General introduction

In this introductory part we first present a primer, "facets of matter", which is intended for non-experts and young students, who would like to enter this research field. After a brief historical overview, the main physics concepts and research objectives addressed in this book are elucidated, using illustrative examples known from standard physics text books. For the more experienced researcher, the subsequent executive summary reviews the main accomplishments and physics goals presented in the five topical parts of the book.

Facets of matter

In the course of the past century, unprecedented progress has been achieved in our understanding of the fundamental laws of nature and their implications for the complex structure of the world at all scales, ranging from the substructure of elementary hadrons to the universe as a whole. The revolutionary concepts of special and general relativity and quantum mechanics have resolved many of the puzzling experimental findings that had accumulated by the beginning of the twentieth century, such as the particle-wave duality. A new wave of enthusiasm inspired the physicists those days. New theoretical frameworks for the basic laws of physics appeared. A wealth of novel so far unknown phenomena were predicted, many of them later on experimentally verified. A famous example is the conjecture suggested from the relativistic formulation of quantum mechanics that each elementary particle has an antiparticle partner, a particle with the same mass and spin but opposite attributes such as electric charge.

Together with the progress in technology, sophisticated devices were developed capable to accelerate elementary particles. Electrons, protons and even heavy atomic nuclei could be boosted to higher and higher energies. It permitted the exploration of the sub nanometer world of atoms and even the femtometer scales (10^{-15} m) of atomic nuclei and their constituents. Probing

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the laws of nature at incessantly finer scales has revealed the existence of a surprisingly large number of elementary particles and provided the means to study their interactions and thus to understand their relationships.

As a result two further interaction were identified in addition to the familiar gravitational and electromagnetic forces. These are the *strong interaction* that causes nucleons to bind into atomic nuclei and the *weak interaction* responsible for certain radioactive transformation processes, such as the β decay that turns a neutron into a proton. While essentially dormant in our familiar terrestrial world, the strong interaction plays an active role in stellar environments. It provides the energy that powers stars such as our sun by causing individual nucleons to fuse into light nuclei. Ultimately the evolution of the universe from the Big Bang to its current state with more than one hundred billion of galaxies each containing billions upon billions of stars, with associated (and possibly inhabited) planetary systems, is the result of the subtle interplay of all four fundamental forces.

The combination of quantum mechanics with special relativity led to the presently most powerful formulation of fundamental physics: *Quantum Field Theory*. This conceptual framework forms the basis for the *Standard Model of Particle Physics*, according to which nature at its fundamental level consists of elementary "matter" particles (which all have half-integer intrinsic spin and are categorised as *fermions*) that interact by the exchange of *boson* field quanta (having integer spin).

A prominent part of the Standard Model is *Quantum Electrodynamics* (QED) which governs the properties of the familiar matter surrounding us in our daily life. The electromagnetic force is mediated by the *photon*, the quantum of light. The photon itself is uncharged but carries one elementary unit of intrinsic spin and has a vanishing mass, which gives rise to the long range of the electric force. The most familiar elementary particles that interact electromagnetically are the electron, which by convention carries one negative unit of elementary charge, $-e$, and the proton carrying the positive elementary charge $+e$. Like the others, the neutron, though electrically neutral, can be deflected by a magnetic field due to its spin. Neutron and proton are the building blocks of atomic nuclei. QED is by far the best established physical theory, experimentally verified to a precision of about 12 numerical digits. Because of this unrivalled success, this type of quantum field theory, which contains so-called *gauge* fields, was generalised to describe all fundamental interactions. This framework then led to the successful formulation of a unified theory of the *strong* force, the *electromagnetic* force and the *weak* force, while it has not yet been possible to encompass the fourth (and weakest) force, *gravity*, into such a unifying scheme.

One of the most important advances in physics during the twentieth century arose from recognising the essential role played by *symmetries* (or invariances). They govern the character of the fundamental interactions. In particular, invariances under temporal translation, spatial translation or spatial rotation, which are all continuous transformations, imply the fundamental conservation laws for energy, momentum and angular momentum, respectively. Furthermore, the discrete symmetries associated with particle-antiparticle conjugation and spatial reflection (parity) allow us to organise the elementary particles into certain groups and to characterise the features of their mutual interactions. In particular, the existence of *quarks* as the fundamental entities in strong-interaction physics was postulated on the basis of symmetry considerations. Their invention and subsequent discovery brought a transparent systematics into the increasing zoo of *hadrons* produced in high-energy collision experiments. There are two known categories of hadrons: *Baryons* (from the Greek word $\beta\alpha\rho\upsilon\sigma$ meaning *heavy*), such as protons and neutrons, which can be thought of as composed of three quarks, and *mesons* (from the Greek word $\mu\epsilon\sigma o$ meaning *medium*), which contain a quark and an antiquark. The strong interaction has the particular feature, called *confinement*, that the elementary constituents, namely the quarks, do not appear in isolation.

Like the electron, the quarks carry half a unit of intrinsic spin. As an unusual feature, however, they have fractional electric charges of $\frac{2}{3}$e or $-\frac{1}{3}$e. Initially just three different types of quarks were needed to explain the hadrons known those days: the very light u (for "up") and d (for "down") quarks with masses of about 2 and 6 MeV,[1] forming e.g. protons and neutrons as (uud) and (udd) bound states, and a somewhat heavier ($\approx$ 95 MeV) s quark, explaining the so called strange hadrons. The property that distinguishes the different quark types is called *flavour*. The lightness of these quarks gives rise to a special symmetry, called *chiral symmetry*. It coins the spectrum of the very light hadrons by a very special mechanism, denoted as *spontaneous symmetry breaking*, cf. p. 19.

It is fascinating to reconcile that the clue for the quark story was not derived from studies of strong interacting physics. Rather *weak* interaction processes delivered compelling arguments that further quark flavours must exist. Two *lepton* families were known those days: the electron e together with its associated neutrino, (e, ν_e), and the muon and its neutrino (μ, ν_μ), respectively. These families should have corresponding partner families in the quark sector, each consisting of two quark flavours. The missing link was indeed soon provided by the observation of a very heavy meson with unexpected long lifetime: the famous "J/ψ meson". It established the existence of the c ("charm") quark with a mass of about 1.2 GeV as the partner of the s quark. The existence of an as yet unknown third quark-lepton family was even postulated. The argumentation based on intricate symmetry considerations in connection with certain symmetry violating weak-decay processes, known as CP violation.[2] Indeed both, a very heavy lepton, called "τ lepton",

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[1] It became customary to quote the masses in terms of the energy needed to create that mass, i.e. in MeV=10^6 eV (mega electron volt) or GeV=10^9 eV (giga electron volt). For example comparison the masses of electron, proton and neutron are 0.511, 938.3 and 939.6 MeV, respectively.

[2] The CP-symmetry refers to the symmetry with respect to the simultaneous particle-antiparticle conjugation, normally referred to as "charge conjugation" (C), and the reflec-

as well as two further very heavy quark flavours, with symbols b (for "bottom" or "beauty") and t (for "top" or "truth"), were then experimentally verified in the following years. These theoretical and experimental successes, awarded by several Nobel prices, founded the nowadays accepted *Standard Model of Particle Physics* with its three quark-lepton families.

What is not directly manifest in the spectrum of hadrons, though, is the way the quarks interact strongly with each other. Here again symmetry arguments gave the hint: the *strong* charge has to come in three different varieties, referred to as *colours* (a term that has nothing to do with our visual perception). Although initially not intended, this nomenclature provides a convenient association: the combination of two or more strong charges resembles the mixing of ordinary colours. In particular, the confinement property requires the total strong charge of any hadron to vanish (i.e. to be "colour neutral" or "white"). Thus, the three colour charges of the constituent quarks in a baryon have to cancel each other, while for mesons the colour charges of the quark and its antiquark partner have to be opposite ("complementary").

