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The Transformation of Elementary Particle Physics into Many-Body Physics

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1. A tribute to Niels Bohr

It is a great honour and a deep pleasure to contribute to this symposium which recalls in today's perspective the momentous scientific achievements of Niels Bohr, the extraordinary radiance and kindness of his personality, and the unique atmosphere of scientific excellence and human warmth which he created at the Copenhagen Institute of Theoretical Physics. I was privileged to enjoy twice the hospitality of the Institute, briefly in 1947 and for a longer period in the following year. The formative value of these stays at Copenhagen was enormous, for me as for so many other young physicists.

An experience which was striking for the newcomers in Copenhagen was the broad spectrum of nationalities present at the Institute on Blegdamsvej and the astounding ease with which everybody was taken up and integrated in the international group. It is therefore not surprising that after World War II Niels Bohr was among the strongest proponents of a collaborative European effort in experimental physics, and that he supported the initiatives which led to the creation of CERN. Although he did not share the prevailing opinion that CERN should start immediately with the construction of a large synchrotron, Niels Bohr put himself and his Institute at the disposal of the provisional CERN organization, set up by an intergovernmental conference at Geneva in February 1952. He accepted the leadership of the Theoretical Study Group which was based in his Institute for several years, and participated with the Council and the other officials of the provisional CERN in the crucial deliberations leading to the establishment of the definitive organization in 1954. From then onward, he served on the Scientific Policy Committee until his death in 1962. As a CERN physicist, it is my privilege at this symposium to pay tribute to Niels Bohr for his contributions to the foundation of CERN and for the devotion with which he put his wisdom, his experience and his influence to the service of this first great venture in European scientific collaboration.

2. *Three ways in which particle physics transformed into many-body physics*

When the organizers of the Niels Bohr Centenary Symposium asked me to speak on what they called the "transmutation" of elementary particle physics into many-body physics, I first was surprised by the suggestion that the branch of physics which is commonly regarded to be the most fundamental one, seemed somehow to be degradated to the rank of an additional chapter in the everwidening physics of complex systems.

I soon realized, of course, that the relevance of the subject does not lie in the question of fundamentality; the search for basic constituents of matter and basic laws of interaction remains the central task of particle physics. What has become apparent, however, is that in recent times most problems encountered experimentally and theoretically in particle physics have characteristics typical of many-body physics, with many features which are of great interest in their own right. As I shall now explain, this occurs in three directions.

2.1. Multiple production of particles

To search for constituents of matter means to probe matter over short distances, which by the fundamental quantum relation $\lambda p = h$ (λ = wavelength, p = momentum) implies that high-energy probes must be used. But one learned very early from cosmic-ray experiments that most high-energy collisions produce large multiplicities of newly created particles. This in itself makes high-energy physics a new chapter of many-body physics, in fact the first chapter of relativistic many-body physics since most particles created have energies large compared to their masses times c^2.

Heisenberg pointed out in 1939 [1] that multiple particle production could be understood in principle in the "meson theories of nuclear forces" (we would now say "strong interaction theories") as a consequence of the non-linear nature of the interactions. This line of work was pursued by Heisenberg and his collaborators during and after the war [2] and was taken up also by Oppenheimer and collaborators [3] in 1948. In the early fifties, it was largely replaced by Fermi's statistical model [4] and Landau's hydrodynamical model [5], which made the linkage with many-body physics particularly obvious. It is remarkable that the hydrodynamical model reappeared in force recently (with improved assumptions on the initial conditions of the hydrodynamical expansion) in the field of relativistic heavy-ion collisions, a recent joint venture of high-energy physics and nuclear physics.

The sixties and early seventies saw two main lines of parallel development in what is now called multiparticle dynamics; one based on specific dynamical models (multiperipheral, Regge, dual and early string models) and the other one based on purely phenomenological approaches (uncorrelated jet model, longitudinal phase space analysis, limiting fragmentation, Feynman scaling, short-range order, Koba–Nielsen–Olesen scaling). The picture was radically changed around 1973 by two breakthroughs, the experimental discovery of collisions producing high transverse momenta (high p_T) at the CERN Intersecting Storage Rings (ISR) and the emergence of Quantum Chromodynamics (QCD) as the new field theory of strong interactions, two very successful advances which have dominated the scene of strong interaction physics in the last ten years.

The many-body problem of multiple particle production in high-energy collisions has thereby come to stand in a completely new light, quite different from what is commonly encountered in other branches of physics. The reason is that the basic fields of QCD have quanta, the *quarks* and *gluons*, which are not appearing as free particles. They carry a new set of (non-commuting) charges called *colour charges*, and all observable hadrons (this is the generic name given to the strongly interacting particles) are supposed to be composites of the above "partons" with vanishing colour charges. This is the principle of *confinement* which is required to make QCD compatible with the facts. For the moment it is an assumption, but lattice calculations suggest that it is likely to be a consequence of the QCD equations. We shall illustrate in section 3 how multiple particle production is now understood in the framework of QCD.

2.2. *Non-trivial structure of the vacuum*

Another development of modern particle physics connecting it with many-body physics concerns the properties of the vacuum state in the field theories describing the various particles and interactions. In practically all field theories now used, one is led to assume *spontaneous symmetry breaking*, in the sense that the vacuum state is supposed to be one of a set of degenerate groundstates, each of which violates one or several symmetries of the Lagrangean. This type of situation is, of course, entirely familiar in condensed-matter physics, e.g. in crystals, ferromagnetic spin systems, superconductivity, etc.

