investigations of nuclei of astrophysical interest as well as tests of fundamental symmetries. Experiments in both nuclear structure physics and in nuclear astrophysics and the development of theoretical concepts are strongly interrelated and evolve through coordinated efforts.

Status and achievements

Experiment

In recent years significant progress has been made by discovering new phenomena in nuclei near stability and by extending the exploration to regions far from stability. In a world-wide effort, the field has been advanced by improvements in the sensitivity of the instrumentation, by the significant increase in computational power and by the dedicated development of beams of short-lived nuclei at several laboratories. For the latter, mainly two different approaches have been pursued: the in-flight technique, where high-energy heavy-ion projectile fragmentation and fission is used as the production method, and the ISOL technique (Isotope Separation On Line), where, after irradiation with intense primary beams, stopped target fragments are post-accelerated. The availability of secondary radioactive beams has initiated the exploration of the structure and dynamics of complex exotic nuclei, which has led to the discovery of several unexpected phenomena. Many of the produced unstable nuclei lie in the path of nucleosynthesis and are important for the process of element formation in the universe and for astrophysics. Furthermore, some of these nuclei provide a testing ground for fundamental symmetries.

Unusual nuclear matter distributions were discovered in exotic nuclei at and near the neutron drip line, where nuclei become unbound. For specific light nuclei ($A < 20$) with large neutron excesses, spatially much-extended halos formed by one, two and even four neutrons were observed. First evidence for neutron skins evolving systematically along chains of neutron-rich isotopes was obtained.

Experimental evidence for the quenching of shell structure in neutron-rich nuclei has been obtained in unstable nuclei around $N = 20$. Further hints at shell quenching effects at $N = 50$ and $N = 82$ were derived from the analysis of the isotopic abundance pattern from the astrophysical r-process nucleosynthesis. In addition, new magic nuclei with unusual neutron/proton ratios have been discovered. Related effects concern significant changes in the single-particle level sequence, sudden onsets of nuclear deformation, and the particular role of the residual pairing interaction among loosely bound valence nucleons. Nuclear reaction studies with radioactive beams close to the Coulomb barrier have provided information on quadrupole moments and single-particle strength distributions.

In nuclei near the neutron drip line, the closeness of the particle continuum leads to a spectral response very different from that of stable nuclei. An extraordinarily large transition strength into the continuum at excitation energies near the particle threshold was observed in break-up reactions with secondary beams of loosely bound nuclei.

Precision mass and decay spectroscopy of unstable nuclei has become feasible by accumulating and cooling beams of exotic nuclei in storage rings. New methods, applicable even to one single stored ion, have been developed for mass and lifetime measurements. Applying these ultra-sensitive, non-destructive methods, the number of precisely known nuclear masses has been substantially extended to very short-lived, rarely produced isotopes.

In an attempt to extend the chart of known nuclei to the highest proton numbers, atoms of the heaviest elements through element number 112 have first been synthesized in heavy-ion fusion reactions. Indications for the elements 114 and 116 have been reported recently. The region of highest stability of super-heavy elements, however, associated with the doubly-magic shell closure for protons and neutrons, still awaits discovery.

In nuclei reachable with stable-isotope beams and targets, many important discoveries and new research directions have emerged in recent years. A new disintegration mode, two-proton radioactivity, was discovered, and evidence was found for the Gamow-Teller giant resonance occuring in β-decay of nuclei near $Z = 50$, $N = 50$. New modes of excitation involving proton-neutron correlations, such as 'shear bands' of magnetic rotation, chiral twin bands, wobbling motion and mixed symmetry states have been discovered. Inelastic electron scattering experiments have demonstrated the existence of orbital modes corresponding to a twist-like or toroidal motion of the participating nucleons, characteristic of an elastic medium. Multi-phonon states have been identified, presenting a challenge to our understanding of the interplay of single-particle motion, the Pauli Principle and quantum coherence in nuclei. The observation of shape transitions as a function of nucleon number and even of critical-point nuclei has stimulated the theoretical development of new analytical dynamical symmetries. A surprising stability of the heaviest nuclei against centrifugal disruption at high angular momentum has been observed. Evidence that the concept of nuclear supersymmetry can describe quartets of nuclei has emerged from high precision experiments. Some key cross sections, masses and life times needed for the study of nucleosynthesis, stellar evolution and supernova explosions that are often governed by nuclear reaction rates with small cross sections, have recently been measured. The tremendeous progress in the field using stable beams is being realized at ion and electron accelerators, underground laboratories or high-intensity neutron sources, equipped with state-of-the-art detection systems.

Theory

The objective of theoretical nuclear-structure physics is to describe the ground-state properties and the excitation spectrum as well as possible in order to allow for stringent comparison with experiment. The long-term aim is to arrive at 'ab-initio' descriptions or 'controlled' approximation schemes on the basis of the best available nucleon-nucleon interactions and reliable three-nucleon potentials.