The resulting fundamental theory describing the strong interaction is therefore named *Quantum Chromo Dynamics* (QCD) – from the Greek word $\chi\rho\omega\mu\alpha$ meaning colour. In analogy with QED, the elementary particles, here quarks and antiquarks, interact via bosonic gauge fields. These quanta are called *gluons*, since they serve to "glue" the quarks together. While there is only one type of photon in QED, which is electrically neutral, in QCD there is an octet of gluons, corresponding to the various elementary ways of transforming one colour into another.[3] The gluons themselves also carry colour charge, which permits them to also interact among themselves, a property which is believed to ultimately be responsible for confinement.

While the strong and the electromagnetic interactions conserve the total net flavours (flavour minus antiflavour), the weak interaction can change the flavour on time scales that are typically sub-nano seconds. Due to the dramatic drop in temperature during the very early evolution of the universe, all initially created heavy-flavour hadrons quickly decayed into up and down flavours and the electrons as present in the stable matter around us today. The further expansion and cooling led to a plasma of very light nuclei (predominantly protons) and electrons, which subsequently combined into electrically neutral atoms (mostly hydrogen) only about 300,000 years later. First galaxies were finally formed after a further few hundred million years.

Parallel to the advances at the elementary level, significant progress was achieved in the understanding of many-body systems such as macroscopic matter. As known from our daily life, a given substance, such as water, can appear in various forms (called *phases*). Depending on the ambient pres-

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tion in space denoted as "parity" (P). This symmetry was observed to be violated in certain weak decay processes.

[3] One might naively have expected there to be nine types of gluon, three colours times three anticolours. However the colour neutral combination must be excluded, leaving eight independent transformations.

sure and temperature water exists in the form of vapour, liquid and solid. The preference for one phase over another results from the interplay of the binding forces between the constituents (e.g. the water molecules), which tend to organise the system into regular structures, and the thermal motion, which drives the system towards disorder. Any given thermodynamic condition usually favours one particular phase over the others. Therefore, by changing the thermodynamic parameters (i.e. the temperature (T), pressure (p), etc.), one can control which phase is preferred and cause the substance to undergo corresponding phase transformations. These properties are conveniently summarised in a *phase diagram*, which delineates the various phases of the substance as a function of the thermodynamic variables, much like a map shows the areas of various countries.

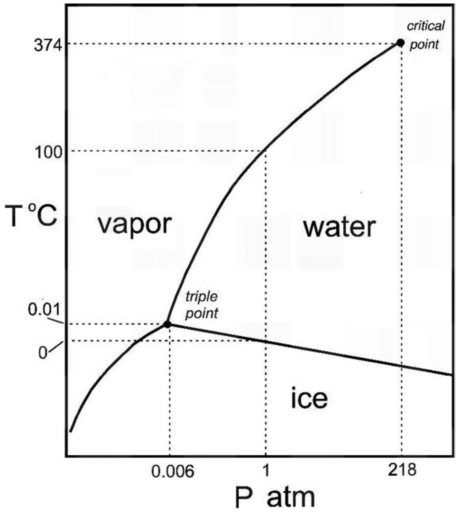

Fig. 1 Phase diagram for water delineating the thermodynamic domains of the familiar gas, liquid and solid phases in the temperature (T) versus pressure (p) presentation (the scales are *not* linear). The three phase boundaries come together at the *triple point*, situated just above 0°C, while the liquid-gas phase boundary terminates at the *critical point*; above the critical temperature there is a smooth transition from the liquid to the vapour phase. [The figure was adapted from http://serc.carleton.edu/ research_education/equilibria/ phaserule.html.]

The phase diagram of water with its three phases of vapour, liquid and (one of several forms of) ice is illustrated in Fig. 1 in the (p, T) plane. Each point on the phase diagram represents a large uniform and thermally equilibrated system of the particular substance at the specified values of pressure p and temperature T. Neighbouring points located on opposite sides of a phase border line represent different phase configurations with the same pressure and temperature which can *coexist*, i.e. they can be simultaneously present under the same thermodynamic conditions. However, they differ in their microscopic organisation and, as a result, they generally have different particle or energy densities. In the latter case one talks about a *first order phase transition*. The crossing of such a phase boundary, i.e. transforming the substance from one phase to the other (such as the change of water into vapour), requires the supply or removal of a certain amount of energy (called the *latent heat*) as well as some degree of compression or expansion. Furthermore, for thermodynamic conditions along a phase boundary the substance will generally appear as a *phase mixture*, e.g. with droplets of the high-density phase immersed in the low-density phase or vice versa. For water, ordinary fog represents such a phase mixture, situated somewhere along the upper-right phase-boundary line in Fig. 1, where liquid droplets coexist with the vapour. However, the particular geometrical organisation of such phase mixtures (e.g. the droplet sizes) depends on specific properties beyond those of uniform matter, such as the surface tension, and cannot be depicted on a standard thermodynamic phase diagram.

A phase separation line may end in a so called *critical end point*, where the differences between coexisting phases cease. The study of the physical properties of a substance under thermodynamic conditions close to the critical point has been a central research interest for decades in condensed matter physics. Systems show some universal behaviour that permits different substances to be classified into certain *universality classes*. Beyond the critical point there is a smooth *crossover* between the phases. This occurs for water, which has a liquid-vapour critical point situated near the upper-right corner of Fig. 1. Furthermore, the simultaneous coexistence of three phases occurs when three phase boundary lines come together in a *triple point*, as it happens for water (see Fig. 1).

Besides the familiar three phases discussed above (gaseous, liquid, and solid) nature exhibits several more phases of matter. Of particular importance in the context of this book is the *plasma* phase, which can be formed at high densities or pressures. Under such conditions the normally electrically neutral atoms (or molecules) of a gas become ionised as some of their outer electrons become unbound and mobile. The electromagnetic forces between these charged constituents are then of primary importance. These conditions are encountered during an electric discharge, in the interior of stars such as our sun, or in large gaseous planets like Jupiter and Saturn.

In addition to the phases discussed above, which principally concern the spatial organisation of the constituents of a system, there are also phase transformations associated with internal degrees of freedom, such as the spin of the constituents. Perhaps the most familiar example of such a phenomenon is *ferromagnetism*, known since ancient times and manifested by the spontaneous magnetisation of certain materials (such as iron) when cooled below the so-called Curie temperature. Another more modern example is superconductivity, the sudden drastic drop of the electric resistance in a conducting material, when its temperature is brought below a critical value.

Both of those examples are particularly relevant to the present discussion. They represent common place illustrations of the concept of *spontaneous symmetry breaking*, a phenomenon that plays a fundamental role in the standard model of particle physics. For the case of a ferromagnet, the thermal preference for disorder prevails at high temperature and the individual spins of the constituents have random orientations. At low temperature, however, the attraction between parallel spins overwhelms the thermal noise and causes the spins to become mutually aligned. It should be noted that even though the basic interactions favour no particular direction, the system automatically settles into one particular (not a priori determined) orientation, thus spontaneously breaking the rotational symmetry. Furthermore, because differently oriented aligned states have the same energy, it takes essentially no energy to introduce a gentle spin wave into an aligned system (see Fig. 2). There is thus no lower bound in the excitation spectrum (it is *gapless*), a characteristic feature of phases exhibiting spontaneous breaking of a continuous symmetry.

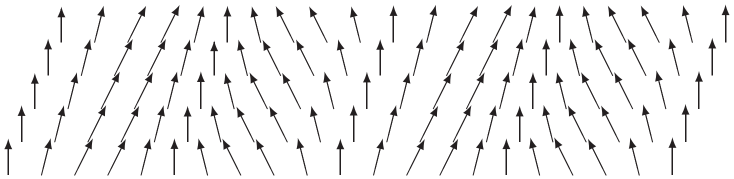

Fig. 2 Illustration of a spin wave in the spontaneously broken phase where all the individual spins are (approximately) aligned along a common (here vertical) direction.

Common to all phase transitions is that symmetry considerations play an import role in characterising the properties of the phase transition. Different substances with identical symmetry properties generally exhibit similar phase-transition behaviours particularly in the vicinity of the critical point.

