NuPECC Long Range Plan 2003

Chapter

QCD

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1 Conceptual framework

Over the last decade the physics of hadrons and the physics of nuclei, once distinct fields explored by separate communities, have grown into a joint venture with a common root: Quantum Chromodynamics (QCD), the theory of the strong interaction. This theory emerged from the current algebras of the 1960's by way of the quark and parton models. By explaining the observed patterns in the spectrum of hadrons and the scaling behaviour seen in deep-inelastic scattering, these developments showed that quarks are the basic constituents of hadrons, and hence of nuclei.

Quarks are fermions with an intrinsic angular momentum (spin) of 1/2 and an electric charge whose magnitude is either 1/3 or 2/3 of the electron's charge. They also carry a property known as "colour" which can take three possible values and which controls the strong interactions between quarks. Six different types of quarks are known. Three of these are light, in the sense that their masses are much smaller than the nucleon mass. These include the "up" and "down" quarks (denoted u and d) which are the primary constituents of normal atomic nuclei. There is also the "strange" quark (s) which is somewhat heavier but which may make significant contributions, particularly in dense matter. Then there are three heavy quarks: "charm", "bottom" and "top" (c, b and t) which play much smaller roles at low energies.

QCD is a quantum field theory of quarks interacting with spin-one bosons known as gluons. Like all theories of fundamental interactions in particle physics it is a gauge theory: its form is unchanged under "rotations" of the three-valued colour charge. What makes QCD fundamentally different from Quantum Electrodynamics is the fact that the gluons carry colour charges and so interact amongst themselves, unlike photons which are neutral. It is this highly nonlinear dynamics of the gluon fields which lies behind key features of QCD such as confinement (the absence of free colour-charged objects in nature) and asymptotic freedom (the fact that quarks and gluons interact weakly at high momenta or short distances).

In any quantum field theory, virtual particles which result from quantum fluctuations lead to the strengths of interactions varying with momentum, or "running". In QCD this means that the coupling strength becomes small for particles with high momenta. On distance scales smaller than 0.1 Fermi, this asymptotic freedom permits us to treat QCD as a perturbative theory of point-like quarks and gluons.

In contrast, at distance scales of the order of 1 Fermi the running coupling becomes large, and a perturbative expansion in powers of this quantity is no longer valid. In this nonperturbative regime, which corresponds to the energies and momenta relevant to most of nuclear physics, the particles we observe are not quarks and gluons but colourless baryons and mesons. Both regimes, perturbative and nonperturbative, are explored experimentally either by studying the responses of hadronic systems to high-precision probes at various energy scales or by creating conditions of high density or temperature in high-energy heavy-ion collisions [1].

Conceptually, low-energy QCD has many features in common with condensed-matter physics. The ground state or vacuum is a complex, strongly interacting system, filled with condensates of quark-antiquark pairs and gluons. The observed particles respect only a subset of the full symmetries of the theory. As in condensed-matter physics, we have two main theoretical tools to try to understand such systems: direct numerical simulation of the theory, and construction of effective theories for the low-energy degrees

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[1] See also the preceding chapter on Phases of Nuclear Matter.

of freedom. The first approach, known as Lattice QCD, is starting to yield reliable results for the ground-state properties of hadrons and for the phase structure of QCD at finite temperature.

Despite the complexity of the QCD ground state, underlying symmetry principles and the patterns of symmetry breaking can provide important guidance for the second approach to the low-energy regime. In particular QCD with light quarks has an approximate chiral symmetry (which would be exact in the limit of massless quarks). This symmetry is spontaneously broken by the condensation of quarks and antiquarks in the vacuum. Pions are identified with the Goldstone bosons corresponding to this symmetry, which explains their small mass and the fact that they interact only weakly at low energies. This makes it possible to represent low-energy QCD by an effective field theory of pions and nucleons (and their strange partners), known as Chiral Perturbation Theory.

While we have controlled expansions of QCD in the two limiting situations, at very high energies as a perturbative theory of quarks and gluons, and at very low energies as a perturbative theory of pions, the true challenges lie between these extremes. Some of the most striking experimental facts which have their origins in the nonperturbative regime and which cannot yet be conclusively derived from QCD are the following:

- **Mass gap**
  There is a characteristic mass gap of about 1 GeV which separates the QCD ground state (or "vacuum") from almost all of its excitations, with the exception of the pion. How do these masses arise for hadrons which are built out of almost massless quarks and massless gluons?

- **Colour confinement**
  Quarks and gluons are not observed as free particles but are always trapped inside colourless hadrons. What are the mechanisms responsible for this phenomenon, and in particular what role do gluon fields play in it?

- **Spontaneous breaking of chiral symmetry**
  Pions are quite distinct from all other hadrons: they have very low masses and interact only weakly at low energies. Their properties can be well explained by treating these particles as the Goldstone bosons associated with spontaneously broken chiral symmetry. How are the condensates responsible for this generated? Under what conditions is this symmetry restored?

QCD is currently the best example we have of a nonperturbative quantum field theory, defined by a set of simple and fundamental rules but giving rise to an enormously rich range of physical phenomena. Moreover it is the only such theory that we are able to probe with high precision and under a wide variety of conditions. How its basic constituents (quarks and gluons) arrange themselves to form baryons and mesons, how these interact collectively in nuclear systems and how such systems behave under conditions of extreme temperature or density, these are key issues for nuclear physics.

With these key questions in mind, we highlight some of the experimental and theoretical challenges for the future. These will then be discussed in more detail in the rest of this chapter.

Substantial progress can be expected over the next decade in the following areas and topics:

- **The role of glue**
  The gluon field is the fundamentally new element of QCD that makes the dynamics

of strong interactions so much different from any other basic force in nature. Gluons play an important role in the intrinsic structure of the nucleon. In particular, being spin-1 bosons, the gluonic contribution to the total spin 1/2 of the nucleon has been a persistent puzzle. In the coming decade several experiments will provide new data on this key issue.

QCD predicts the existence of gluon-rich states known as glueballs. It also predicts hybrid states consisting of quark-antiquark pairs with excitations of the gluon field that holds the pairs together. The search for such states, the study of their decay modes and the investigation of their mixing with "conventional" states is one of the major experimental and theoretical challenges for the future.

- **Quark dynamics**
  The internal quark-gluon structure of hadrons is encoded in a well-defined hierarchy of correlation functions, the simplest of which are the parton distributions. In recent years, much progress has been made in developing a broader framework of so-called Generalised Parton Distributions (GPDs) which promise a clearer connection between fundamental QCD, phenomenology and experimental observables. Significant advances in this field are anticipated in the near future, especially because observables (such as single-spin asymmetries and exclusive cross sections) have been identified that can be used to extract information on parton correlations and quark orbital motion, for which no data exist so far.

  The spectroscopy of hadrons and the detailed investigation of their decays has been a traditional cornerstone in the understanding of the physics of strong interactions. Meson and baryon spectroscopy for systems with charm quarks is less well studied. Precision experiments which can explore these states will provide much novel information.

- **New theoretical developments**
  Increasingly accurate results are now emerging from large-scale simulations of QCD on four-dimensional Euclidean space-time lattices. Improved analytical methods for removing artifacts of discretisation, together with steadily increasing computer power, give rise to the expectation that decisive breakthroughs are at hand.

  "Integrating out" the colour degrees of freedom from QCD leads to an effective field theory of hadrons. The spontaneously broken chiral symmetry of QCD is the basis for a systematic expansion of this theory at low energies. The resulting Chiral Perturbation Theory is applied to mesonic systems as well as to a variety of processes involving mesons in interaction with a single nucleon. These studies are essential for analysing the response of the nucleon to low-momentum electromagnetic probes. The approach is being extended to describe nuclear forces and low-energy properties of light nuclei [2].

  While lattice QCD and effective field theory methods are promising theoretical tools, each within its own limits of applicability, much of the current experimental interest lies in regimes where no systematic expansion of QCD is known and for which lattice QCD is poorly suited. In these areas, as well as in the rapidly developing field of Generalised Parton Distributions, there is a useful role to be played by well-founded models, inspired by QCD but based on quasiparticles, such as consituent quarks, and collective degrees of freedom, such as Goldstone bosons and instantons. It will

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[2] See also section 2 of the chapter on Nuclear Structure.

be important to develop these approaches further, and in particular to make closer contact with lattice QCD and systematic expansions.

- **Chiral symmetry**
  Dynamics based on the approximate chiral symmetry of QCD forms a guiding theme for the well-developed programmes exploring the low-energy frontier of strong interaction physics. These include high precision experiments on meson-meson and meson-nucleon scattering processes and, in particular, the use of electromagnetic probes to map out a vast amount of detailed information about the pion cloud of the nucleon and the structure of the pion itself. Form factors, electromagnetic polarisabilities and meson production at threshold are crucial testing grounds for chiral perturbation theory. Applications of effective field theory methods to near-threshold reactions involving two nucleons will provide further systematic information. The challenges posed for the next decade are the further improvement of experimental precision and the selection of the most significant observables.