Due to its complexity, the nuclear many-body problem cannot be solved from first principles in most cases. For three- and four nucleon-systems, exact few-body calculations with modern nucleon-nucleon potentials are possible, however. In addition, exact Greens-Function Monte Carlo calculations are available for nuclei up to $A = 10$ and will eventually be extended to somewhat heavier nuclei. In all cases quantitative agreement with experiment is reached provided phenomenological three-nucleon interactions are included. Thus, exact calculations in light nuclei have emerged as the major testing ground for the three-nucleon interaction and further developments thereof. Because of the rapid growth in computational power, one is now also able to perform full shell-model calculations for systems up to $A = 12$ without a 'passive core', albeit without three-nucleon interactions so far.

For nuclei with $A < 60$ a number of 'controlled' methods, based on variational approaches or systematic expansions of the many-body wave function have been developed and successfully applied in the past decade in specific cases. They continue to be extended and refined and will ultimately become applicable to larger systems. It has also become possible to perform shell-model calculations with realistic interactions in very large model spaces in this mass range. With the use of Monte Carlo techniques, the finite-temperature behavior of the low-lying spectra can be studied reliably and the results have been used extensively in various astrophysical applications. Modern developments based on 'effective field theory' become increasingly important in this context. Using renormalization-group techniques, it has become possible to deduce unique effective interactions from modern nucleon-nucleon potentials, eventually to be used in conjunction with the three-nucleon interaction in large-scale calculations.

For nuclei with $A > 60$ it is currently impossible to obtain 'controlled' approximations to the many-body Schrödinger equation in the shell model sense, although shell-model calculations with schematic interactions are rapidly developing. Especially in very heavy nuclei, one has to rely on non-relativistic or relativistic mean-field methods, approaching the solution of the nuclear many-body problem by resummations of certain classes of diagrams. In practice, models using 'parameterized' phenomenological interactions are widely used, e.g. non-relativistic Skyrme density functionals and relativistic mean-field models. Non-relativistic mean-field calculations including pairing correlations are possible without any restriction on the spatial symmetry and have been successfully used in the study of ground-state properties such as masses, matter distributions, moments of inertia, etc., for nuclei in the valley of stability.

Quantum fluctuations of the mean field are directly observable as dynamical processes in the excitation spectrum of a nucleus. Theoretically, the Random Phase Approximation (RPA) and extensions thereof provide suitable tools for studies of nuclear response functions over large mass regions. They have led to a microscopic understanding of the systematics of collective modes, including damping mechanisms through collisions of quasiparticles in the mean field. RPA calculations, in conjunction with shell-model Monte Carlo results, also show promise in the astrophysical context, providing, for instance, fairly reliable electron-capture rates for collapsing massive stars at high densities and temperatures. At present, relativistic RPA results are available only in spherical geometry, whereas non-relativistic, fully three-dimensional calculations have recently become possible for carbon and oxygen nuclei. It is foreseeable that in the future the quantum spectrum of medium-heavy and heavy nuclei of arbitrary shapes can be treated.

In parallel, medium-heavy and heavy nuclei can be described using collective models that single out those aspects of the dynamics that dominate the low-lying excitations. One class of models starts from surface vibrations and rotations and a second one from paired fermions that are mapped onto bosons. In addition, symmetry arguments are used intensively to describe nuclear excitations. Discoveries of critical point symmetries, supersymmetric partners and chiral bands are some recent examples of the achievements in this field. The manifestation of quantum many-body chaos and its interplay with collective motion at high level density is an interesting cross-disciplinary topic.

Nuclear theory plays an important role in nuclear astrophysics because it is impossible to measure all relevant reaction rates. Statistical model calculations have to be adjusted in the vicinity to the valley of stability and are then used to extrapolate to nuclei close to the drip lines. The description of Gamow-Teller strength distributions, gamma-ray strength functions and alpha-nucleus potentials are of key interest.

Scientific questions and challenges

Experiment

The structure of nuclei has been studied for almost five decades. Nevertheless, some of the most fundamental questions are still not answered: what exactly are the very limits of nuclear existence? How many protons and neutrons can be bound in a nucleus by the strong force? Which new phenomena are associated with the loose binding of nucleons and the proximity of the continuum near the neutron drip line? Answers to these and other key questions are expected from the exploitation of advanced detector systems at facilities using both stable and unstable isotope beams. In particular, the availability of intense neutron-rich nuclear beams will be essential for investigating these frontiers. Such beams will also allow the synthesis of superheavy nuclei with much larger neutron excesses than stable isotope beams. In the neutron-rich region, heavy and superheavy nuclei are predicted to have much longer half-lives, i.e. in the minute to hour range or even longer, opening up interesting opportunities for studies of the chemistry of these heavy elements.