An important facet of matter concerns its response to external perturbations such as the application of electric and magnetic fields. Often a given material responds quite differently from what would be naively expected from the properties of its constituents. For example, although the elementary carriers of the electric current in matter are negatively charged electrons, there are materials whose electric properties are most conveniently described as if the mobile particles carry a positive charge. This phenomenon has led to the notion of *quasi-particles*, dynamical entities that behave like particles with modified properties: a particle moving through matter interacts with the surrounding particles and polarises the medium. The resulting *collective* excitation can be effectively expressed as if the perturbing particle had acquired a modified mass and/or charge. A widely known example of such a phenomenon is the change of the index of refraction in a dielectric medium, such as glass or water. In the medium, a photon of given frequency propagates with a different velocity than in vacuum, with the consequence that a light ray will be deflected in the medium relative to its direction outside. Moreover, in bulk matter, excitation modes exist that behave similar to particles or waves, such as e.g. spin waves or acoustic waves (called *phonons*), although they have no counter part in the spectrum of the stable particles.

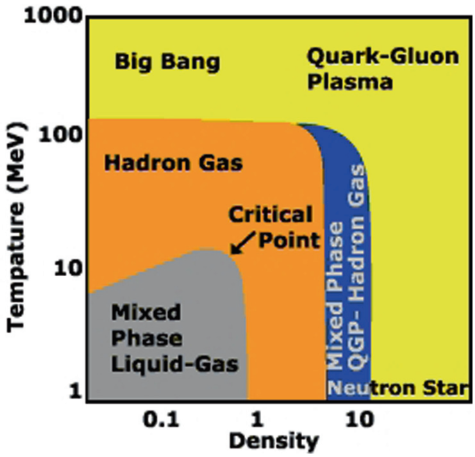

Fig. 3 The hypothetical phase diagram for strongly interacting matter in the plane of net baryon density (in units of the nuclear bulk density) and temperature (in MeV), both scales being logarithmic. At low temperatures, nuclear matter has a liquid-gas type phase transition and the corresponding region of phase coexistence is highlighted (*grey*). When the temperature and/or (net) density is raised sufficiently, the hadrons dissolve into a quark-gluon plasma. At low temperature, the deconfinement transition is presumably of first order with an associated region of phase coexistence (*blue*), whereas a smooth crossover happens at low density. Also the matter conditions prevailing during the Big Bang or existing in the interior of neutron stars are indicated. [The figure is from http://www.lbl.gov/abc/wallchart/chapters/09/0.html.]

In the present book we are interested in matter governed by the *strong force*, rather than the matter encountered in our ordinary terrestrial world, which is bound by the electromagnetic force. One form of such matter, though at zero temperature, exists inside large atomic nuclei and is referred to as *nuclear matter*. The associated scales of force and density exceed the familiar scales of ordinary terrestrial matter by more than twelve orders of magnitude (i.e. by factors beyond 10^{12}). In order to obtain such densities one would have to compress our planet into a sphere of less than a few hundred meters in diameter. The typical binding forces in nuclear matter are in the range of $\sim 10\,\mathrm{MeV/fm} = 10^{22}\,\mathrm{eV/m}$, which vastly exceeds the typical strength of chemical bonds between atoms, $\sim 10^9\,\mathrm{eV/m}$. Nuclear matter of even higher densities exists in the interior of compact (neutron) stars. Furthermore, strongly interacting matter in the form of a hot *quark-gluon plasma* (QGP) prevailed during the first microseconds of the early universe.

Many of the various facets of normal matter discussed above are also expected to appear in the strong-interaction regime, i.e. in QCD matter. In particular, different phases are expected to occur as the temperature and density are changed as illustrated in Fig. 3. Together with the change of the matter conditions, the properties of particles moving through the matter are also expected to be strongly modified.

It is a characteristic feature of QCD that the mutual coupling between quarks and gluons decreases as the collision energy is raised, a property referred to as *asymptotic freedom*. Because of this inherent feature, one expects that the quarks and gluons will essentially become free in matter at very high temperatures T. Far before this asymptotic scenario, already at temperatures of $T \approx 150\text{–}200\,\mathrm{MeV}$, conditions are reached where the hadrons dissolve into individual quarks forming a *quark-gluon plasma*. Similar to an ordinary plasma, the colour charged particles (quarks, antiquarks and gluons) can then move throughout the entire volume of the system. Our current understanding of QCD suggests that this transformation occurs in a smooth manner as the temperature is raised, provided that the net baryon density ρ or the associated chemical potential μ is small. However, at large values of ρ (or μ) one expects a true phase transition from a confined (hadronic) to a deconfined (plasma) phase. It is a major goal of the compressed baryonic matter (CBM) experiment to investigate these phenomena. The associated critical point forms a natural focus for these efforts.

At very low temperatures and densities the confined phase primarily consists of individual nucleons and a few very light composite nuclei. As the density is raised, nuclear liquid becomes the favoured state. The associated liquid-gas phase transition is of first order. It has been the subject of extensive experimental investigations in the 1980s and 1990s. At densities significantly larger than those in ordinary nuclei (possibly present in the interior of neutron stars), one may encounter a variety of ordered phases with novel properties, most notably colour charge superconductors. Unfortunately, it appears to be unlikely that these dense but relatively cold phases could be produced in collision experiments, in which large compressions tend to be accompanied by large temperatures.

A particularly important symmetry in particle physics is *chirality* (from the Greek word $\chi\varepsilon\iota\rho$ meaning *hand*), which characterises the orientation of a particle's internal spin relative to its direction of motion. As illustrated in Fig. 4, a quark's spin can be oriented either along its velocity (giving it a

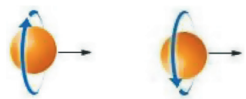

Fig. 4 Illustration of left- and right-handed quarks: the direction of motion is given by the *black arrows*, while the direction of the spin rotation is given by the *curved arrows*; for left- or right-handed particles the spin direction is anti-parallel or parallel to the direction of motion, respectively.

right-handed chirality) or in the opposite direction (giving it a left-handed chirality). In the sector of *up* and *down* flavours the basic QCD interaction has approximate *chiral symmetry*, because the masses of the u and d quarks nearly vanish. One might therefore expect that the resulting hadrons (bound solutions to the QCD field equations) would reflect this property by appearing in (approximately) degenerate chiral pairs.

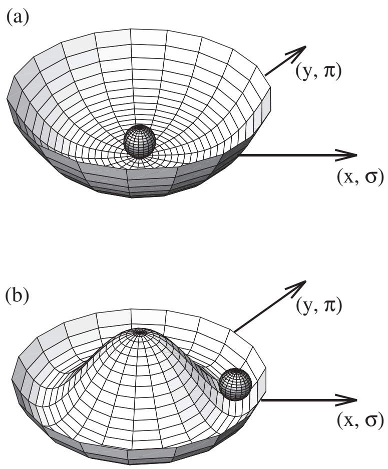

Fig. 5 Pictorial representation of spontaneous symmetry breaking in terms of a ball moving in a rotationally symmetric potential, assuming that this "effective" potential can change with temperature. At high temperature (*top*) the ball achieves its stable position in the potential minimum which is locate at the centre: so the equilibrium configuration preserves the symmetry. Towards low temperatures (*bottom*) the effective potential changes its form taking the shape of a *sombrero*, or a "Mexican hat", thus energetically disfavouring the central region. While to potential is still rotationally symmetric, the ball has to spontaneously settle in an asymmetric configuration at the bottom of the potential. [The figure is from V. Koch, Int. J. Mod. Phys. **E6** 203-250 (1997).]

However, this is not what is found in nature, where the chiral partners exhibit large mass differences. This apparent paradox was resolved by a mechanism analogous to the spontaneous magnetisation of a ferromagnet below the Curie temperature (illustrated in Fig. 5), namely the concept of spontaneous breaking of chiral symmetry. Then the earlier discussed gap-less feature of the ideal excitation spectrum suggests the existence of certain modes related to chiral symmetry that are nearly massless. Such modes indeed exist in the form of the π mesons (*pions*), whose masses ($m_\pi \approx 140\,\text{MeV}$) are abnormally small. The fact that the pion masses are non zero is due to the small but finite masses of the u and d quarks which explicitly break the symmetry. This leads to a slight preference for one particular chiral direction, much like the tendency of ferromagnetic material to align its magnetisation with the orientation of an externally applied magnetic field. In the bottom picture of Fig. 5 this explicit symmetry breaking is achieved by slightly tilting the Mexican hat, which defines a minimum at a preferred position due to a "soft" restoring force along the bottom of the potential. The concept of chiral symmetry, even extended to include the relatively light strange quark, turns out to be a powerful tool for understanding the mass spectrum of light hadrons.