  Insight into the physical mechanisms governing the mass gap in the hadron spectrum can be gained from studies of changes to this spectrum in nuclear systems, and from analyses of these changes in the context of the broken chiral symmetry of QCD. Experimental programmes which can shed light on this include high-energy heavy-ion collisions as well as high precision measurements of low-energy meson-nuclear states.

- **QCD and nuclear matter**
  Several distinct QCD-related phenomena occur in interactions of partons (high-momentum quarks and gluons) with a nuclear environment. One of them goes under the name of colour transparency. This refers to the formation of colour dipoles, such as quark-antiquark pairs, and their propagation through the medium. Another important issue is the energy loss that partons experience when passing through matter. A detailed description of the underlying physics of such processes is crucial in a broader context. Specifically it is needed for understanding the mechanisms involved in the ultra-relativistic heavy ion collisions which are being used to explore the QCD phase diagram. This field draws together parton physics and the study of hadronic matter under extreme conditions.

  A valuable source of information on non-conventional forms of baryonic matter is provided by systems with one or more strange or heavy quarks. Hypernuclei (nuclei containing strange quarks) have long been used for this and such studies should be pursued further, especially now that new facilities become available which feature an unprecedented energy resolution. Additional insights are forseen if nuclear systems with one or more charm quarks can be produced and studied at an appropriate facility.

2 Physics issues

2.1 New theoretical developments

2.1.1 Lattice QCD

The non-perturbative nature of QCD at large distances forms an obvious barrier for analytic treatments. However, important conceptual and technical progress has been made towards accurate simulations of the theory on a discrete lattice of space-time points. These demand both sophisticated numerical methods and raw computing power. Developments on both fronts mean that the quality of lattice computations is now beginning to reach the level at which meaningful comparisons with actual observables are feasible. Recent results include hadron masses and form factors, key properties of the nucleon (such as magnetic moments and the axial coupling constant relevant to neutron β-decay), as well as moments of structure functions.

These simulations use Monte-Carlo methods to perform a path integral over configurations of gluon fields. In the absence of quarks, the weighting of any configuration can be obtained from its action. In QCD, integration over the quark fields introduces the determinant of the quark Dirac operator into the weighting. Constructing this entails the high computational expense of inverting a huge matrix. This is often circumvented by an enormous simplification: the quenched approximation, in which this determinant is replaced by a constant. Doing this amounts to discarding most of the quantum fluctuations of the quark fields, in particular the multiple quark loops representing virtual quark-antiquark pairs, and it means that some contributions from such "sea" quarks are missing from physical observables.

While up to now most lattice calculations have relied on the quenched approximation, the steadily increasing power of large-scale computing facilities is starting to permit more extensive simulations of the full theory, including quark loops to all orders. Even so, current calculations are limited to relatively large quark masses, typically an order of magnitude larger than the actual masses of the u- and d-quarks. These correspond to pion masses of at least 0.5 GeV, which is too large to reliably predict chiral aspects of pion and nucleon dynamics in the real world.

Further significant improvements in lattice technology are expected in coming years. Although simulations with realistically small quark masses may still be out of reach for the foreseeable future, ultimately such efforts may not be necessary. Low-energy QCD in the light-quark sector is realised in the form of an effective field theory based on chiral symmetry. This theory can be used to extrapolate from lattice results obtained at higher u- and d-quark masses to the real world. Once lattice calculations are possible with pion masses of around 300 MeV, reliable extrapolations using these methods should be able to close the remaining gap between lattice QCD and actual observables. In combination with improvements in gluon and quark actions which permit the use of larger lattice spacings, as well as further increases in computing speed, this sets the scene for lattice QCD to make major contributions to the field as a whole.

2.1.2 Parton distributions

The asymptotic freedom of QCD means in effect that small-sized configurations of quarks and gluons can form useful probes of hadronic structure. Such configurations can be created in reactions such as deep-inelastic scattering (DIS), semi-inclusive DIS, Drell-Yan processes, or hard exclusive reactions. A crucial feature of all these processes is "factorization": the fact that one can cleanly separate the hard (high-momentum) and soft (low-momentum) aspects of the interactions. The hard part of the scattering amplitude can be calculated using QCD perturbation theory whereas the soft parts of the amplitude, which describe how a given hadron reacts to some small-sized configuration, or how such a probe is transformed into hadrons, lie in the realm of non-perturbative QCD. These parts can be parametrized in terms of quark and gluon distributions, whose extraction requires close collaboration between experimentalists and theorists.

The unpolarized distributions describe the probability that a particular flavour of quark or a gluon carries a fraction x of the momentum of a fast-moving nucleon. QCD predicts how these distributions evolve with the hard resolution scale and this is now routinely calculated to next-to-leading order (NLO) in the strong coupling constant. Higher-order treatments are also under development. Analyses of DIS data have now mapped out the unpolarized quark and gluon distributions down to momentum fractions $x \sim 10^{-4}$ and over a wide range of scales. These results provide a benchmark for the steady progress being achieved in perturbative QCD.

For the helicity distributions, the present state-of-the-art is at next-to-leading order in the strong coupling constant. Analyses of polarized DIS have shown that less than a third of the spin of the nucleon is carried by the intrinsic spins of the quarks. The origin of the remainder of the nucleon's spin is an important open question. In fact the NLO analysis of these experiments suggests that the gluons make an important contribution. However the present data cover only a limited range of resolution scale and so there is still a large uncertainty on the polarized gluon distribution extracted in this way. A more direct determination is possible using the photoproduction of heavy quarks, and in particular the production of pairs of charmed mesons. Recently, NLO analyses of this process have become available and these will allow us to pin down much more accurately the gluonic contribution to the spin of the nucleon.

The above mentioned distributions are incoherent single-parton densities in the nucleon. Information on coherent effects in the nucleon wave function can be obtained from hard scattering processes where a finite momentum is transferred to a nucleon. Examples include deeply virtual Compton scattering ($ep \to ep\gamma$) and exclusive electroproduction of light mesons. Qualitatively one can think of these as removing from the nucleon a quark of given flavour, momentum and spin, and replacing it in a controlled way by another quark, in general with a different flavor, momentum and spin (see Fig. 1). Work in the last few years has shown that the amplitudes for such processes factorize into hard scattering parts and a set of generalized parton distributions (GPD's) which contain new information on the nonperturbative structure of the nucleon. In the forward limit these GPD's reduce to ordinary parton distributions but when a finite momentum fraction is transferred the GPD's become sensitive to coherent effects such as quark-quark momentum correlations or quark-antiquark configurations in the nucleon. Integrals of these distributions over the average momentum fraction carried by the quarks can provide information on properties of the nucleon that are not otherwise accessible. In particular, the second moment of a

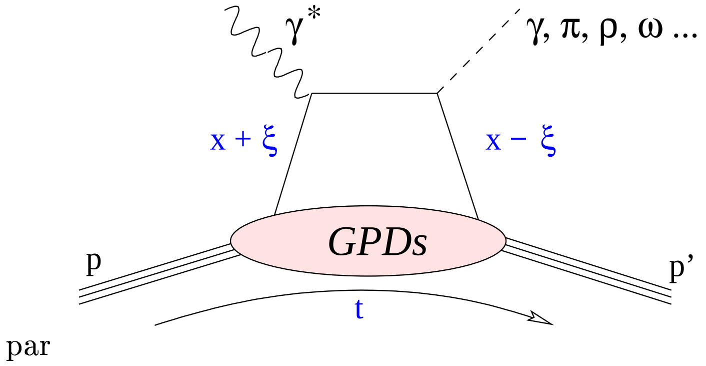

Figure 1: A hard electroproduction process on a proton, leading to a photon or a meson in the final state. Such reactions can be used to investigate Generalised Parton Distributions (GPD's).

specific combination of GPD's gives a measure of the total angular momentum carried by quarks in the nucleon, information which would be complementary to that extracted from polarized DIS.

2.1.3 Effective field theory

Effective field theory (EFT) has become a major tool for nuclear physics in recent years. Underpinning it is the observation that field theories do not have to be fundamental; all that is needed is a clear separation of scales between the physics of interest and the underlying physics. Nonrenormalizable field theories, which in principle depend on an infinite number of parameters, can then be very useful at a given level of finite "resolution".

To formulate such a field theory, one first finds the important degrees of freedom for the problem and writes down a Lagrangian containing all possible terms allowed by symmetries. Next one identifies a principle for systematically organising these terms in order of importance: a "power counting" which associates with each term some power of a small quantity. At a given order in these small quantities, only a limited number of terms are needed, whose strengths can be determined either from experiment or with other theoretical methods. The importance of this approach is its generality: if any further assumptions are introduced, they are clearly visible. These theories play an important role in three areas of nuclear physics: low-energy meson physics, single-nucleon processes near threshold, and the low-energy physics of two or more nucleons.