The stability of nuclear matter is governed by the interplay of the proton-neutron (isospin) symmetry of the strong force and the isospin-violating Coulomb force. Unbalanced proton and neutron numbers decrease the stability of a nucleus. With the addition of more and more neutrons to a nucleus of given proton number, the binding energy of the last neutron drops steadily until the nucleus decays spontaneously by neutron emission; i.e., the nucleus becomes unbound and the neutron drip line is reached. At present, the neutron drip line is known only for light elements up to oxygen ($Z = 8$). The challenge is to reach this boarder for heavier nuclei. Reaching it for nuclei up to $Z = 25$ appears feasible at the planned facilities (see 'New equipment'). The wealth of data that is expected to emerge from experimental investigations of neutron-rich nuclides will provide a crucial test of theoretical predictions that indicate a weakening of the mean field and an increased role of long-range correlations among nucleons near the drip lines.

To date, we have a qualitative understanding of many aspects of stellar nucleosynthesis. Atomic nuclei in the universe have been - and still are - being created in stars. A number of key reactions in the quiescent burning phases, such as hydrogen and helium burning, involve nuclei close to stability. The reactions have to be measured very precisely at high-intensity accelerators using high-efficiency detectors because of the extremely low cross sections at the astrophysically relevant energies. These results are also essential for the solar neutrino problem and for cosmological questions. Most of the heavy nuclei originate from the s- and r-processes. For the s-process, capture cross sections of branching point nuclei need to be measured using radioactive targets or in inverse photo-disintegration reactions. In the r-process, whose astrophysical site is still uncertain, masses and half lifes of very neutron-rich nuclei are important. These may also affect the explosion mechanism of supernovae. Inelastically scattered electrons as precision probes, in conjunction with detailed theoretical analysis, will be important to accurately pin down key response functions related to electron capture. They also promise significant potential to determine other specific reactions rates of astrophysical importance. The nucleosynthesis of neutron-deficient nuclei in the p-process is a sensitive probe of astrophysical scenarios such as type-I and type-II supernovae and requires photo-disintegration rates of many nuclei. In addition, proton capture of unstable nuclei is relevant for the so-called rp-process as well as for the energetics and dynamics of novae and X-ray bursters.

The Standard Model of elementary particle physics has withstood three decades of extensive scrutiny, although it is felt that it might eventually have to be replaced by a more complete theory. Besides high-energy experiments aimed at a search for possible extensions of the Standard Model, low-energy precision experiments in nuclear and atomic physics also have a unique discovery potential. The major thrust of the nuclear physics experiments focuses on the weak interaction, in particular on precision experiments of the β-decay of specific nuclei, emphasizing symmetry violations and different interaction types of the weak force. In these measurements the accurate detection of the recoiling nucleus is essential for the reconstruction of the neutrino momentum and will require the use of atomic traps. Such studies comprise accurate tests of parity and time-reversal invariance, and sensitive searches for other than vector-axialvector couplings, which would hint at the existence of additional exchange bosons of the weak interaction. High precision measurements of super-allowed $0^+ \rightarrow 0^+$ transitions beyond the present limit of $Z = 27$ will permit reduction of systematic uncertainties in the determination of the V_{ud} matrix element at the hadronic vertex of the weak interaction and thereby provide more stringent tests of the unitarity of the Cabibbo-Kobayashi-Maskawa matrix.

Theory

Despite its success for stable nuclei, it remains a challenge for nuclear theory to make quantitative predictions for nuclei under extreme conditions of isospin, density, angular momentum and temperature. Here large extrapolations from stable nuclei are involved. Masses, half lives, reaction rates - especially for nuclei far from stability - and a precise knowledge of the nuclear equation of state are needed in nuclear astrophysics for the synthesis of elements under various cosmological conditions, supernova explosions, the structure and dynamics of neutron stars, and the formation of black holes. A key role for the microscopic understanding of astrophysical reaction rates will be played by new developments in reaction theory. Another exciting perspective of modern nuclear theory is to incorporate results from other fields of hadron physics, as nuclei are ideal laboratories for studies of fundamental properties of hadrons and their interactions in a non-perturbative many-body environment.

When calculating the properties of light nuclei with large isospin from ‘first principles’ as well as the equation of state of asymmetric nuclear matter, three-nucleon interactions are of crucial importance. Their microscopic origin remains so far elusive. Important contributions come from the coupling to sub-nucleonic degrees of freedom by intermediate excitations of nucleon resonances. Multipion-exchange mechanisms are involved, which may be treated using chiral perturbation theory. Variational calculations with phenomenological three-nucleon interactions indicate a pronounced density dependence, changing from attractive at low densities to strongly repulsive at high densities. Little is known about the isospin dependence, for which studies of strongly asymmetric nuclei will be indispensable.