With respect to the properties of hadronic matter, the chirally broken phase occurs at low temperatures and/or low densities of the phase diagram. Much like the spontaneous magnetisation in a ferromagnet, though, it is expected that the chiral symmetry breaking will gradually weaken as the temperature or the density is increased. This eventually leads to novel phases of strongly interacting matter in which chiral symmetry is (approximately) restored. Such a change in the hadronic environment causes dramatic modifications in the hadronic excitation spectrum. In particular, in the chirally restored phase the mass distributions of chiral partners would become (nearly) identical. Furthermore there are conjectures that the chiral transition may occur in close proximity to, or even simultaneously with, the deconfinement–confinement transition.

In addition to the fundamental aspects raised above, experimental investigations of compressed baryonic matter would also elucidate a number of astrophysical issues: What does matter look like under the very large gravitational pressure in the interior of neutron stars? Do nucleons still exist there or does matter melt into matter of quarks? What limits the total mass of a neutron star? How does a *super nova* collapse and the subsequent explosion of the burnt out star evolve? Do such processes create the composition of elements that we find in our planetary system?

The opportunity to analyse such forms of matter in all its facets in the laboratory is truly fascinating. However, it is not as straight forward as the investigation of ordinary matter. Neither are there appropriate vessels to contain this kind of matter and to exert pressure on it, nor is there any standard flame that could heat it. The only possibility is to collide two heavy nuclei, so that they inter-penetrate and compress but also heat each other due to the microscopic collisions (see Fig. 6). Still, the analysis of such collision events is intricate due to the transient nature of the reaction, where the object of interest, the compressed and heated zone is of finite small size and fades away in the very short time of less than 10^{-22} s. Furthermore, there is no light by which one can illuminate the collision scene in order to watch and record the event, like with a movie camera, as we are used in daily life observations. Rather the only observation comes through the reaction products themselves, i.e. the particles emitted from the reaction zone into the detectors. Thereby the different nature of the various particle species can provide information on different aspects of the collision event. The most abundant particles produced are hadrons. Due to their strong interactions with their environment, they tend to quickly adjust to the evolving conditions and therefore mostly reflect the conditions that prevailed during the later stages of the collision event. However, there are also electromagnetic "flashes" of photons and pairs of elec-

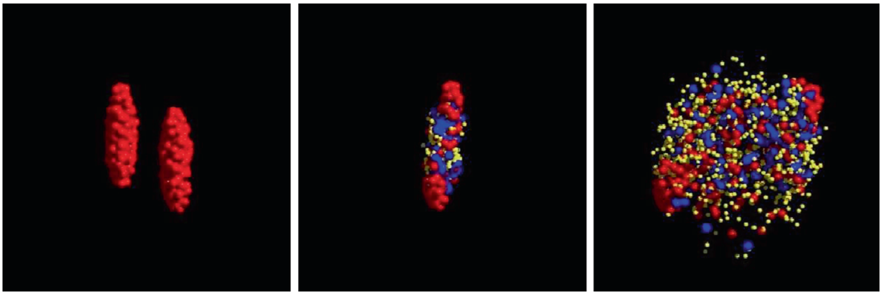

Fig. 6 Three snapshots illustrating a nuclear collision of two uranium nuclei in a future CBM experiment with a projectile energy per nucleon of 23 GeV on a fixed target. The snapshots are taken in the reference frame in which both nuclei have the same but opposite velocities. *Left frame*: The two incident nuclei (with the incident nucleons in *red*) are Lorentz contracted as the incident velocities are already close to the speed of light. The *middle frame* shows the moment of highest compression, i.e. the configuration of interest, while the *right frame* displays the expansion stage, when most of the particles already no longer interact strongly. The final situation is called *freeze-out*. The newly created baryon resonances are in *dark blue*, while the created mesons are given in *yellow color*. The pictures resulting from a simulation code calculation are extracted from a movie on http://th.physik.uni-frankfurt.de/∼weber/CERNmovies/.

trons and positrons emitted that are hardly affected at all during their propagation through the collision zone. Since these so-called *penetrating probes* tend to be produced primarily when and where the system is hottest, they are particularly suited as "messengers" of this stage.

In order to perform such experiments, accelerators are needed that are capable of accelerating atomic nuclei to the desired energies. The most efficient workhorses in this respect are *synchrotrons*. These are circular accelerators that work a bit like hammer throwers, operating at more than a million turns per second. In each turn the ionised atoms gain further energy through alternating electric fields, while magnets with synchronised field strengths hold them on their circular orbits inside the ring. Once the desired beam energy is reached, a short pulse of ions is directed onto a suitable target, usually a foil sufficiently thin to ensure that the collisions occur at time intervals long enough to permit the detection system to complete the event recording. The construction of a modern heavy-ion accelerator facility is a complex project that challenges the frontiers of science, technology and engineering. The variety of physical conditions opened to experimental exploration has steadily grown as the accelerators have become ever more powerful and the associated detectors have acquired ever more sophisticated capabilities.

The field of high-energy nuclear collisions, often called relativistic heavy-ion physics, originally evolved around the BEVALAC facility at the Lawrence Berkeley Laboratory in the 1970s. Subsequently, beams of higher quality and intensity became available in the same energy range of 1–2 GeV at GSI in Darmstadt (SIS 18). At these energies it was possible to study hot and compressed matter within the confined phase region only. The deconfined region could not be probed until it became possible to generate ultra-relativistic beams, where the kinetic energies of the particles far exceeded their rest masses, as first achieved at the Brookhaven AGS and at the CERN SPS. In all of these early experiments the accelerated nuclei were bombarded on a stationary target as explained above. Much higher effective collision energies can be achieved with a so-called collider, in which two beams collide head-on. Over the past several years, the main experimental activity in the field has occurred at the Brookhaven Relativistic Heavy Ion Collider (RHIC). Even much higher collision energies will soon be available at the CERN Large Hadron Collider (LHC).

In collisions at the very high energies characteristic of the collider facilities, a large number of newly created particles will fill the collision zone which by far surpasses the number of incident particles. As the newly created particles are balanced with respect to their matter–antimatter content, the net baryon density is relatively small in such matter. Therefore one explores the baryon-poor (but very hot) region of the phase diagram (Fig. 3), where a cross-over transition from the quark-gluon plasma to the hadron gas is expected.

Complementary to the research activities at the colliders, there is a strong scientific interest to explore the first-order phase transition region and the critical end point. For this purpose one needs to generate collision events that lead to much higher net baryon densities at relatively moderate temperatures. It follows from the above discussion that such matter is best investigated at lower collision energies, where the degree of stopping is then larger, and the amount of newly produced particles is less. There are currently several efforts underway worldwide towards this goal. In particular, a planned energy scan at RHIC will carry out a series of measurements at the lowest possible collision energies for the primary purpose of finding evidence of the expected critical end point. Furthermore, the Facility for Antiproton and Ion Research (FAIR) soon being constructed at GSI (see Fig. 7) will offer nuclear beams of unprecedented quality and intensity. At one of the experimental sites a dedicated detection system, the CBM detector (see Fig. 8), will be built for the purpose of studying compressed baryonic matter, in particular to search for the expected first-order phase transition. Finally, vigorous planning is in progress at JINR in Dubna, Russia, for the construction of a Nuclotron-based Ion Collider fAcility (NICA) for the purpose of studying strongly interacting matter in the mixed phase.

The nuclear beams for the CBM experiment, like the beams for other users at FAIR, will originate from an ion source at GSI. The ions are first sent through and pre-accelerated by the existing UNILAC/SIS-18 facility, displayed on the left side of Fig. 7, before being injected into the new double synchrotron SIS 100/300 (upper right portion of the diagram in Fig. 7), which will have a circumference of 1,100 m.