Spontaneous breaking of chiral symmetry requires the presence of a set of very light particles, known as Goldstone bosons. For QCD, these particles are the pions, which are separated from all other states by a mass gap of order 1 GeV. Goldstone's theorem requires that the interactions of these particles vanish at very low energies. Kaons and η mesons may also be treated in this way, albeit with caution because their masses are between three and four times larger than that of the pion.

The resulting EFT is then a low-energy expansion formulated in terms of the Goldstone bosons with a small parameter provided by the ratio of the energy or momentum to the mass gap. The systematic expansion in this small parameter, chiral perturbation theory, is now basis for much theoretical work in this area. In the meson sector the combination of EFT and dispersion relations is proving to be a very useful tool. Applications to pion-pion scattering are now theoretically fully under control.

In the baryon sector too, there is an energy gap between the nucleon and its excited states. The effective field theory here describes states with a single nucleon and any number of Goldstone bosons, and the power counting is in terms of the momentum divided by the mass gap. A significant technical complication, the presence of the large nucleon mass in all calculations has been solved by making a nonrelativistic reduction. Calculations now routinely include the first three orders in the expansion and have been applied with some success to processes such as meson-nucleon scattering, meson photoproduction, and Compton scattering (see Fig. 2). Other areas under active investigation are the inclusion of the Δ resonance, and the treatment of relativistic effects, particularly in nucleon form factors.

In recent years there has been major progress in extending these ideas to systems of two or more nucleons. The problem which had to be overcome here is that simple dimensional counting of energies over a mass gap leads to very large higher-order corrections. This is because there is a bound state just below threshold, the deuteron, in the $^3S_1$ channel and a resonant state just above threshold in the $^1S_0$ channel. Since perturbation theory cannot generate bound states, some terms in the interaction must be resummed to all

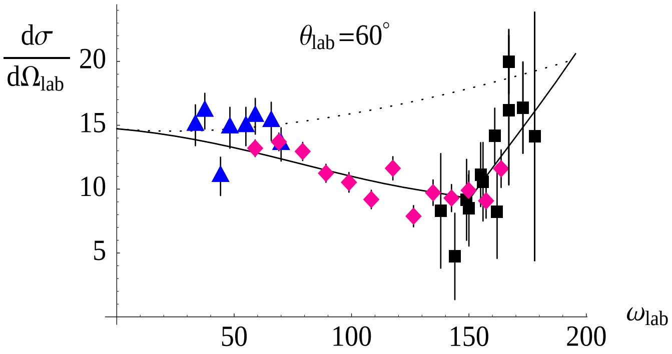

Figure 2: Prediction of fourth-order chiral perturbation theory (solid line) for Compton scattering cross section on the proton, compared with recent data from Mainz (diamonds) and older data from Illinois (triangles) and Saskatoon (squares). Also shown is the prediction of the Born and π^0 anomaly terms only (dotted line).

orders, while still retaining a well-defined ordering principle. This was achieved using renormalisation group arguments to incorporate an additional low-energy scale in the counting, namely that of the large scattering lengths.

At very low energies, well below the pion threshold, the resulting EFT provides a systematic way to extend the effective-range expansion to describe electromagnetic and weak interactions of two-nucleon systems. Progress is now being made towards applying it to three-nucleon systems. At higher energies, pions should be included as explicit degrees of freedom. However the strong pion-nucleon coupling makes this problematic, at least in the s-wave channels. In more peripheral partial waves, the centrifugal barrier means that nucleon-nucleon interactions are weaker. Analyses of these channels now show good evidence for the two-pion exchange force predicted by the chiral expansion.

2.1.4 QCD-inspired models

At this point, it is important to stress the distinction between theory and models. A theory is a framework in which observables can be calculated directly from underlying principles, in the present case those derived from QCD. Its application generally involves various approximations but, at least in principle, these can be improved upon systematically. In addition a theory should be capable of specifying the limits of its validity. An approach which does not satisfy simultaneously *both* of these criteria is a model.

Perhaps the most important use for models is to identify the dominant physics involved in particular processes and hence to indicate what might be learned from future experiments. Successful model descriptions can provide bridges from areas where QCD can be applied directly to a broader range of phenomena where rigorous approaches are not at present available.

A first class of such models is based on quasiparticle and collective degrees of freedom. These can provide a reasonably good description of the hadron spectrum in terms of constituent quarks. The addition of a flux tube picture for the gluonic degrees of freedom makes it possible to reproduce most of the spectrum. While flux tubes have been shown to exist using lattice QCD (at least for infinitely heavy quarks), the emergence of constituent quarks remains mysterious. It is generally believed that their masses are associated with the spontaneous breaking of chiral symmetry. This is embodied in versions of constituent quark models which include couplings to pions and so satisfy constraints of chiral symmetry. Attempts to connect these models more closely to QCD invoke configurations of gluon fields such as instantons and colour monopoles.

Closely related to these are collective models, where baryons emerge as solitonic configurations of Goldstone boson fields (Skyrmions). Many of their predictions correspond to those of a quark model with a very large number of colours of quark. Recent versions of these models, where the mesons are generated as quark-antiquark pairs, naturally give rise to an antiquark "sea" and can be used to predict sea parton distributions. However connecting these models more closely to QCD remains an open problem.

The second class of models is based entirely on hadronic degrees of freedom. These are typically Lagrangians which satisfy some constraints of chiral symmetry and which are formulated in terms of physical mesons and baryons, including resonances. At present they provide one of the main tools for understanding the intermediate-energy domain. More systematic applications of chiral symmetry constraints and matching to QCD short-distance behaviour will lead to further progress in this area.

Finally, further improvement is also to be expected in the use of unitary resummations to extrapolate the results of chiral perturbation theory to higher energies. These approaches are able to describe several intriguing properties of the scalar meson sector as well as excited baryons.

2.2 Role of glue

2.2.1 Spin of the nucleon

In the naive quark model, the spin of the proton is carried by its three valence quarks (see Fig. 3). However, in recent years we have learned that the gluons and possibly the orbital angular momentum of the quarks and gluons also contribute to the total spin content of the nucleon. This is commonly expressed by the following equation

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z, \tag{1}$$

where $\Delta\Sigma$ represents the summed contributions of the quarks spins, ΔG the contribution of the gluons, and L_z the orbital angular momentum of the partons.

Experimental information on the summed quark contributions has been obtained in polarized deep-inelastic scattering experiments. The results of such experiments are expressed as the longitudinal spin (or helicity) distribution function $g_1(x)$. When integrated over, this yields a value for $\Delta\Sigma$. Data on $g_1(x)$ have been obtained in various experiments carried out at CERN, DESY and SLAC. Their results are in good agreement with each other. On the basis of these data the total quark spin contribution $\frac{1}{2}\Delta\Sigma$ to the nucleon spin is found to be 0.1–0.3, indicating that additional carriers of angular momentum are needed in the nucleon.

To understand further the spin structure of the nucleon, the flavour dependence of the spin distribution functions has been determined. This is done in semi-inclusive deep-inelastic scattering experiments, in which one of the final hadrons is detected. The type of hadron (usually a π^+, π^-, K^+ or K^- meson) provides a tag on the flavour of the struck quark. The results of such measurements reveal that the polarization of the u-quarks is parallel to that of the proton, while the polarization of the d-quarks has the opposite orientation. Most importantly, the sea quarks have been found to carry very little polarization.

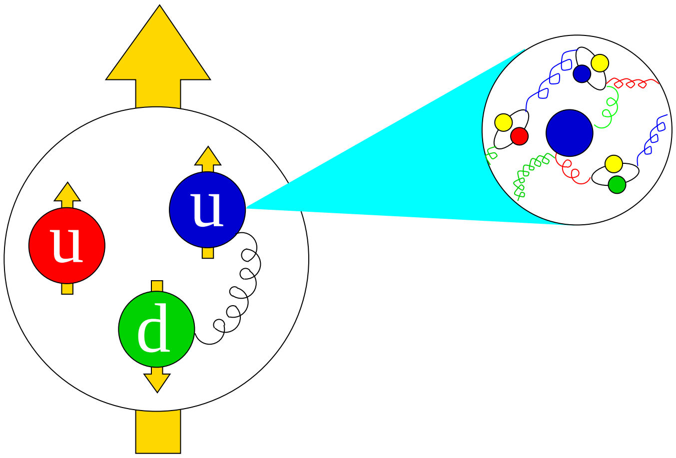

Figure 3: The (spin) structure of the nucleon. Apart from the contribution of the valence quarks, the gluons and sea-quarks may contribute as well (enlargement). Not shown in the figure is a possible orbital angular momentum contribution of the quarks and gluons.