In stable heavy nuclei the mean field dominates the quantum spectrum. Although mean-field theories have been quite successful for ground-state properties as well as the single-particle spectrum of stable nuclei, their limitations become apparent as one moves away from the valley of stability. Here the predictions often vary widely, indicating that the effective interactions are not yet well constrained. For the description of systems with very large isospin it will be essential to determine reliable effective interactions in regions of low density and large neutron or proton excess. Eventually these have to be anchored in the underlying nucleon-nucleon potential and supplemented by reliable three-nucleon interactions.

In the vicinity of the drip lines the mean-field picture may cease to be valid because for loosely bound nucleons the strength of the residual interactions becomes comparable to the mean-field potential. In fact, recent developments in theory and experiment indicate that, far from stability, quantum fluctuations become increasingly important, giving rise to a transition from mean-field dominance to a new kind of long-range correlation dynamics in the ‘strong-coupling regime’. An immediate consequence is that the seemingly well-established shell structures begin to dissolve. To describe this transition will be a major challenge for nuclear many-body theory in the next decade. Many-body methods, such as the systematic $1/N$ expansion, may come to bear, but large-scale ‘first-principles’ calculations will also become increasingly important. However, the proximity of the particle continuum will pose major difficulties, especially at the numerical level. First attempts towards a continuum shell model are being made, but an approach allowing for arbitrary numbers of unbound nucleons is pending.

An interesting prospect for nuclear theory are extensions beyond isospin into the full $SU(3)$ flavor sector.

This is achieved with the formation of hypernuclei in strangeness-changing reactions. Hypernuclei are the ideal testing ground for in-medium baryon-baryon interactions since they are the only source of information on hyperon-nucleon and, eventually, hyperon-hyperon interactions under controlled conditions. In the past, work has concentrated mainly on light single-Λ hypernuclei because of the rather involved production and detection processes. Hypernuclei have been described by a variety of many-body methods, including shell-model calculations and mean-field models. Hyperon matter has also been studied as an important prerequisite for neutron star calculations. Open questions remain on the structure of the in-medium interactions and on how to integrate them with nucleon-nucleon results into an as-yet-to-be-developed $SU(3)$ scheme. With the expected progress in nuclear many-body theory it is conceivable that crucial information will become available from comparisons of detailed calculations with precise hypernuclear spectroscopic data.

New equipment

Based on long experience in providing more than 600 different radioactive beams, including even pure isomeric beams produced with the laser ion source, a broad program has started at REX-ISOLDE and ISOLDE also with beams of proton-rich nuclei and nuclei on the $N = Z$ line. Here, systematic high-resolution nuclear reaction studies and spectroscopy will allow, e.g., tracking the spin-orbit splitting to the borders of stability.

A major advancement in the field of nuclear structure physics world-wide is expected from an upgrade of the GSI facility in Darmstadt. The GSI proposal foresees a synchrotron accelerator complex that provides ion beams of all elements from hydrogen to uranium with intensities of up to 10^{12} ions/s, thereby exceeding present intensities by up to two orders of magnitude. In this high-intensity mode, the beam energy is variable up to 1.5 AGeV. Exotic nuclei will be produced by in-flight fragmentation, which is the optimum production method for the most exotic nuclei. An improved projectile-fragment separator (Super-FRS) will not only accept projectile-fragmentation products, but also projectile-fission fragments with much larger efficiency than the present FRS. Fission of uranium is a prolific source for very neutron-rich medium-mass nuclei. Intensities of secondary, isotopically pure beams will be increased by a factor of up to 10.000. The Super-FRS serves experiments for reaction studies, allows the injection into storage rings, and provides energy-focused, low-energy secondary beams after slowing-down in solid or gaseous material. A major new initiative for the study of exotic nuclei is the Advanced Gamma Ray Tracking Array (AGATA), which will provide both a higher sensitivity and the needed Doppler corrections. The storage ring system comprises a Collector Ring (CR) and the New Experimental Storage Ring (NESR) for the accumulation, storage and cooling of the large-emittance fragment beams. Both fast stochastic pre-cooling in the first ring and subsequent electron cooling in the second ring will be applied to allow high-precision experiments including reaction studies. The addition of a small electron ring operating in the colliding mode will permit electron-scattering experiments with unstable nuclei. With the highest beam energies and coupled storage rings, the planned facility at GSI provides unique, unsurpassed experimental possibilities. The proposed physics program is highly competitive with those at the most advanced facilities worldwide, in particular with the RIKEN exotic-nuclear beam factory, under construction in Japan, and the RIA facility, currently under consideration in the USA.