A single high-energy nucleus–nucleus collision at RHIC or LHC typically produces thousands of reaction products. Even at the lower energies rele-

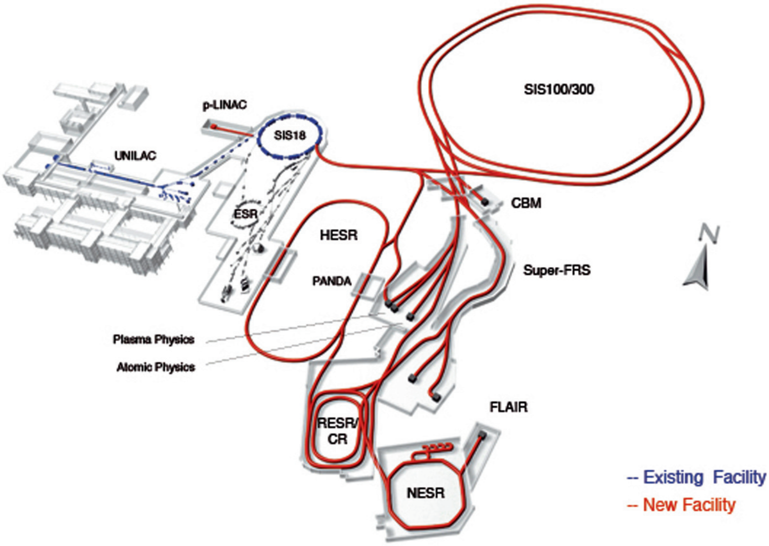

Fig. 7 FAIR, the new Facility for Antiproton and Ion Research under construction at GSI. The double synchrotron SIS 100/300 directly provides the nuclear beams for the CBM experiment. In parallel operation it can also feed complementary experiments with beams, where mostly secondary beams of antiprotons or rare nuclear isotopes are produced by means of a production target, filtered by the new fragment separator (super FRS) and subsequently stored and further manipulated in special purpose storage rings, such as the HESR for antiproton research at the PANDA detector or for Nuclear structure and atomic and plasma physics investigations at the other rings.

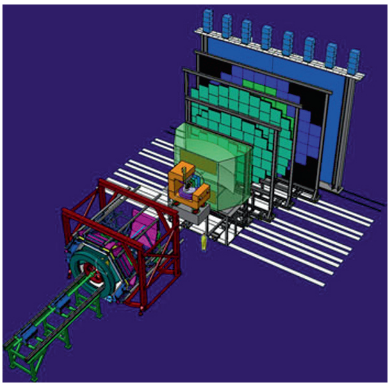

Fig. 8 The detector complex planned for the CBM (Compressed Baryonic Matter) experiment at FAIR. Some explanations are given in the text. The complete detector description can be found in Part V, Chap. 2.

vant for exploring the high-density region there will typically be hundreds of particles per collision event – mostly neutrons, protons and pions. The experimental task of detecting these reaction products, i.e. identifying their species and measuring their mass, energy and emission angle, requires a detection system that is optimised for the specific physics objective. The proposed CBM detector is shown schematically in Fig. 8. It is a multi-particle detector, which is able to resolve and to detect most of the particles simultaneously emitted in a collision event. It consists of several detector layers, each serving a different purpose for the complex detection strategy. It enables to trace rare probes such as particles carrying multiple strangeness or charm quarks. It is further capable of singling out the extremely rare electron–positron or muon pairs, that carry the message from the hottest part of the collision zone.

It is obviously a difficult task to anticipate the outcome of such collisions, to identify the novel physics phenomena that may occur, and to determine how they are best observed. In an attempt to provide a useful resource for this challenging endeavour, the present book reviews the status of the field, discusses important recent developments, and outlines future prospects and perspectives, as well as important theoretical challenges. The highlights of the various parts of this book are summarised in the subsequent "Executive Summary". Part I concentrates on topics related to the bulk properties of strongly interacting matter, its phase structure and the equation of state. Part II considers medium modifications of hadrons travelling through such a medium. Part III discusses the various dynamical treatments developed for the description of the collision dynamics. Relevant experimental observations and their physical interpretations, together with specific predictions for the CBM experiment are reviewed in Part IV. Finally Part V describes the technical aspects of the CBM detector complex.

Executive summary

The purpose of this book is to describe our present understanding of the physics of hot and dense strongly interacting matter, with emphasis on aspects relevant for the planned nuclear-collision experiments in the intermediate beam energy range of 10–50 AGeV, as seen in the target rest frame. Such experiments are foreseen at RHIC (BNL, USA), FAIR (GSI, Germany) as well as NICA (JINR, Russia). It is expected that nuclear collisions at these energies will produce matter at moderate temperatures and high baryon densities. These research programs present unprecedented opportunities for exploring the phase diagram of Quantum Chromodynamics (QCD) at densities and temperatures complementary to those probed in nuclear collisions at the highest energies at RHIC and LHC. In particular, in the indicated energy range, it is expected that the properties of hot hadronic matter and of the deconfinement/chiral phase transition can be probed at the highest baryon densities available in laboratory experiments.

The topics addressed in this book are organized into five main parts, preceded by an elementary introduction to the properties of strongly interacting matter at high densities and temperatures and to the relevant experiments (*Facets of Matter*). First the properties of strongly interacting matter in thermal equilibrium are addressed in Part I, while the in-medium properties of particles and excitation modes in such systems are discussed in Part II. The theoretical tools required for describing the transient dynamical situations of the nuclear collision experiments are presented in Part III. They provide the bridge between the bulk matter properties on the one hand, and the experimentally observed data on the other. The data aspects are discussed in Part IV, where besides the results from dynamical models for already completed experiments also predictions for the planned future experiments are discussed. Finally, in Part V the conceptual designs for the projected second-generation type experiments in this beam-energy range are presented. This part also includes an appendix summarising the various first-generation experiments at AGS, SPS and RHIC.

I Bulk properties of strongly interacting matter

A unified theoretical description of the thermodynamics of strongly interacting matter at all densities and temperatures does not yet exist. Our present understanding of this subject is based on results obtained with a variety of approaches ranging from systematic solutions of QCD on a computational lattice to effective models that exhibit some of the relevant symmetries of QCD.

Symmetries play a crucial role in the classification of the various phases and phase transitions. An instructive example is provided by the approximate chiral symmetry of QCD, which arises from the smallness of the masses of the u and d quarks. Chiral symmetry is spontaneously broken at low temperatures and densities and thereby plays a crucial role in the generation of hadron masses, leading to a significant mass splitting of the so-called chiral partners (such as the ρ and a_1 mesons), which would otherwise be degenerate. The spontaneous breaking of chiral symmetry is reflected in a non-vanishing expectation value of the quark condensate. In strongly interacting matter at sufficiently high values of the temperature and/or density chiral symmetry is restored and, accordingly, the quark condensate is very small. Thus, the quark condensate is an order parameter that characterizes the spontaneous breaking of chiral symmetry. Because the u and d masses are in fact not strictly zero, chiral symmetry is not exact and, consequently, the chiral phase transformation is generically not of second order. At finite temperature and vanishing baryon density it is most likely of the crossover type, similar to the gradual ionization of a gas (leading to an electromagnetic plasma) as the temperature is raised. Model calculations suggest that at low temperatures and finite baryon densities the transition is of first order. Consequently, there should be a critical end point somewhere in the plane of temperature and baryo-chemical potential.

The deconfinement phase transformation is also related to an approximate global symmetry, namely the center symmetry of the color gauge group (the center of the $SU(3)$ group is $Z(3)$). This symmetry is exact for infinitely heavy quarks but only approximate for physical quark masses. A suitable order parameter for the deconfinement transformation is the so-called Polyakov loop, which is related to the free energy of a single quark. The $Z(3)$ symmetry is broken in the deconfined phase and the order parameter is non-vanishing, while it is restored in the confined phase where the order parameter vanishes.