As the polarizations of the valence and sea quarks taken together cannot account for the full spin of the nucleon, efforts are now being made to measure the gluon polarization. Although QCD analyses of the polarized structure function $g_1(x)$ indicate that the gluon polarization could be large and positive, no direct measurements of ΔG exist. The proposals for determining ΔG are based on identifying photon-gluon fusion events in deep-inelastic scattering experiments. In these processes the virtual photon annihilates with a gluon from the target to produce a quark and its antiquark. The asymmetry of the process is sensitive to the gluon polarization.

HERMES has recently explored this process by detecting pairs of hadrons with high transverse momentum. This has yielded a positive value for ΔG but with large statistical and systematic uncertainties. The recently started COMPASS experiment at CERN will provide a much more precise measurement of the gluon polarization based on the identification of photon-gluon fusion events by detecting either charmed particles or high-p_T pairs of hadrons. This experiment has been designed to be able to map out the x dependence of ΔG. In the future, complementary data on the gluon polarization are expected to come from the RHIC-spin program at BNL using polarized proton beams.

2.2.2 Glueballs and hybrids

Simple constituent quark models have been remarkably successful in explaining most features of the observed meson spectrum. However, the QCD spectrum is much richer in content than that of the naive quark model. Gluons, which mediate the strong force between quarks, also carry colour charges and are able to interact with each other. The gluon-gluon interaction is the distinct feature of QCD held responsible for one of its spectacular consequences: confinement. It is also the source of another striking prediction of QCD: the existence of gluon-rich states known as glueballs, and of mixed states of quarks and gluonic excitations known as hybrids.

QCD-based "chemistry" suggests a variety of unconventional hadron configurations, such as meson-meson molecules bound by residual QCD forces, or more complicated color-neutral multiquark states such as $qq\bar{q}\bar{q}$ or $qqqq\bar{q}$. All these states should appear superimposed on the ordinary meson and baryon spectra.

The experimental observation of these exotic particles, in particular glueballs, would confirm one of the most important features of QCD. On the other hand, the non-existence of such states would pose a genuine problem for our understanding of hadronic physics in the context of QCD.

At present, the best candidate for the ground state glueball has emerged from antiproton-proton annihilation experiments performed at LEAR. This rather narrow state, the $f_0(1500)$, has the quantum numbers $J^{PC} = 0^{++}$. Its mass and width are consistent with predictions of lattice QCD for the ground state scalar glueball. However, the definitive identification of the $f_0(1500)$ as a glueball is complicated by its possible mixing with nearby conventional $q\bar{q}$ scalar mesons. The unambiguous identification of those $q\bar{q}$ states, including the scalar $s\bar{s}$, and the clarification of the multiquark ($qq\bar{q}\bar{q}$) content of the $a_0(980)$ and $f_0(980)$ mesons, are important steps that need to be further pursued. This last issue is being explored by the KLOE experiment at DAΦNE.

The mixing between predominantly gluonic bound states and neutral, flavour-singlet mesons means that some "conventional" meson states may contain significant glueball admixtures in their wave functions. Indeed, the possibility of a glueball component in the η' meson has been argued for many years. However, the recent measurement of the ratio $\Gamma(\phi \to \eta'\gamma)/\Gamma(\phi \to \eta\gamma)$, by the KLOE experiment at DAΦNE finds a value which limits the glueball content of the η' to at most 10–15%.

Candidates for hybrid states have been identified in $\pi^- p$ reactions at BNL and in $\bar{p}p$ annihilation at LEAR. A striking feature is that their production rate in $\bar{p}p$ annihilation is comparable to that of normal $q\bar{q}$ states. However, several predictions put the 1^{-+} hybrids at masses around 2 GeV/c^2. The discrepancy between these predictions and the experimentally measured states needs further clarification.

The COMPASS experiment at CERN can study Primakoff and diffractive production of light-quark hybrid mesons in the 1.4–3.0 GeV/c^2 mass region, including the candidates just mentioned. A 200 GeV pion beam will be used to measure pion-photon and pion-Pomeron reactions leading to selected hadronic final states. The relative strength for production of hybrids compared with other close-lying states is expected to be significantly larger than in previous experiments, leading to substantially reduced uncertainties.

Until now, the search for glueballs and hybrids has been mainly restricted to the mass range below 2.2 GeV/c^2. In the case of central production in proton-proton collision, another gluon-rich process, production of higher mass states is limited by the fall-off of the cross section with the inverse square of the mass of the state. Also, radiative J/Ψ decay, which could produce gluonic hadrons up to 3 GeV/c^2, lacks the required statistics. For a more complete understanding of the nature of gluonic excitations, a careful study of the spectrum of glueballs and hybrids up to 5 GeV/c^2 is an absolute necessity.

Central parts of the physics programme using the PANDA detector at the High-Energy Storage Ring (HESR) planned at GSI are the search for gluonic excitations in the charmonium sector and the continuing hunt for glueballs, including highly excited states with exotic quantum numbers. Light hybrids (with masses up to 2.5 GeV) will be a focus of the proposed 12 GeV upgrade of the Jefferson Lab facility.

Going to higher masses in the search for gluonic hadrons provides several advantages:

- Normal light-quark systems have a complicated spectrum. Nearly a hundred states with widths of ~100–400 MeV are known in the mass interval 1–2 GeV/c^2. In the charmonium region only eight narrow states exist in the 0.8 GeV/c^2 interval below the $D\bar{D}$ threshold, and the continuum above is relatively smooth. This makes it likely that any exotic states in the 3-5 GeV/c^2 mass region can be resolved and identified unambiguously.

- Lattice QCD and various models all predict low-lying charmonium hybrids with masses between 3.9 and 4.5 GeV/c^2, the lowest state having the exotic quantum numbers $J^{PC} = 1^{-+}$. Three of the eight lowest-lying charmonium hybrids have spin-exotic quantum numbers, hence strong mixing effects with nearby $c\bar{c}$ states are excluded.

- Quantum number conservation and dynamical selection rules imply that charmonium hybrids below the $\bar{D}D^{**}$ threshold of 4.3 GeV/c^2 cannot decay into D mesons and so their widths should be small. Hybrids that can decay into $D\bar{D}$ are expected to have widths similar to the 25–40 MeV widths of the known vector states $\Psi(3S)$, $\Psi(4S)$ and $\Psi(5S)$.

- Nucleon-antinucleon annihilation can produce gluons as well as quark-antiquark pairs within a volume corresponding to the range of the strong interaction. As a result ordinary mesons and gluonic hadrons should have similar chances of being formed. Indeed, experiments at LEAR indicate that production rates of $q\bar{q}$ states are similar to those of states with exotic quantum numbers.

- In the mass range that is accessible to the HESR project, lattice QCD suggests the existence of about 15 glueball states, some with exotic quantum numbers. For example, the lightest glueball with the exotic quantum numbers 2^{+-} is predicted to have a mass of 4.3 GeV/c^2. For such glueballs the mixing with normal mesons should be suppressed. As a consequence they are predicted to be rather narrow and easy to identify experimentally.

Searches for glueballs and hybrids in this energy region can be performed in parallel with studies of charmonium spectroscopy at the proposed PANDA detector. In addition, by comparing different production mechanisms it should be possible to find unambiguous signatures of these exotic states.

2.3 Quark dynamics

2.3.1 Transversity

"Transversity" refers to a third structure function which describes a novel aspect of the dynamics of quarks in the nucleon. While the structure functions $f_1(x)$ and $g_1(x)$ represent the momentum and spin distributions of the quarks (see sections 2.1.2 and 2.2.1), the third function $h_1(x)$ represents the transverse spin distribution of quarks, that is the probability of finding a quark with its spin-orientation parallel to that of the nucleon when the nucleon spin is perpendicular to the incident beam (see Fig. 4). Almost nothing is known at present about the transversity distribution $h_1(x)$, even though it is of great interest since data on it would enable us to investigate two remarkable QCD-based predictions.

Gluons are predicted not to contribute to the transverse spin distribution and so the structure functions $f_1(x)$ and $h_1(x)$ are expected to differ considerably. As a result both the dependence of $h_1(x)$ on Q^2 and the integral over $h_1(x)$ (known as the tensor charge, $\delta\Sigma_q$) should be quite different from their longitudinal counterparts. The well-known QCD scaling behaviour of $f_1(x)$ (which is largely driven by the gluon contributions) is predicted to be essentially absent for $h_1(x)$. In addition the tensor charge is predicted to be much larger than the integral over $g_1(x)$ which leads to $\Delta\Sigma$.

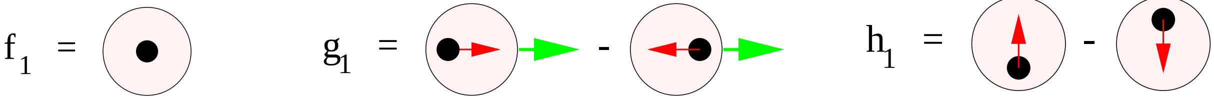

Figure 4: The different spin orientations of the three functions $f_1(x)$, $g_1(x)$ and $h_1(x)$ that give a full account of the momentum, helicity and transverse spin structure of the nucleon.