An alternative approach for the production of exotic nuclear beams is pursued in the MAFF project at the new neutron source FRM II in Garching. Fission products are produced with unprecedented intensities ($10^{14} - 10^{15}$ fissions /s) in a nuclear reactor, extracted, and post-accelerated to provide intense beams of neutron rich nuclides in the element range around proton numbers 35 and 55 (e.g. 10^{10} ^{132}Sn ions/s). The energy of these beams is a few AMeV for studies of reactions near the Coulomb barrier. This opens up a physics program with a high discovery potential. It provides new possibilities, e.g., for the synthesis of superheavy elements and spectroscopic investigations of neutron-rich nuclei with state-of-the art γ-detector arrays like MINIBALL.

The facilities planned worldwide and in particular also in Germany offer a broad research potential and will significantly enhance our knowledge of the structure of atomic nuclei and its relevance for nuclear astrophysics in the future.

Relativistic Nuclear Collision Physics

The emphasis of this field is to produce hot and dense matter in the laboratory and to study its properties. Research activities have focussed on hadronic and quark-gluon equation of state studies, on the behavior of hadrons immersed in a dense medium, and on the discovery of the quark-gluon plasma and the delineation of its properties. The research is pursued at the SIS, AGS, SPS, and RHIC accelerators, spanning the energy range from $2 < \sqrt{s} < 200$ GeV in the nucleon-nucleon center of mass. Future activities encompass studies at the high energy frontier with the ALICE experiment at the LHC, currently under construction, and at the high baryon density frontier with the planned future GSI facility. In a more general context, both experimental and theoretical investigations aim at a detailed understanding of the different phases of QCD, and the corresponding QCD phase diagram. These investigations are of relevance for a description of the development of the early universe and the interior of neutron stars. Furthermore, the reaction dynamics of nuclear and hadronic collisions at high energies is an interesting research area in its own right, in particular concerning the evolution of systems often very far off equilibrium, the rate of entropy production, and chaotic and turbulent behavior.

Status and Achievements

Experiment

Major progress in our knowledge of the QCD phase diagram has been made experimentally. This is summarized in Fig. 1. In this plot of temperature vs. chemical potential of QCD matter, the location of the phase boundary between hadronic matter and the quark-gluon plasma is indicated by the blue line, taken from the latest calculations within the framework of lattice QCD. The data points in this figure represent the work of many collaborations at all currently available beam energies. Analyses of measurements of the abundances of all hadronic particles produced in relativistic nuclear collisions demonstrate that the fireballs created in the collisions are near a state of chemical equilibrium. The corresponding thermodynamic parameters, temperature T and chemical potential μ_B, can then be extracted at each beam energy as the 'freeze-out' points in Fig. 1. The purple line connecting the red data points demonstrates, in the framework of the hadron resonance gas model, that chemical freeze-out appears to take place at constant total baryon density $n_b = 0.12/\mathrm{fm}^3$. The freeze-out line so determined approaches the calculated phase boundary at roughly full SPS energy.

This fact lends strong support to the interpretation that the matter produced in nuclear collisions at SPS and RHIC energies is first thermalized in the deconfined quark-gluon plasma phase and subsequently expanded through the phase boundary into a thermal gas of (weakly interacting) hadrons. This interpretation is further buttressed by the observation, at SPS energy, of anomalies in the production of J/ψ mesons and low mass dilepton pairs. The apparent suppression of J/ψ mesons, compared to what one expected by simple extrapolation from nucleon-nucleon collisions, is indicative of the break-up of these mesons in the hot fireball. Enhanced production of low mass dilepton pairs reflects the in-medium change of the properties of the ρ meson (the shift and broadening of its spectral distribution), which is the principal source of such lepton pairs. Direct photons have also been observed for the first time, and their rate is consistent with emission from the plasma phase.

At the lower AGS and SIS energies the freeze-out points deviate strongly from the phase boundary. This implies the existence of a dense hadronic medium between the freeze-out curve and the phase boundary. In this medium, at intermediate temperatures but rather high baryon densities, the properties of K mesons are