So far lattice QCD simulations are well established at vanishing baryon chemical potential μ_B. First results for finite but still small μ_B have recently been obtained using various methods for extrapolating from $\mu_B = 0$. At low temperatures and densities systematic calculations involving a low-temperature and low-density expansion are available in the framework of chiral perturbation theory. Conversely, at very high temperatures and/or baryon chemical potentials QCD is, due to asymptotic freedom, weakly interacting and perturbative calculations of thermodynamic functions become applicable. Unfortunately, at the densities and temperatures of interest here, neither of these methods can be applied with confidence. Consequently, much of our present understanding of hot and dense matter is based on results obtained in various effective models. Although some of these models are constrained by the model-independent results obtained in lattice QCD, chiral perturbation theory and perturbative QCD, the predictions at temperatures near the expected deconfinement/chiral transition, in particular at non-zero densities, remain model dependent. Consequently, progress in this field requires intensive exchanges between theory and experiment as well as the development of novel theoretical methods for describing the truly non-perturbative phenomena of strongly interacting matter near the phase transition.

Chapter 2 introduces QCD and the thermodynamics of strongly interacting matter. The relevant symmetries of the QCD Lagrangian are identified and the systematic approaches as well as the models used to describe the thermodynamics of QCD are presented. The general features of thermodynamics of phase transitions are also discussed and universality arguments that can be used to classify phase transitions based on their symmetry breaking pattern are applied to the QCD phase transformations. Then, in Chap. 3, systematic approaches to the thermodynamics of strongly interacting matter are introduced and subsequently Chap. 4 discusses a variety of models used for the description of strongly interacting matter near deconfinement.

II In-Medium Excitations

The symmetries of QCD are essential not only for characterizing its phase diagram but also for determining its spectrum of excitations. In Part II the properties of in-medium excitations are discussed and utilized to link observables with symmetry and transport properties of QCD at finite temperature and density. One basic idea is that the spontaneous breaking of chiral symmetry (SBCS) is reflected in the properties of hadrons. Thus, by studying hadron properties in matter one can explore the (partial) restoration of the chiral symmetry including, e.g., the connections to hadronic mass generation. Another central idea is to use (hadrons containing) the heavier strange and charm quarks to access (chemical and kinetic) transport properties of the QCD medium.

The in-medium modifications of hadrons are best explored with so-called *penetrating* (electromagnetic) probes, since they escape essentially unaffected from the strongly interacting medium. The relations of dileptons and photons to the in-medium properties of hadrons are discussed in Chap. 2. The light vector mesons ρ, ω and ϕ play a special role due to their direct decay into dileptons (e^+e^- or $\mu^+\mu^-$ pairs). The dilepton production rate probes the in-medium current-current correlation function, which is sensitive to the in-medium spectral functions of the vector mesons. Thus, the dilepton invariant-mass spectrum, measured in heavy-ion collisions, is expected to unveil the in-medium properties of the light vector mesons.

The ρ meson has been at the center of attention because it is short lived and hence likely to decay inside the medium, and because of its strong connection with chiral symmetry. However, since experimental access to the chiral partner of the ρ meson, the a_1 meson, in the medium is extremely difficult, one has to resort to other means to clarify the characteristics of chiral symmetry restoration. A basic problem here is that the fate of e.g. the ρ meson mass spectrum in matter is not uniquely determined by chiral symmetry. Hence, various effective hadronic models, satisfying constraints of chiral symmetry, can imply different dynamics and therefore predict different properties of the

ρ mass spectrum at finite temperature and density. A program is outlined which utilizes chiral sum rules to connect chiral order parameters (as evaluated, e.g., in lattice QCD) with in-medium ρ and a_1 properties computed within effective models which, in turn, can be tested in dilepton experiments. Eventually, hadronic spectral functions may be computed directly from lattice QCD.

Much progress has been achieved in recent years. It is discussed how a large variety of constraints, derived e.g. from QCD sum rules and from elementary reactions on ground-state nuclei, are implemented into effective hadronic models presently employed to compute dilepton production rates. These approaches yield a broadening (and ultimately "melting") of the ρ meson spectral function without an appreciable shift of its mass. This is in contrast to the vector manifestation approach, where both the ρ mass and its coupling to dileptons approach zero as chiral symmetry restores. The close connection to production rates for single photons (and, to a lesser extent, to photon pairs) is pointed out. The enhancement of dileptons found in nucleus–nucleus collisions is largely consistent with the broadening scenario, and, in particular, identifies baryons as the prevalent source of medium effects. This implies that the energy range of FAIR, where baryon-rich matter is produced, appears ideal for the next generation of dilepton experiments.

Chapter 3 discusses the spectroscopy of hadronic resonances in the light quark (u, d) sector. The in-medium mass distribution of the $\Delta(1232)$, $\rho(770)$ and possibly "$\sigma(500)$", close to the freeze-out transition, may be observed via the invariant-mass spectra of the decay products. Such data could provide information complementary to that obtained from the penetrating probes, in particular from the dilepton spectrum of the ρ meson. For the Δ resonance $\pi^{\pm}p$ invariant-mass spectra have been measured at BEVALAC/SIS and RHIC energies, without conclusive evidence for the relevance of medium effects. Such an analysis is rather challenging due to large backgrounds and resonance widths, combined with phase space and rescattering effects. This also applies to $\pi^+\pi^-$ spectra which are particularly interesting due to the close connection of ρ and σ mesons to chiral symmetry.

The role of strangeness is addressed in Chap. 4. The strange (s) quark is considerably more massive than u and d quarks. However, on the scale of SBCS, the s quark may be considered light and therefore treated on the same footing as u and d quarks. In nuclear collisions, however, s quarks differ in an important aspect from u and d in that there are essentially no s and $\bar{s}$ in the initial state. Strangeness-carrying hadrons in the final state have to be produced in the collision, rendering them an important messenger of flavor chemistry in nuclear reactions. For example, the production of strangeness is expected to be enhanced in a deconfined, chirally restored QGP, due to a much reduced mass threshold for (bare) $s\bar{s}$ pairs compared to, e.g., kaon-antikaon pairs. In nuclear collisions at AGS energies and above, the multiplicity of strange particles is consistent with the saturation of phase space, which is not the case in elementary hadron-hadron collisions. However, the connection to QGP formation is still somewhat tentative since at this point other effects cannot be excluded from playing an important role in the chemical relaxation of the strangeness degrees of freedom. Chapter 4 focuses on in-medium modification of anti-/kaons and their coupling to baryonic excitations, which is particularly relevant close to the threshold for strangeness production, i.e., at SIS/BEVALAC energies. Analogous considerations may apply to charm production near threshold, to be explored at FAIR. (One should realize, however, that the timescales for strangeness and charm production are presumably rather different and thus the analogy may be of limited use.) A lowering of the $\bar{K}$ energy in matter, as predicted by model calculations, implies an enhanced production in nucleus-nucleus collisions close to the production threshold. The observed enhancement of the $\bar{K}$ multiplicity compared to elementary reactions at SIS energies is, at least on a qualitative level, consistent with this picture.

Chapters 5 and 6 address the physics of charm in nuclear collisions which plays a prominent role in the analysis of the produced medium. The c quark is heavy compared to the typical temperatures in the hot collision region. Consequently, the population of charm quarks ought to be determined in early hard collisions and remains unaffected by lower-energy secondary reactions in the QGP and in the hadronic phase. The number of charm quarks should therefore follow from an extrapolation of binary nucleon–nucleon collisions. At present, neither experimental proton–proton data nor perturbative QCD calculations can deliver the desired accuracy for the elementary production processes at the relevant collision energies near threshold.

As discussed in Chap. 5, if a reliable baseline for the initial spectra can be established, open charm is an ideal probe to study the transport properties of the medium and to possibly gain insight into hadronization mechanisms. Roughly speaking, the c quark is sufficiently light to undergo significant rescattering in the medium, yet heavy enough not to (fully) equilibrate, thus carrying information especially on the early phases of the medium produced in nuclear collisions. A theoretically appealing aspect is the possibility of a Brownian motion treatment of charm diffusion.