Inclusive deep-inelastic scattering can be used to measure only chirally even quantities, whereas $h_1(x)$ is chirally odd and so to obtain information on $h_1(x)$ we must combine it with another chirally-odd observable. An example of such a function is the one needed to describe the azimuthal dependence of pions produced in deep-inelastic scattering. Therefore, one possible way to determine the transversity distribution is to use transversely polarized targets in combination with measurements of the azimuthal dependence of the produced hadrons.

A first hint of a non-zero transversity distribution has been reported by HERMES. In this experiment the single target-spin asymmetry for leptoproduction of pions was measured on a longitudinally polarized hydrogen target. The data show a small positive single-spin asymmetry. Similar data have been obtained on a longitudinally polarized deuterium target.

The data can be explained by a model calculation assuming reasonable estimates for both the transversity distribution $h_1(x)$ and the corresponding (chirally odd) fragmentation function. However, the small azimuthal asymmetry might also be caused by a final state interaction between the spectator system and the current quark jet. Future measurements using a transversely polarized target will be able to resolve this ambiguity, as the two processes give rise to a transverse single-spin asymmetry with different dependence on the azimuthal angle between scattering plane, transverse spin direction and plane of the produced hadron.

On the basis of the small asymmetries measured with longitudinally polarized targets, it is expected that sizable asymmetries will be observed if transversely polarized targets are used. Such experiments have recently been started at both COMPASS and HERMES. They will not only be able to measure the contribution of contaminating final-state interaction effects, but they will also allow the first direct measurements of the transversity distribution.

It should be emphasized, however, that considerably higher statistics will be needed to extract an accurate value for the tensor charge of the nucleon and to study the Q^2 dependence of the transversity distribution. Hence, although COMPASS and HERMES will provide very important first data in this otherwise virgin field, a full investigation of this aspect of nucleon structure can only be carried out at a new high-luminosity lepton scattering facility. Such a facility will make it possible for the first time to verify the predictions of QCD for the transverse spin structure of the nucleon, namely a large tensor charge and weak evolution of $h_1(x)$ with Q^2.

2.3.2 Generalised parton distributions

Generalized parton distributions (GPD's) offer a more comprehensive description of quark dynamics in the nucleon, since they can take account of correlations between different quark momentum states, and between longitudinal momentum and transverse position. They are universal non-perturbative objects entering the description of hard exclusive electroproduction processes such as $ep \to e'p + \gamma, \rho, \omega, \pi$. Using QCD factorization theorems, the amplitudes for such processes can be split into hard scattering amplitudes

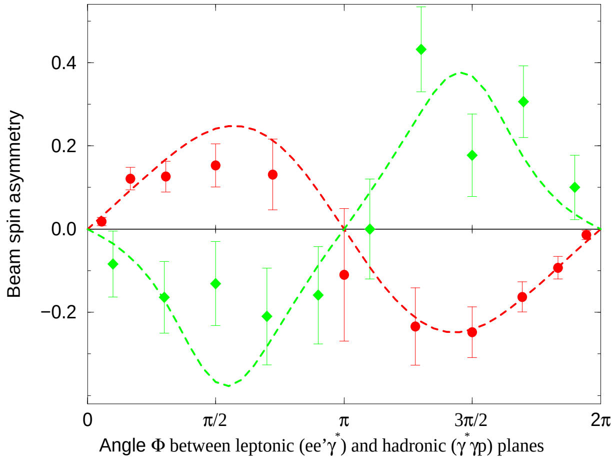

Figure 5: Beam spin asymmetry in the process $\vec{e}p \to ep\gamma$ from CLAS at JLab (red points) with electrons and from HERMES (green) with positrons, in somewhat different kinematical regions. The approximate $\sin\Phi$ dependence is suggestive of the applicability of the GPD formalism, as illustrated by the theoretical curves.

between partons and GPD's, as shown in Fig. 1. From the theoretical point of view, the introduction of these new distributions builds a bridge between fundamental QCD, phenomenology and experimental observables. Moreover, such measurements are sensitive to the total angular momenta carried by quarks of given flavour in a polarized nucleon.

Several observables in deeply virtual Compton scattering (DVCS) and exclusive deeply virtual meson production (DVMP) provide a handle on the experimental determination of these distributions. However the hard production of photons within the target nucleon is indistinguishable from the Bethe-Heitler process in which the photons are emitted by the incident or scattered electrons. At high enough energies, DVCS is nonetheless expected to dominate in most of phase space, whereas at somewhat lower energies, the interference between the two processes may be used to study DVCS at the amplitude level.

The first experimental results do indeed indicate that Compton scattering at the parton level has been observed. Cross sections measured by the H1 and ZEUS collaborations at HERA are in qualitative agreement with estimates based on gluon and quark GPD's. Beam spin asymmetries, measured both at HERMES and JLab/CLAS (see Fig. 5), display a characteristic $\sin\Phi$ dependence due to the above mentioned interference. Moreover, the first measurement of beam charge (e^+/e^-) asymmetry at HERMES is indicative of the anticipated $\cos\Phi$ dependence and identifies the role of $q\bar{q}$ configurations in the proton.

Dedicated DVCS experiments, using new additions to existing detectors, will be performed at JLab and HERMES starting in 2004. These will provide much better statistics and an improved separation of the exclusive process by detecting all final state particles. This allows the study of the scaling behaviour of observables, putting on a firm ground the underlying theoretical description. Looking further ahead, such measurements are among the primary goals of the 12 GeV upgrade at JLab. Measurements at COMPASS, with 100–200 GeV μ^+ and μ^- beams hold great promise for mapping out the t-dependence of the GPD's.

The cross sections and asymmetries for exclusive leptoproduction of vector and pseudoscalar mesons are sensitive to different combinations of GPD's. Hence data on the various reactions can lead to information on the distributions for different flavours. Of particular interest is the production of longitudinally polarized vector mesons on a transversely polarized proton target. In these processes, the transverse target asymmetry is sensitive to the contribution of the total angular momentum of the quarks, J^q, to the proton spin. Specifically, ρ^0, ρ^+ and ω electroproduction are sensitive to the combinations $2\,J^u + J^d$, $J^u - J^d$ and $2\,J^u - J^d$ respectively. Measurements of this kind were started at HERMES and COMPASS in 2002. With the 12 GeV upgrade, JLab/CLAS should be able to measure cross sections up to $Q^2 \sim 8$ GeV^2.

In order to fully exploit the potential of GPD's, a new lepton scattering facility is needed. Precise measurements of the associated deeply virtual and exclusive reactions require both sufficient beam energy and high luminosity. This will permit the dependence on different kinematic variables to be studied systematically, which is crucial for extracting the distributions from data. The existing facilities in Europe operate at luminosities that do not allow such studies. In the United States, the CEBAF accelerator will make a major step forward, but even when upgraded in energy to 12 GeV, it does not cover all of the necessary kinematical domain. Finally, further theoretical studies are needed to evaluate the role of higher-twist effects, as well as other possible applications of the GPD formalism.

2.3.3 Light-quark hadrons

At longer distances corresponding to the confinement scale of 1 Fermi and beyond, one cannot directly "see" quarks, but the underlying quark dynamics is nevertheless at the origin of ground-state properties of hadrons, their excitation spectrum and the interaction between them.

Our QCD-based understanding of such fundamental issues has been promoted significantly by recent high-precision measurements. In particular, results from MAMI on the neutron electromagnetic form factors and nucleon polarisabilities clearly indicate the importance of the pion cloud in the structure of the nucleon (see Section 2.4).

Strange elastic form factors of the proton have also been extracted from experiments on parity violation in electron scattering. The first results from JLab and MAMI suggest that the strange-quark content of the nucleon is small, as probed by vector currents. These results require further experimental and theoretical investigation.

The excitations of a quantum system can provide important information about the wave functions of its constituents. Modern precision experiments and detectors are shedding new light onto the old subject of baryon spectroscopy. For example, the recent determination of the quadrupole component in the electromagnetic $N \to \Delta$ transition (at MAMI, ELSA, LEGS and JLab) also points to the role of the pion cloud surrounding the nucleon.

Furthermore, sum rules directly connect low-energy properties to the polarized and unpolarized photoabsorption cross sections on the nucleon. In particular, the contribution to the Gerasimov-Drell-Hearn sum rule from the resonance region has been measured at MAMI and ELSA. The extension of such sum rules to the forward scattering of virtual photons will allow quantitative studies of the transition from a resonance-dominated description at lower Q^2 to a partonic description at larger Q^2. Such measurements are being carried out at ELSA, HERMES, MAMI and JLab.