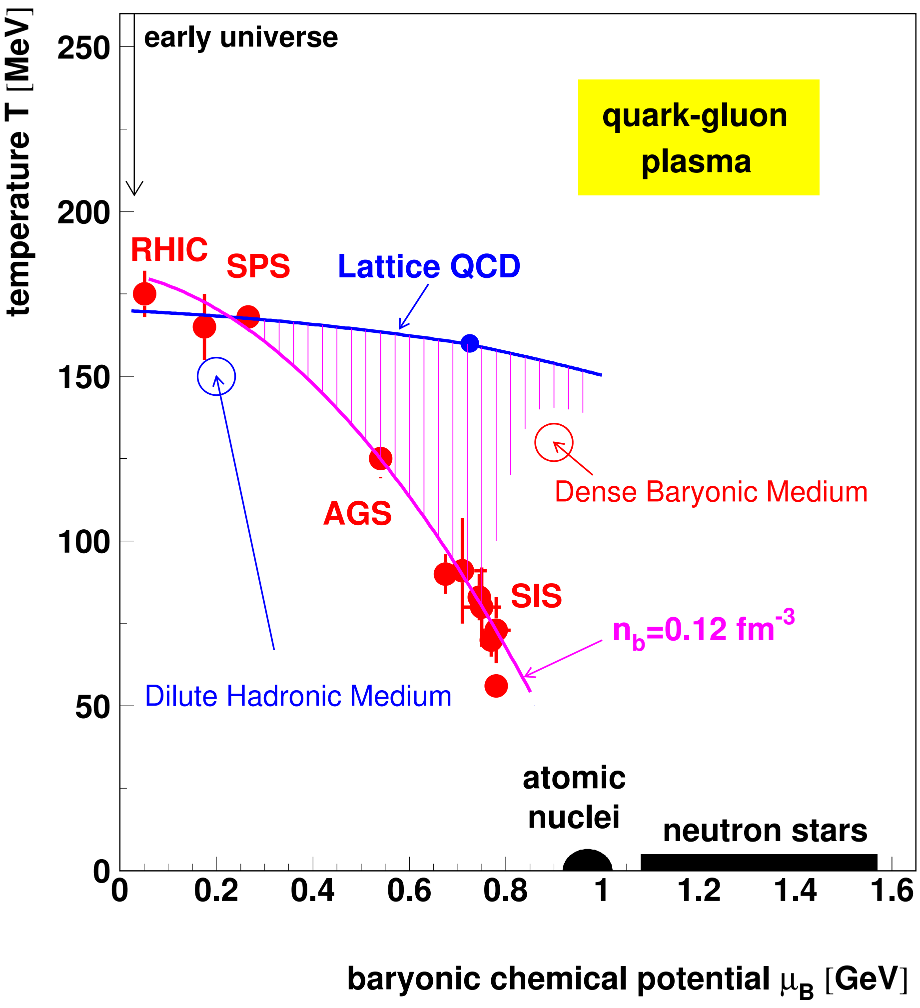

Figure 1: The QCD Phase Diagram in the context of the current knowledge of relativistic nuclear collisions.

also expected to be changed. At SIS energies this may explain the striking enhancements observed in the production probabilities for kaons.

At all energies, the fireball created in nuclear collisions exhibits collective features, resulting in the observation of radial and transverse flow as well as strong azimuthal anisotropies for particle production in the plane perpendicular to the beam direction. These data are currently being analyzed in multiple-collision models and hydrodynamical approaches in order to determine the underlying equation of state. Evidence for considerable softening of the equation of state with increasing beam energy has been observed, with particularly impressive results at RHIC energies, although a complete determination of the equation of state has not yet been achieved.

Theory

In the past decade much progress has also been made in the theoretical understanding of the phase diagram of hadronic matter. 'First principles' calculations of the QCD partition function on Euclidean space-time lattices have provided detailed information on the finite-temperature behavior of strongly interacting matter. The transition temperature to a deconfined quark-gluon plasma has been calculated with an accuracy of better than 10%. Chiral symmetry restoration appears at the same critical temperature. The equation of state, inferred from the simulations, shows rapid variations of the thermodynamic variables near the phase boundary. A comparison of pressure and energy density reveals that, even for temperatures significantly above T_c, the quark-gluon plasma is far from an ideal gas. The critical behavior, susceptibilities and the screening masses of various mesonic channels have been studied. The latter indicate that the restoration of chiral symmetry leads to a degeneracy of mesonic 'parity partners'. Employing methods from image reconstruction in astronomy, attempts have been made recently to deduce the finite-temperature behavior of mesonic spectral functions. These are important for the physical understanding of the relevant degrees of freedom in the non-ideal quark-gluon plasma, the medium modification of hadrons below T_c and the electromagnetic response of hot and dense matter produced in heavy-ion collisions. Lattice calculations at finite chemical potential have been tried for almost two decades. They are complicated by the fact that the measure in the path integral is no longer real, invalidating Monte-Carlo techniques. Various algorithms have been proposed to remedy this deficiency, with varied success. Most recently there have been promising developments involving improved overlap methods. These provided first estimates of the phase boundary in the $T-\mu_B$ plane, albeit with large uncertainties.

There have also been major advances in the understanding of the thermodynamic behavior of hadronic matter from sources other than lattice QCD. These range from applications of chiral perturbation theory – relevant at small temperatures and baryon density, to perturbative QCD calculations at asymptotically large T and μ_B. From the latter it has recently been concluded that hadronic matter at high density and low temperature is realized in the form of a 'color superconductor' with a rich phase structure. Models of the Nambu-Jona-Lasinio type and Dyson-Schwinger approaches with parameterized, non-perturbative gluon propagators also continue to give valuable insights. Below the phase boundary, hadrons are the proper degrees of freedom for the description of the thermodynamic behavior and the modifications of spectral functions. Various effective Lagrangians, based on chiral symmetry, have been used to compute the in-medium properties of mesons.