In Chap. 6 the study of hidden-charm bound states (charmonia) in nuclear collisions is presented. Charmonium production in nucleus–nucleus collisions is believed to probe the properties of the potential between two heavy quarks, as well as pertinent dissociation mechanisms. Originally, a suppressed production of J/ψ mesons was suggested as a signal of deconfinement, as a consequence of color-Debye screening melting the hidden-charm bound states. However, at present, the problem appears to be much more involved than anticipated. While significant suppressions have been observed at SPS and RHIC, their levels are very similar, despite an increase of the collision energy by more than an order of magnitude. It has been suggested that this is due to a competition between enhanced charmonium suppression, on the one hand, and charm coalescence becoming increasingly important at higher energies, on the other hand. Much activity is presently devoted to the problem of in-medium charmonium properties in both lattice QCD and potential models, as described in Chap. 6. This work has advanced the understanding of color screening and melting of charmonia in a hot environment. Phenomenological applications are discussed in the framework of transport approaches including both dissociation and regeneration mechanisms. A more stringent connection between theory and phenomenology, and additional measurements at LHC and FAIR, will contribute to clarifying the fate of charmonia in the QGP and the relation to observables.

Finally, Chap. 7 discusses selected aspects of color-superconductivity, the state of matter expected at very high baryon densities and low temperatures. In particular, the excitation spectrum in a two-flavor color superconductor (2SC phase), as well as precritical phenomena in normal quark matter near the transition to the superconducting phase, are discussed. Other aspects of color superconductivity were explored in Sect. 3.5 of Part I.

III Collision dynamics

Many of the theoretical concepts discussed in Parts I and II are formulated for idealised systems that are uniform in density and temperature and in global thermodynamic equilibrium. However, the experimental situation in relativistic nuclear collisions is very different. There one expects strong non-equilibrium effects, requiring non-equilibrium many-body approaches to describe the reaction dynamics and ultimately provide the bridge between the observables properties of the reaction products and those of the idealized uniform and static systems of strongly interacting matter. Since a full dynamical treatment of such collisions is intractable, one must resort to reduced schemes that are computationally practical. These range from kinetic transport models of the Boltzmann equation type on the microscopic level to macroscopic (multi) fluid approaches. In this part of the book, we review the various dynamical frameworks and models employed for the description of nuclear collisions, as well as the further conceptual developments needed for extending their applicability to the FAIR energy range.

The introductory chapter, Chap. 1, covers the general features, like collision geometry, typical time scales, the relevant degrees of freedom at various beam energies, as well as the achieved densities and the relation to the equation of state. Chapter 2 describes the simplest, and historically earliest, microscopic transport treatments, the so-called cascade models. There the participating particles move on straight trajectories, while accumulating the effects of sequential random binary collisions that are treated according to elementary cross sections. Later on, refinements based on perturbative QCD were introduced to compute the early highly non-equilibrium state of nuclear collisions at very high energies.

In the beginning of Chap. 3 the most commonly used transport approaches are presented. They rest on the Boltzmann-Uehling-Uhlenbeck equation, which includes an effective one-body field that governs the motion of the individual particles in between their binary collisions. The latter may be either Pauli suppressed (for fermions) or (less commonly) Bose enhanced (for bosons). Kinetic models of this type are well justified for dilute systems, where single-particle excitations are well approximated by quasiparticles of infinite lifetime. At collision energies above 1 A GeV hadron resonances with broad spectral widths will be produced. Also stable particles will acquire non-trivial spectral functions due to the high collision rates in the dense medium. Therefore a large portion of this chapter is devoted to the transport treatment of particles with broad spectral widths. This includes the derivation of generalized phase-space transport equation from the underlying quantum Kadanoff-Baym equations by means of a systematic gradient expansion, questions of detailed balance and unitarity, as well as issues of conservation laws. A further important facet of transport in dense systems is the relevance of multi-particle collisions. General aspects of this problem are discussed and various implementations are presented. Chapter 3 closes with descriptions of the various specific transport models which are presently used. After some general remarks on the technical issues, each model is briefly presented.

In Chap. 4 the attention is turned to many-body models, which are capable of retaining many-body correlations. The most extensively used versions for simulating nuclear collisions from low up to relativistic energies are the so called quantum molecular dynamics (QMD) models. In these treatments, the mean-field dynamics described above is replaced by classical many-body dynamics subjected to smooth two-body forces that can be density and momentum dependent. In order to obtain smooth phase-space densities, each particle is represented by a Gaussian in phase space, while the strong short-range part of the interactions is still represented by a collision term as in the Boltzmann treatments. True quantum mechanical schemes were developed on the basis of Slater determinants built from single-particle Gaussian wave packets. While these fermionic (FMD) or anti-symmetrised (AMD) molecular dynamics approaches are capable of delivering even quantitative results for nuclear structure and can be applied to low-energy collisions, applications to high-energy nuclear collisions are not foreseen.

Dynamical instabilities, such as those caused by phase transitions, may occur during the evolution. Such scenarios were addressed in the context of multi-fragmentation at lower beam energies, where the liquid-vapour phase transition causes the expanding system to condense into nuclear clusters of various sizes. In order to meet this challenge, a variety of dynamical schemes were developed that account for fluctuations beyond the average dynamics. Of particular importance are Boltzmann–Langevin and the Quantum–Langevin approaches. While their applications have so far been relatively limited, due to the significant computational requirements, such techniques may become important also for the dynamics related to the transition between the quark-gluon plasma and the hadronic resonance gas.

Macroscopic transport approaches in terms of fluid dynamical concepts are described in Chap. 5. They offer an alternative to the kinetic descriptions above discussed and provide a direct link between the equation of state (EoS) discussed in Part I and the collision dynamics. In ideal hydrodynamics, which assumes instantaneous local equilibration, the EoS is the only dynamical input needed. The corresponding evolution is then generally isentropic. However, there are circumstances where ideal hydrodynamics fails. One such situation occurs during the initial stage of the collision, where the bulk of the matter has the character of two counter-streaming hadronic or partonic currents. At high energies, the equilibration of such a system is within ideal hydrodynamics attained instantaneously in an idealized shock front, while a more realistic description involves a gradual approach to equilibrium. Another case concerns the dynamics of phase separation occurring when bulk matter evolves into a mechanically unstable state. In ideal fluid dynamics, the lack of a finite spatial scale precludes a proper treatment of such instabilities. A more realistic treatment is obtained by allowing for the finite relaxation time scales encoded in the coefficients of shear and bulk viscosity, as well as heat transport.

Various strategies have been developed to circumvent such problems. Particularly powerful are hybrid approaches that link kinetics with fluid dynamics and multi-fluid concepts that model the mutual thermalisation between the fluid components by a phenomenological dissipative coupling. Recently also viscous fluid dynamics treatments have been developed and applied. Fits to elliptic flow data from RHIC suggest a very small shear viscosity which has led to the expectation that the matter near the QCD phase boundary is strongly coupled. Non-equilibrium multi-fluid models can also accomodate a first-order phase transition from the quark-gluon plasma to the hadronic phase. Due to the reduction of the entropy density across the transition, the phase conversion takes time during which the volume significantly grows, new hadrons are created and the normal temperature drop due to the expansion is compensated by the release of latent heat. The resulting approximate chemical equilibration among the hadrons at the end of the transition has provided support for the use of thermal freeze-out models for the observed yields, cf. Part IV.

Once the system is dilute, the particles also decouple kinetically and become free. In most hydrodynamic calculations the decoupling is treated arbitrarily as a sudden freeze-out on a hyper-surface, a crude concept that is not void of deficiencies. Indeed recent progress indicates that a sudden freeze-out is not possible; the typical time scale that emerges for the freeze-out process is of the same order as the expansion time scale. A discussion of these developments is followed by a brief review on the use of final-state correlations for imaging of the source (HBT) in the context of the finite decoupling duration.

In Chap. 6 the characteristic dynamical behavior such as the various flow phenomena are discussed in some detail. In the last chapter the status of the field is briefly reviewed and perspectives for future developments as well as the challenges lying ahead are outlined.

IV Observables and predictions

Progress in the exploration of hot and dense strongly interacting matter requires, on the one hand, a comprehensive set of high quality data, and on the other hand dynamical models that make contact between theoretical concepts and experimental observables. Part IV reviews the relevant experimental data, the corresponding results of simulations as well as predictions for observables that are not yet measured in the intermediate energy range. This part starts with an outline of the physics program of the Compressed Baryonic Matter (CBM) experiment at FAIR.