The constituent quark model predicts more excited states of the nucleon than have been observed so far. The search for such states is a major thrust of many experimental programs in the years to come, and it will also require renewed theoretical analyses. Resonance decays such as $N^* \to N\pi\pi$ are being investigated in neutral channels at GRAAL and in charged channels at ELSA/SAPHIR and JLab/CLAS. Such experimental capabilities will be significantly enhanced in future with the use of the SLAC Crystal Ball at the upgraded MAMI and of the LEAR Crystal Barrel at ELSA. Similarly, studies of two-pion production in nucleon-nucleon collisions have been started at CELSIUS and COSY; these are sensitive to the properties and decays of the baryon resonance $N^*(1440)P_{11}$. The channel $N^* \to \Lambda K$, which can be studied at ELSA and Jlab, is also a promising one for the discovery of new baryon resonances.

Turning to the interactions of nucleons, detailed studies of proton-proton scattering have been performed as a continuous function of the beam energy at COSY/EDDA, with either unpolarized or polarized beam and target. These results significantly constrain nucleon-nucleon phase shift analyses up to 2 GeV and yield tight upper limits on the elastic widths of (hypothetical) narrow dibaryons.

Meson production dynamics in few nucleon systems may also reveal new features of the strong interaction. For example, η meson production at threshold in the 2, 3 and 4 nucleon systems already gives strong indications of the existence of a quasi-bound $\eta - He$ state. It will be the task of CELSIUS/WASA and COSY to search for more direct evidence for such a state.

2.3.4 Charmed quark systems

The importance of precision studies of the charmonium system, compared to the other quarkonia $s\bar{s}$ and $b\bar{b}$, relies on its privileged position, lying in the region of intermediate distances where the domains of perturbative and non-perturbative QCD come together. It is for this reason that the charmonium system provides a unique testing ground for QCD. Indeed, the masses and widths of the $c\bar{c}$ states directly reflect the basic $q\bar{q}$ interaction; the various terms in the interaction are connected with different specific features of the spectrum. Moreover, it is in charmonium spectroscopy where the gluon condensate of the QCD vacuum can be determined. Finally, from an experimental point of view, charmonium states below the $D\bar{D}$ threshold are limited in number, have small widths, and are well resolved.

Discovery of the missing levels and accurate measurement of all states will provide significant additional insights into QCD. It will help to differentiate among various QCD inspired potential models and to fill in blanks in our understanding of the basic $q\bar{q}$ interaction. Such a program is complementary to the physics of light-quark systems for which the large value of the strong coupling constant rules out the use of perturbation theory. At the other extreme, the spectroscopy of the bottomium system is characterized by the almost static behaviour of the very massive b quark.

Charmonium spectroscopy was extensively studied at e^+e^- colliders during 1974–80. However, the technique of studying charmonium via e^+e^- annihilation had important limitations. In particular, only the vector states, $J^{PC} = 1^{--}$ $(J/\Psi, \Psi', \ldots)$, could be directly formed, all other states having to be produced by radiative transitions from the J/Ψ or Ψ', with consequent limitations in precision. The masses of several states were well determined but not, in general, their widths.

Experiments R704 at CERN and E760/E835 at Fermilab demonstrated that charmonium formation using $p\bar{p}$ annihilation has two significant advantages compared to e^+e^- annihilation. The first is that, since $p\bar{p}$ annihilation must proceed via two or three intermediate gluons, it can lead to the direct formation of charmonium states with all possible quantum numbers. This means that the precision achievable for all states depends only on the quality of the antiproton beam and not on the detector properties. The second advantage comes from the possibility of cooling antiproton beams (stochastically and/or with electrons) to obtain a momentum resolution of one part in 10^5, which translates directly into improved mass resolution.

With this technique, impressive progress has recently been achieved in the determination of masses and widths of several states, including the χ_1 and χ_2 states, and the first observation of the h_c. The latter is the long awaited $^1P_1$ state whose mass can yield information about the spin-spin interaction between quarks.

Despite these efforts, there remain a number of unresolved fundamental questions concerning the charmonium system. These will be addressed by experiments focused on charmonium spectroscopy, using the PANDA detector system at GSI/HESR. This facility will offer improvements beyond the Fermilab program, by providing higher-energy antiproton beams (15 GeV), higher luminosity, better cooling, and a state-of-the-art hermetic detector for both electromagnetic and charged particles. Particular topics from its program are as follows:

- Little is known about the ground state $\eta_c(1^1S_0)$. Its first radial excitation $\eta_c'(2^1S_0)$ has only been hinted at in an early e^+e^- experiment and was not observed in $p\bar{p}$ experiments. A possible explanation for this non-observation might be a shift of the mass of $\eta_c(1^1S_0)$, due to a mixing with a nearby 0^{-+} glueball.

- The singlet P-wave resonance $h_c(^1P_1)$ is particularly important for determining the spin-dependent component of the confinement potential. Very little is known about this state so far.

- Essentially no states are known above the $D\bar{D}$ breakup threshold, so there are potentially significant new discoveries to be made. For instance, most of the d-wave states are still missing.

- Exclusive charmonium decays can provide a testing ground for QCD predictions, particularly for the study of higher Fock state contributions, which might produce sizeable effects in certain cases.

When running at full luminosity, HESR will produce a large number of D-meson pairs. Thus, it can also be regarded as a hadronic factory for tagged open charm. The high yield and the well-defined production kinematics of these pairs would allow studies of rare processes in the charm system such as CP-violation or flavour mixing, and determininations of the decay constants of charmed mesons. Measurements of CP-violation and rare D decays could open a new window into physics beyond the Standard Model.

Finally, it is worth mentioning the exciting signals reported by the SELEX Collaboration at Fermilab, which hint at the first observation of three doubly charmed baryon states. The study of these systems, whose existence is required by broken $\mathrm{SU}(4)_f$ symmetry, is an experimental challenge because of the very low cross sections and small branching ratios.

2.4 The low-energy frontier and chiral dynamics

2.4.1 Chiral symmetry and hadron physics

The chiral symmetry present in QCD is spontaneously broken. As a consequence there is a set of light particles, called Goldstone bosons, whose interactions are strongly constrained by this symmetry. Even though the underlying QCD interactions which cause spontaneous symmetry breaking are strong, Goldstone bosons interact weakly at low energies. In fact, in the limit of massless quarks and zero energy, their interactions strictly vanish. This makes it possible to build an effective field theory with a well defined expansion in powers of energy, momentum and quark masses: chiral perturbation theory.

During the last decade major progress has been made in applications of chiral perturbation theory and comparisons with accurate low-energy experiments. Precise measurements of $\pi\pi$ scattering near threshold at the Brookhaven National Laboratory and the detailed theoretical analysis of these data have settled the question of the quark condensate in the limit of vanishing up and down quark masses. Further advances can be expected from studies of pionic bound states with the DIRAC experiment at CERN. Given the high precision that both experiment and theory have now reached, the inclusion of electromagnetic radiative corrections becomes an important task. This will demand close collaboration between theory and experiment in order to succeed.

Over the next decade improvements are also foreseen in the three-flavour sector, which includes strange quarks. Many processes involving kaons and η mesons have now been systematically analysed. Such studies will allow examination of the dependence of low-energy QCD dynamics on the number of flavours. They could also indicate whether the pattern of spontaneous chiral symmetry breaking remains the same in the presence of strange quarks. It is therefore important to investigate as many observables as possible that depend strongly on the strange quark mass. Examples of these are the study of η decays at WASA/CELSIUS in Uppsala and KLOE/DAΦNE in Frascati. More precise measurements of various electromagnetic and semileptonic decay form factors of the charged and neutral kaons will provide strong tests. Differences between kaon and eta properties and the equivalent pion ones can also yield important clues. Strange-quark mass effects on pionic observables can be studied in this way, providing a direct equivalent of measurements of the strangeness content of the proton.

Significant progress is also expected from the pionic hydrogen measurement at PSI and the DEAR experimental programme at DAΦNE. One of the goals of DEAR is to measure the energy shift and width of the K_α line in kaonic hydrogen with a precision at the percent level. This will provide a new degree of accuracy in our understanding of the low-energy kaon-nucleon interaction.

2.4.2 Structure of the nucleon

Many new insights have been gained from high-precision experiments exploring the low-energy structure of the nucleon and its pion cloud, primarily with electromagnetic probes. The significant observables can be roughly grouped into three classes, for which we summarise a few recent highlights:

- Ground state properties
  These are in particular form factors and polarisabilities. At the Mainz Microtron MAMI, the Bates Linear Accelerator Center in the U.S. and the Amsterdam Pulse Stretcher (AmPS), the magnetic and electric form factors of the neutron have been measured over the last years in the momentum range $Q^2 < 1$ GeV^2. These results hint at the importance of the pion cloud in the structure of the nucleon and represent a constraint for chiral dynamics. Also at MAMI precise values have been obtained from Compton scattering of real photons ($Q^2 = 0$) for the electric and magnetic polarizabilities, as well as generalized polarizabilities (at $Q^2 > 0$) from the $p(e, e'p)\gamma$ reaction. These results have set strong constraints on QCD-inspired models.