In connection with heavy-ion experiments at CERN and, possibly, at RHIC, non-strange and strange vector mesons are of particular interest, since they dominate the electromagnetic current for invariant masses below ~ 1.5 GeV and contribute to low-mass photon and dilepton radiation from a heavy-ion collision. Describing their properties in hadronic models has led to a quantitative agreement of the calculated rates with experiment. At invariant masses above 2 GeV the J/ψ meson shows up as a prominent narrow resonance in the e^+e^- channel. Its suppression observed in nucleus-nucleus collisions at SPS energy has been interpreted theoretically as a signal for the presence of deconfined matter with a large gluon density.

All these theoretical approaches are based on simplifying the actual reaction dynamics by using equilibrium properties of nuclear, hadronic and quark matter. Heavy-ion collisions, however, are extremely complex, and a quantitative understanding of the collision dynamics is a prerequisite for actual comparisons with experiment. In the past 15 years significant progress has been made in the development of theoretical and numerical tools to describe a high-energy heavy-ion collision throughout its various stages. Relativistic hydrodynamic and transport methods have been employed and provide a good description of heavy-ion collisions from SIS- to SPS energies. Transport models are now able to treat the off-shell behavior of colliding particles as well the detailed balance of multiparticle reactions. Both are crucial for the understanding of electromagnetic signals and the yields of rare species, such as antiprotons. Flow observables and particle production rates, which aim at a determination of the equation of state, have been studied extensively. At SIS energies the theoretical interpretation of the the data is consistent with a compression modulus for cold nuclear matter of K = 230 MeV. This is in the range of values inferred from the systematics of the giant monopole resonance in stable nuclei. Investigations of particle yields also provide valuable insight into in-medium properties, in particular the effective masses of hadrons. The kaon yields and spectra measured at GSI can only be understood if an attractive, density-dependent potential for the antikaons is invoked, in agreement with general theoretical predictions of kaon properties in dense matter.

Future Scientific Questions and Challenges

Experiment

At SIS energies a major new focus will be measurements of dilepton production in hadron-nucleus and nucleus-nucleus collisions with the HADES detector, which is currently in the commissioning phase. These experiments should shed new light on the properties of the ρ and ω mesons in a nuclear medium as well as provide a solid basis for our understanding of dilepton production in pion-nucleus and proton-nucleus collisions.

At the SPS accelerator the nuclear collisions program will focus, in the next 2 years, on the completion of a detailed excitation function for hadronic observables. Furthermore, the currently unexplored open-charm observable will be studied at full SPS energy, in order to provide further understanding of the J/ψ measurements discussed above.

The current and planned RHIC and future ALICE program at the LHC will explore symmetric quark-gluon matter with equal numbers of quarks and anti-quarks at high temperature (several times the critical temperature) and at small values of the baryon chemical potential ($\mu_B < 45$ MeV). Energy densities of up to 50 GeV/fm^3 at RHIC and 1000 GeV/fm^3 at LHC will be reached.

At RHIC a main priority will be to quantitatively determine the degree of thermalization and to measure the equation of state of the quark-gluon plasma near T_c. Major new emphases will be on the study of open charm and charmonia production and on the emerging role of jets to diagnose the plasma state.

Completely novel physics can be studied with nuclear collisions at LHC energy, since the energy increase between RHIC and LHC is larger than the corresponding step from SPS to RHIC. New topics include the study of QCD at very high field strength, where the corresponding gluon fields are predicted to undergo a transition to a “colored glass” condensate, leading to radical changes in the parton momentum distributions that will be observable, for example, in jet rates at large transverse momentum. Furthermore, heavy quark production will be copious at LHC energy and can be used to provide quantitative insight into the degree of deconfinement of the matter produced in the collision, which could lead to a quantitative determination of the energy loss of (heavy) quarks in an ultra-hot QCD medium.

The ultra-high baryon density frontier will be studied with experiments at the planned new GSI facility. As illustrated in Fig. 1, the hadronic matter underneath the phase boundary for small ($\mu_B < 300$ MeV) values of the baryon chemical potential is always dilute: the total baryon density never exceeds that of normal nuclear matter. It is only at lower beam energies – between 5 and 50 GeV/nucleon – that one can distinguish between chemical freeze-out and the phase boundary a phase of dense hadronic matter, shown by the hatched area in Fig. 1. It is precisely this energy range, where the relative strangeness content of the hadronic medium has also been determined in recent SPS experiments to reach a maximum, which will be investigated by experiments at the planned GSI facility. The major emphasis of these experiments will be to provide simultaneously a precision determination of charmonium, open charm, and dilepton production probabilities in nuclear collisions and to probe deep into the high baryon density regime, where novel phenomena (or at least their precursors), such as color superconductivity, can be expected.