Chapter 2 gives an overview of our present knowledge of the QCD phase diagram. The challenging goal of the future experiments at RHIC and FAIR is to discover the most prominent landmarks of the QCD phase diagram - the theoretically anticipated first-order phase transition and the corresponding critical endpoint. Furthermore, the dependence on beam energy of the region in the phase diagram probed in nuclear collisions is discussed on a qualitative level.

The highlights of the experiments conducted so far at SIS, AGS, SPS and RHIC are presented in Chap. 3. In particular, data relevant for the extraction of the nuclear equation of state, data on strangeness production, studies of the fireball geometry using HBT correlations, data on collective flow, jet quenching as well as measurement of hadronic resonances are discussed.

The measured excitation function of hadron abundances is discussed and compared to results of various model calculations in Chap. 4. The general trend of particle yields can be understood in terms of a transition from baryon-dominated matter below to meson-dominated matter above the low SPS energy range. However, the observation of a sharply peaked structure in the ratio of strangeness-to-entropy as a function of energy cannot be reproduced by purely hadronic models.

In the same beam energy range, the excitation function of the inverse slope parameters of the transverse mass spectra of strange mesons measured in heavy-ion collisions exhibits a step-like structure which also is in disagreement with the expectations of hadronic models. Moreover, the inverse slope parameter rises with increasing mass of the particle species up to about the proton or Λ mass, and then drops for particles with higher masses such as Ω and charmonium. This observation indicates that the heavy particles containing strange and charm quarks are produced in the early (partonic) phase of the collision. These features of the transverse mass spectra are reviewed in Chap. 5.

The collective flow of particles is discussed in Chap. 6. At FAIR energies and above, the elliptic flow is driven by the pressure generated in the reaction volume and it is therefore a sensitive probe of the equation of state of strongly interacting matter. At RHIC energies the elliptic flow exhibits partonic collectivity, i.e. its strength scales with the number of constituent quarks. Hydrodynamical calculations suggest that the elliptic flow disappears at the phase transition.

The data on lepton-pair production in nuclear collisions measured at the BEVALAC, at SIS, SPS and RHIC are presented in Chap. 7 together with various theoretical interpretations. The yields and invariant mass distributions of dileptons produced in proton–nucleus collisions are in agreement with the expected contributions from known lepton-pair sources such as vector mesons and other hadronic sources (the so called cocktail) – in the case of electron–positron pairs these include e.g. Dalitz decays of pions and Delta resonances. The dilepton invariant mass spectra obtained in nucleus–nucleus collisions, however, exhibit an enhancement above the cocktail in the mass range between 0.3 and 1 $\mathrm{GeV/c^2}$, which is attributed to a broadening of the ρ meson mass distribution in the dense and hot nuclear medium. The slope of the transverse momentum distribution of the lepton pairs rises with increasing invariant mass up to about 1 $\mathrm{GeV/c^2}$ and then falls again, indicating a partonic source for lepton pairs with invariant masses above 1 $\mathrm{GeV/c^2}$.

The production of charm in nuclear collisions is reviewed in Chap. 8. A significant suppression of J/ψ production relative to that obtained by scaling of proton–proton scattering is observed in central collisions of heavy nuclei at SPS and RHIC. Indeed, the suppression is larger than expected from extrapolation of the influence of cold nuclear matter. However, the theoretical interpretation of these results is subject of debate. On the one hand, within transport models, the suppression of both J/ψ and ψ' is attributed solely to collisions of the charmonium with comovers. On the other hand, the solution of kinetic rate equations within an expanding thermal fireball, suggest that interactions in the QGP are responsible for an important contribution to the dissociation of J/ψ. Furthermore, in models of the latter type, the suppression of ψ' mesons is mainly due to the decay into a pair of $D\overline{D}$ mesons in the hadronic phase, a process which requires a reduction of the D meson mass in the medium. The resulting ratio of J/ψ to D meson yields computed within a hadronic transport model (HSD) is larger than that obtained in the statistical hadronization model, where the yields of hadrons containing charmed quarks are determined by assuming canonical chemical equilibrium (the total number of charm quarks is fixed in the initial hard collisions) near the phase boundary. In order to narrow down the range of theoretical interpretations, data on open charm and on transverse spectra of charmed hadrons will be very valuable. For instance, the flow of D mesons encode information on the transport properties of open charm in strongly interacting matter, and, hence, on the dynamics of charm-carrying degrees of freedom in the fireball.

In Chap. 9, critical fluctuations and correlations of various observables are discussed as signatures for phase transitions in general and for the QCD critical endpoint in particular. Thermodynamic and mechanical instabilities are expected in the vicinity of the critical end point, and in the presence of a first-order phase transition when the bulk of the fireball enters the corresponding spinodal region. If, as a consequence of these instabilities, the plasma is decomposed into “blobs”, which hadronize independently at different locations in space with distinct flow velocities, fluctuations in event-by-event correlations of the proton rapidity difference and in the strange particle abundance are expected. Indeed, event-by-event fluctuations of the K-to-π ratio have been observed in central Pb+Pb collisions at the SPS. However, the interpretation of these data is still under debate. Finally, the idea that relative charge fluctuations are suppressed in a QGP environment relative to a hadron gas, and hence may serve as a signal for deconfinement is discussed.

In Chap. 9 it is also noted that fluctuation signals from the QGP may be severely reduced by subsequent hadronic interactions. The point is made, that a careful scrutiny of relevant processes, such as resonance scattering and decay, is clearly needed. Furthermore, it is noted that fluctuations of conserved quantities, such as charge and baryon number, depend strongly on the actual kinematic domain experimentally covered. To properly account for detector acceptance and for the event classes employed in the analysis, detailed transport simulations are required.

The prospects for producing composite objects with multiple units of strangeness in heavy-ion collisions is discussed in Chap. 10. According to model calculations, the yield of meta-stable exotic multi-hypernuclear clusters (consisting of nucleons and hyperons) increases with increasing baryon density and reaches a maximum at FAIR energies. Such objects can be identified e.g. via their weak decay into a pair of Λ hyperons plus nucleons.

The most promising experimental observables and diagnostic probes of dense and hot baryonic matter produced in high-energy heavy-ion collisions are summarized in Chap. 11. It is pointed out that progress in this field is dependent on a comprehensive set of new high-quality experimental data and that novel theoretical tools are needed to trace the observables back to the early phases of the collision where matter presumably was in the form of partons.

V The CBM experiment

The goal of the CBM (Compressed Baryonic Matter) experiment at FAIR is to explore the phase diagram of strongly interacting matter in the region of high baryon densities. The CBM research program, as outlined in Chap. 1 of Part V, addresses the equation of state of baryonic matter, the deconfinement phase transition and its critical endpoint, chiral symmetry restoration at high baryon densities, and the in-medium properties of hadrons. The corresponding key observables comprise low-mass vector mesons decaying into lepton pairs which serve as penetrating probes, hidden and open charm produced at threshold beam energies, (multi-) strange particles, and global features like collective flow and event-by event fluctuations. Lepton pairs and particles containing charm quarks have not yet been measured in heavy-ion collisions at AGS and low SPS energies, and only very little data on multi-strange hyperons have so far been recorded. The CBM experiment at FAIR is designed to perform these measurements with unprecedented precision.

The CBM detector concept is outlined in Chap. 2. The experimental challenge is to identify both hadrons and leptons, and to select events containing charm or lepton pairs in a heavy-ion environment with up to about 1,000 charged particles per central collision at reaction rates of up to 10 MHz. Such measurements require fast and radiation-hard detectors, self-triggered read-out electronics, a high-speed data acquisition system, and online event selection based on full track reconstruction.

In Chap. 3 the results of feasibility studies are presented, demonstrating that both frequently produced as well as rare particles can be measured with excellent statistics within beam times of several weeks. Finally, a brief review of complementary experimental approaches such as the NA61 experiment at CERN SPS, the RHIC beam energy scan program and the NICA project at JINR in Dubna, currently under consideration, is given in Chap. 4. The subsequent appendix covers technical features and main accomplishments of past and present detector arrangements employed in high-energy heavy-ion reaction experiments.