- Baryon resonances
  Meson decays and in particular electromagnetic transition rates can provide decisive

information on the wave functions of the constituents of hadrons. The recent determination of the quadrupole component in the $N \to \Delta$ transition has already been mentioned in Sec. 2.3.3. A particularly informative method for investigating the resonances of the nucleon is the determination of absorption cross sections in separated decay channels, using circularly polarized photons on polarized protons. This is relevant to the Gerasimov-Drell-Hearn (GDH) sum rule. The GDH collaboration at MAMI and ELSA could measure these cross sections for the first time, providing insight into the first ($\Delta(1232)P_{33}$), second ($N(1520)D_{13}, N(1535)S_{11}$) and third ($N(1680)F_{15}$) resonance regions of the nucleon. The detector SAPHIR at ELSA allowed new studies of hyperon resonances and saw indications of a new resonance in the ejectile asymmetry.

- Meson production at threshold
  Meson production at threshold provides particularly good tests of soft-meson physics and chiral perturbation theory. The description of the production of pions from the nucleon in the $p(\gamma, \pi^0)N$ reaction at MAMI was a triumph for chiral perturbation theory. It showed that the low-energy theorem based on tree-level diagrams gave an E_{0+} amplitude about a factor 2 too large, whereas the next-order loop correction could reproduce the observed amplitude. Similar results have also been obtained for the p-wave amplitudes and the Coulomb amplitude L_{0+}.

The power of precision studies using electromagnetic probes at low momentum transfer as described above has been demonstrated by the experiments at MAMI and ELSA. The challenges posed for the next ten years lie in the further improvement of the precision and the selection of the most significant observables. The first is an experimental challenge, whereas the second calls for collaboration between theorists and experimentalists.

At the Mainz Microtron MAMI the maximum energy will be increased from 855 MeV to about 1.5 GeV. This will be accomplished by the addition of a fourth double-sided harmonic microtron stage to the existing cascade of three "race track" microtrons. The construction of this extension is well underway and the commissioning of the upgraded machine is planned for mid 2004. In order to take full advantage of this upgrade two major new experimental equipments will be installed: the SLAC Crystal Ball and the GSI forward magnetic spectrometer (KAOS@MAMI).

The installation of the Crystal Barrel detector and the TAPS photon detector wall at the ELSA stretcher ring in Bonn make this a unique facility for studying the electromagnetic coupling of baryon resonances. In particular, it can explore the energy region $1.5 < E_\gamma < 3.5$ GeV which cannot be covered by MAMI.

2.4.3 Chiral dynamics in nuclear systems

The existence of the mass gap in the spectrum of light hadrons and its possible connection with the spontaneously broken chiral symmetry of QCD raises an important issue: how do properties of hadrons and their mass spectra evolve with changes of thermodynamic conditions? This is one of the driving motivations for the use of high-energy heavy-ion collisions to study matter at high densities and temperatures [3].

Related questions of particular interest concern the interactions of a Goldstone boson with the nuclear medium. Accurate data from a GSI experiment on $1s$ states of negatively charged pions bound to Pb and Sn isotopes have recently revived this discussion and its

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[3] See section 1.4 in the chapter on Phases of Nuclear Matter.

implications for in-medium chiral dynamics. Such experiments will be pursued further and extended to searches for quasi-bound nuclear states of kaons and η mesons.

2.5 QCD and nuclear matter

Apart from the low-energy aspects just mentioned, there are specific QCD phenomena related to the propagation of high-energy particles in matter to which we now turn our attention.

2.5.1 Colour transparency

Quantum Chromodynamics not only provides a highly successful description of strong-interaction phenomena at high energies, but it also leads to several remarkable predictions for the interaction of strongly interacting particles traversing dense nuclear matter.

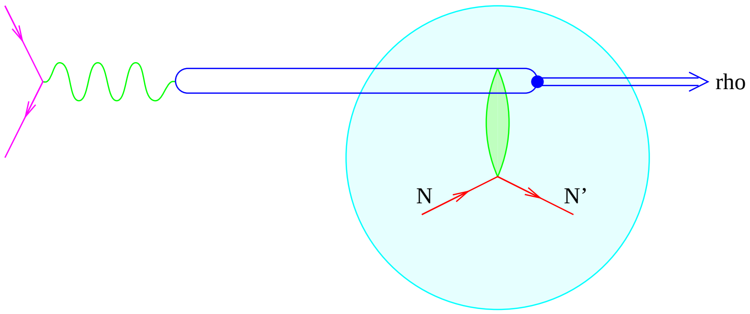

Figure 6: The interaction of a $q\bar{q}$-fluctuation of a virtual photon with a nuclear target. If the interaction of the $q\bar{q}$-fluctuation is reduced as compared to the normal hadronic interaction, colour transparency is said to occur. At the same time the Q^2-dependence of the length of the hadronic fluctuation (i.e. the coherence length) may mimic colour transparency effects.

An explicit example is provided by the interaction of a $q\bar{q}$-pair (originating from the hadronic structure of a virtual photon) with a nuclear target. At high enough Q^2 the $q\bar{q}$-pair can be assumed to have a small transverse size and so it acts as a (white) color dipole interacting only weakly with the neighbouring nucleons (see Fig. 6), an effect known as Colour Transparency (CT). Although this striking QCD phenomenon was predicted twenty years ago, the first evidence for it emerged only recently and further experimental investigation is needed.

One of the difficulties in finding unambiguous evidence for colour transparency is the fact that other effects may resemble the anticipated reduced interaction effects. If the Q^2 dependence of ρ^0 vector meson production on nuclei is considered, for instance, the observed transparency will not only be governed by the possible occurance of colour transparency, but as well by the duration or length of the hadronic fluctuation (see Fig. 6). Since the corresponding coherence length is inversely proportional to Q^2, an increase of Q^2 shortens the coherence length, reducing the strong interactions of the fluctuation and thus mimicking the effect of colour transparency.

Nevertheless, in recent years new experimental evidence supporting colour transparency has been collected: (i) the observed A-dependence of 2-jet production in a pion induced experiment (E791 at FermiLab) at $E_\pi = 500$ GeV ($A^{1.61\pm0.08}$) is in agreement with the CT-based prediction ($A^{1.54}$); (ii) the slope of the t-dependence of vector meson production measured at HERA shows the expected reduction with Q^2 ('shrinkage'), albeit with poor statistics, and (iii) the Q^2 dependence of of coherent ρ^0 production on ^{14}N in fixed coherence-length bins observed at HERMES shows a constant rise which is consistent with the prediction based on colour transparency.

Despite the recent progress, more data are needed to fully establish this QCD prediction. Further experimental studies to test the colour transparency hypothesis are foreseen at HERMES and at COMPASS, where it will be possible to extend the kinematic range of the measurements. Moreover, at COMPASS it will be possible to separate transparency effects for longitudinal and transversely polarized virtual photons.

2.5.2 Parton propagation in matter

The energy loss dE/dL experienced by partons propagating through nuclear matter is an important issue. Experimental information on parton energy loss in (cold) nuclear matter can be obtained from semi-inclusive deep-inelastic scattering on heavy nuclei. By comparing the hadron yield per DIS event on nuclei to the same yield on deuterium, an (energy dependent) attenuation will be observed. This hadron attenuation can be related to the energy loss of the propagating parton and the length of its trajectory, or – in other words – the time it takes before the hadron is formed.

Existing knowledge about the parton energy loss and hadron formation times is extremely limited. However, it would be very interesting to obtain experimental information on these quantities since they represent fundamentally new knowledge of composite systems of quarks and gluons. Moreover, quantitative information on the parton energy loss in matter and hadron formation times is needed for the interpretation of relativistic heavy ion collisions, which it is hoped will provide evidence for a new state of matter: the quark-gluon plasma.

Experimental information on parton propagation effects in matter can be obtained by embedding the hadron formation process in a nucleus, as depicted in Fig. 7. In the nucleus, the produced hadron will reinteract with the surrounding nucleons, and as a result fewer hadrons will be produced. The reduction in the observed number of hadrons depends on both the parton energy loss and the hadron formation time. Hence the ratio of the number of hadrons produced on a heavy nucleus to that on deuterium can provide information on these quantities.

Experimental information on hadron attenuation in various nuclei has recently been obtained by the HERMES experiment at DESY. The ratio of hadrons produced on ^{14}N (or ^{84}Kr) and ^{2}H (normalized against the number of deep-inelastic scattering events in each case), was measured as a function of the fraction of the energy transfer carried by the observed hadron. As this fraction increases, the data show a decrease of the rate of hadrons produced in nitrogen (or krypton) relative to deuterium. Qualitatively this implies that fast hadrons have a relatively short formation time, leading to a relatively strong reduction of the ratio.