Theory

Major theoretical challenges lie in the further development of lattice QCD calculations. For the detailed understanding of the structure of light hadrons in vacuum, their medium modifications and the chiral phase transition, it will be mandatory to extend the simulations to realistic values of the up and down quark masses. These will require, on the one hand, a significant increase in computational power and, on the other hand, 'controlled' extrapolations via the use of chiral effective field theory. First attempts in this direction show great promise. For the QCD phase diagram it is expected that a critical point exists in the $T-\mu_B$ plane where the phase transition changes from first order to a cross over. A first-principles determination of this point as well as a study of the critical behavior is extremely important and will require simulations at finite baryon chemical potential. Although progress has been made recently, this remains a difficult task.

Lattice results can provide only limited insight into the underlying physical processes involved in relativistic heavy-ion reactions that proceed through various stages, beginning with a highly nonequilibrium state in the incoming channel and ending in a possibly equilibrated state. All the observables represent time-integrations over all stages of this reaction history that thus has to be treated reliably; static or quasistatic descriptions have only very limited value.

In the description of these complicated reaction dynamics of heavy ions, conceptual challenges remain in the area of hydrodynamics as well as in transport theory. Up to bombarding energies of 2 A GeV, all essential baryonic and mesonic resonances have been incorporated into existing transport codes. High-lying hadronic states are modelled in terms of string-like excitations. At higher bombarding energies, large baryon densities are reached and nucleons may begin to overlap, raising questions about the proper degrees of freedom. The theoretical challenge is to describe the time development through such a state of matter in a way that is consistent with QCD and quantum mechanics. Such calculations must ultimately be able to reproduce the experimentally determined freeze-out curve in Fig. 1.

At RHIC energies and beyond, the initial state of a nucleus-nucleus collision cannot be described in terms of string excitations, as is demonstrated by comparison of model predictions to the recent observation of large elliptic flow up to transverse momenta of 10 GeV/c. A more natural interpretation is to describe this state in terms of quark and gluon degrees of freedom. This initially hot and dense system expands and cools until T_c is reached. While phenomenological analysis of the RHIC data implies rapid thermalization on time scales of the order of 1 fm/c, a theoretical understanding of this evolution is currently missing. Furthermore, what exactly the effective degrees of freedom of a strongly interacting plasma near T_c are remains to be explored. At the highest collision energies, such as at the LHC, one initially enters deeply into the partonic regime and an important task is to formulate and implement partonic transport models which include many-body channels and treat the coherent emission of gluons and the corresponding degradation of the initial Q^2 in line with the DGLAP evolution equations of QCD. Finally, the hadronization process, which converts partons back into the observed hadrons, is not yet under control. There is so far no dynamical treatment of hadronization which is generally accepted, although model studies towards this end have recently emerged.

New Equipment

Experiment

The HADES detector is presently being commissioned at GSI and will provide unprecedented rate capability for the measurement of dilepton production in nuclear collisions. It consists of a state-of-the-art ring-imaging Cerenkov detector with high precision tracking in a toroidal field, combined with shower and time-of-flight detectors for electron and hadron identification.

The ALICE experiment currently under construction at the LHC will be built inside a very large solenoidal magnet and combine a six layer Si-based inner tracking system with a 90 m^3 time-projection chamber, followed by a transition radiation detector and time-of-flight apparatus. Specialized detectors for photon and high transverse momentum hadron detection and a large muon arm in the forward direction complement the inner detectors. New electronics technologies for the inner detectors are being developed to readout the many-million detector channels. The experiment will be complete in 2006 and provide unprecedented opportunities and experimental possibilities for nuclear collision studies at LHC energy, where up to 10^5 particles will be produced in one collision.

The planned Compressed Baryon Matter (CBM) experiment at the future GSI facility will be a second generation fixed-target experiment. The detailed layout is currently being designed with Si-detector based tracking in a very high magnetic field as a crucial component, followed by several large particle identification detectors downstream. The technologies currently developed for the ALICE experiment, in particular those concerning Si-pixel detectors, transition radiation detectors, and time-of-flight detectors based on the resistive plate chamber principle, will play a major role in the future CBM experiment, with very large synergies expected in this area. The studies planned with CBM at the new GSI facility require very high accuracy and integrated luminosity to determine the fate of vector mesons as well as strange and charmed hadrons in dense matter. These possibilities – unique in the world – will be opened up by the beams from the SIS100/200 facility.

Theory

To stay competitive at an international level, especially with the US and Japan, it is crucial that large computational capabilities both for lattice calculations and for large-scale dynamical simulations will be made available to the theoretical nuclear physics community in the near future.