The data are well described by QCD-inspired calculations if a value of $dE/dL \approx 0.3$ GeV/fm is taken for the partonic energy loss in cold nuclear matter. This value can be compared to the energy loss of 0.25 GeV/fm derived from recent PHENIX data on π^0 production in Au+Au collisions at $\sqrt{s} = 130$ GeV. If the PHENIX number is converted to a corresponding energy loss in the initial hot stage of the Au+Au collision, a value of about 5 GeV/fm is found. Comparing this number for hot nuclear matter with the value derived from the HERMES data for cold nuclear matter, it can be seen that the gluon density (which drives the energy loss) is possibly an order of magnitude larger in the initial phase of the Au+Au collision. This result reflects a new synergy between two fields that used to be essentially independent: relativistic heavy-ion collisions and deep inelastic scattering.

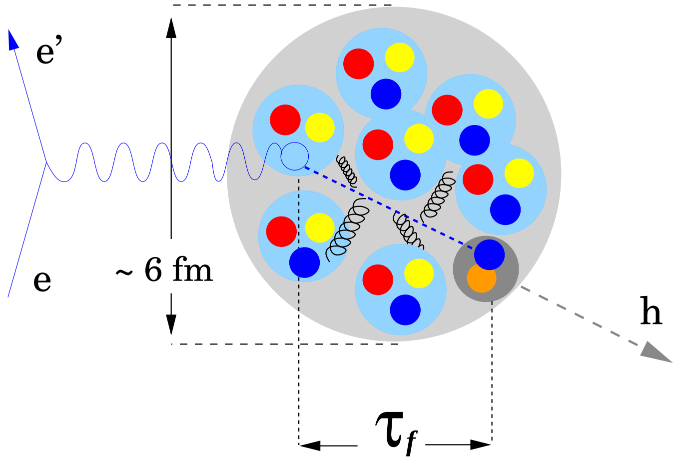

Figure 7: Hadron formation in deep-inelastic electron scattering from a nucleus. A quark in one of the nucleons is hit, resulting in the formation of hadrons. Due to parton energy loss and hadron rescattering the number of hadrons observed will be reduced compared to the free case.

The few available data show the potential of this new field at the interface of deep-inelastic scattering and relativistic heavy-ion collisions. Systematic data on a range of nuclei are necessary for an in-depth study of parton propagation effects in matter. High statistics are needed to explore the various kinematic dependences independently, and to test QCD predictions for the parton energy loss in nuclear matter. Moreover, such measurements will make it possible to carry out studies of flavour dependence by comparing data for various hadron types (π, K and p).

2.5.3 Strange and charmed quarks in matter

An ordinary nucleus is a many-body system composed of protons and neutrons. When one or more hyperons are implanted in the nuclear medium a new quantum number, strangeness, is added to the nucleus, thereby opening a new dimension to the nuclear chart. Hypernuclear physics merges isospin and strangeness into the enlarged field of flavour $SU(3)$ many-body dynamics. The main emphasis is on the non-perturbative dynamics of u, d, and s quark systems at finite density as realized by protons, neutrons and hyperons in a nucleus close to the ground state.

These exotic nuclei provide a variety of new and exciting perpectives, ranging from the exploration of nuclear structure via the single-particle behaviour of hyperons in the nucleus to the study of the baryon-baryon strangeness changing weak interaction, which can be addressed only in the non-mesonic weak decay of hypernuclei. They can also aid the experimental study of hyperon-nucleon interactions which are, at present, still poorly known. Moreover, the study of basic properties of hyperons and strange exotic objects like the hypothetical H-particle, which is of fundamental importance for the understanding of QCD, can also be addressed with hypernuclei.

Hypernuclear physics has made significant progress in the last fifteen years, mainly at BNL, KEK and COSY where it has drawn the attention of a large community. Experimental studies on hypernuclei are continuing at different laboratories in the USA

(JLab and BNL), in Japan (KEK), and in Europe using the DAΦNE machine at Frascati National Laboratory.

At DAΦNE the FINUDA experiment will exploit low-energy (16 MeV) K^- particles from ϕ decay to produce large numbers of Λ-hypernuclei by the (K^-_{stop}, π^-) reaction on several nuclear targets. The momentum transfer involved is such that the whole spectrum of allowed hypernuclear states will be populated. The good energy resolution of 750 keV for nuclear levels, twice as good as the best so far, will lead to a substantial step forward in hypernuclear spectroscopy. Starting in 2003, FINUDA will take data for the following three or four years. Its main goal will be to study with unprecedented precision the weak reaction $\Lambda N \to NN$ which can occur only in a nuclear medium. This process gives basic insights into the strangeness changing baryon-baryon weak interaction.

For the future, kaon beams with intensities one order of magnitude larger than presently available could be provided by the Japanese Hadron Facility (JHF). A hypernuclear physics program is also foreseen in the context the HESR project at GSI. This can lead to a detailed spectroscopic study of singly and multiply strange hypernuclei produced in collisions of antiprotons with nuclei.

Hypernuclei are the first examples of exotic *flavoured* nuclei. The investigation of charmed hypernuclei, containing a charmed baryon, is an interesting option of the physics programme of HESR at GSI. The lightest mesons carrying charm $C = \pm 1$ are the $D^{\pm,0}$ states with a mass of about 1865 MeV, while the spectrum of charmed baryons starts with the Λ_c^+ at about 2.3 GeV. So far nothing is known about charmed nuclei and hence experimental studies of such systems offer new insights into the dynamics related to breaking of $SU(4)$ flavour symmetry by the large mass of the charmed quark.

Another novel item in the scientific programme covered by PANDA at HESR/GSI will be the study of D-mesons interacting with a nuclear medium. The D-meson is the prototype of a heavy-light quark-antiquark system in QCD, so this project offers unique possibilities for exploring a single, localised light quark interacting with nucleons in a nucleus and for investigating the resulting change of the D-meson mass in matter.

3 Outlook

The topics described in this Chapter demonstrate that the study of QCD and the structure of hadrons is entering a new phase. Much new high-precision data will become available in the near future from existing facilities. These experimental developments must be accompanied by similar theoretical efforts. Considerable progress can be expected on a timescale of five to seven years. However, it is also clear that many of the questions outlined here will remain unanswered without new experimental facilities. On the basis of such considerations the following list of recommendations has been prepared.

- **Maintain – and expand where necessary – the infrastructure for adequate theoretical support in the field of QCD.**
  In particular, young theorists must be encouraged by creating an adequate number of positions for this area of physics. Also, further substantial investments in computational infrastructure are required for large-scale lattice QCD calculations.

- **Exploit the current European frontier facilities in our field – including modest upgrades where appropriate – until they are surpassed by new facilities.**
  The unique deep-inelastic scattering facilities at CERN (COMPASS) and DESY

(HERMES-II) especially should be fully exploited through measurements of the gluon polarization, generalized parton distributions and transversity distributions. At somewhat lower energies, the ϕ factory at Frascati (DAΦNE) and the new lepton beam facility at Mainz (MAMI-C) will provide competitive measurements of meson and baryon structure, respectively. Lastly the existing facilities in Bonn (ELSA), Grenoble (GRAAL), Juelich (COSY) and Uppsala (CELSIUS) are expected to provide important data on various hadronic channels.

- **Prepare for the construction of the High-Energy Storage Ring (HESR) at GSI.**
  The planned GSI International Accelerator Facility for Beams of Ions and Antiprotons has been approved and will play a crucial role in promoting our understanding of the physics of the strong interaction. This facility will provide 1.5–15 GeV/c (cooled) anti-proton beams impinging on fixed (internal) targets. It will make possible searches for new charmonium states including hybrids ($c\bar{c}g$) and also for glueballs, while improving our knowledge of other states. It will also open new perspectives for exploring interactions of charmed hadrons with nuclear systems. It is strongly recommended that Europe-wide joint activities be directed toward the construction of HESR and its general-purpose detector system PANDA.

- **Prepare a full proposal for a high-luminosity lepton scattering facility.**
  This will be the new frontier QCD facility in the second decade of the 21st century. Experiments at such a facility will provide precision tests of several QCD predictions for aspects of hadron structure not dominated by gluonic contributions. These include transversity distributions and generalised quark distributions, as well as their evolution with Q^2. The proposal could be based on several recently prepared documents which describe how such a project could be incorporated in either existing or planned large-scale accelerator facilities in Europe and in the United States.

- **Continue and further develop international world-wide collaboration in the field of QCD.**
  European participation in new large-scale projects in both the USA and Japan is encouraged. The exchange of ideas, instrumentation and personnel between the EU, the USA and Japan will stimulate progress. Moreover, the complementarity of proposals for projects around the world will ensure a healthy competition without unnecessary overlaps.