In particle physics, one of its simplest versions is the so-called *Higgs mechanism* [6] for spontaneous breaking of gauge symmetries, which postulates the existence of one or more scalar fields Φ and of a potential $V(\Phi)$ which reaches its minimum $V_{\min}$ at non-vanishing values of Φ. The true vacuum is then one of the states for which the expectation value(s) $\langle\Phi(x)\rangle$ are constant and obey $V(\langle\Phi(x)\rangle) = V_{\min}$. These non-vanishing *scalar condensates* are non-perturbative in the sense that the perturbative vacuum has $\langle\Phi\rangle = 0$. Perturbative methods can nevertheless be applied by expanding in $\delta\Phi = \Phi - \langle\Phi\rangle$. The Higgs mechanism has the remarkable property of giving masses to gauge bosons. It is postulated to apply in the *electroweak theory* of Glashow, Weinberg and Salam which successfully unifies the electromagnetic and weak interactions. Although the predicted weak gauge bosons W, Z^0 were discovered in 1983 in experiments at CERN, there is still no experimental verification of the Higgs mechanism.

Also quantum chromodynamics (QCD) is assumed to have a nontrivial vacuum structure, but it is of a more subtle type than the Higgs mechanism, in the sense that it should follow from the QCD Lagrangean without addition of *ad hoc* fields and interaction terms. The non-trivial vacuum structure is manifesting itself in this case through *two-field condensates*, i.e. non-vanishing vacuum expectation values of type $\langle\bar{q}q\rangle$ and $\langle g^2 G_{\mu\nu} G^{\mu\nu}\rangle$, where q stands for the quark field operators ($q = u, d, s, \ldots$, for the various quark flavours), $G_{\mu\nu}$ for the gauge-field tensor and g for the coupling constant. These condensates are supposed to be of *non-perturbative* nature, which means that their finite numerical values are supposed to remain after the divergent expressions obtained for the expectation values in perturbation theory are eliminated by renormalization.

The quark condensate $\langle\bar{q}q\rangle$ is a manifestation of spontaneous breaking of chiral symmetry. That the latter symmetry is approximately valid and would hold in the limit of zero pion-mass was recognized in the fifties, and Nambu proposed in 1960 [7] that it should be regarded as spontaneously broken. This proposal was inspired by Nambu's fundamental paper elucidating the question of gauge invariance in the Bardeen–Cooper–Schrieffer theory of superconductivity [8]. With the advent of QCD in 1973 it was readily understood that the quark condensate was the appropriate "order parameter" for spontaneously broken chiral symmetry (although chiral symmetry may also be broken in a more trivial fashion by non-vanishing mass terms for the quarks).

The story is different for the QCD gauge-field condensate $\langle g^2 G_{\mu\nu} G^{\mu\nu}\rangle$, also called gluon condensate because the gauge-field quanta are called gluons. The first indication that the QCD vacuum state must be abnormal with respect to the gauge-fields came in 1975 with Polyakov's discovery of non-perturbative "instanton" solutions of the classical gauge-field equations [9]. These instantons are localized both in space and in imaginary time, and they have an energy lower than the perturbative vacuum. As one possible structure the true groundstate of QCD can contain a gas of such instantons in Euclidean space-time (ordinary space and imaginary time). It would give a vacuum correlation $\langle g^2 G_{\mu\nu}(x)\, G^{\mu\nu}(x')\rangle$ which would vary rapidly in x and x', a situation referred to as "twinkling vacuum" in a recent review by Shuryak [10]. A second indication for an abnormal QCD vacuum was found by Savvidi who pointed out in 1977 that the energy of the perturbative vacuum gets lowered by the introduction of an external, constant Gauge-field of magnetic type [11]. If this is the main mechanism of instability of the perturbative vacuum, the true vacuum might have a smooth correlation $\langle g^2 G_{\mu\nu}(x)\, G^{\mu\nu}(x')\rangle$ and would be "homogeneous" in Shuryak's terminology [10].

In both cases one wonders about the translation and Lorentz invariance of the vacuum state, a basic property automatically verified in perturbation theory but easily violated by condensates. For example, is $\langle g^2 G_{\mu\nu}(x)\, G^{\mu\nu}(x')\rangle$ invariant and therefore depending only on the invariant space-time distance $(x - x')^2$, or could the vacuum have a non-invariant micro-structure which is invisible at presently accessible scales? This question is not answered (the opposite question of apparent Lorentz invariance for theories with non-invariant Langrangeans has been addressed by various authors, see e.g. ref. [12], where earlier work is quoted). Another problem connected with QCD instantons is that they induce a violation of *CP* and *T* invariance which must be assumed *ad hoc* to be extremely small [13].

A very interesting development initiated in 1979 by Shifman, Vainshtein and Zkharov [14] has permitted to relate the quark and gluon condensates to observable quantities in a rather direct way. We shall briefly describe their method in section 4.

2.3. Field theory at positive temperature

The third domain where particle physics meets many-body physics concerns the behaviour of modern field theories at positive temperatures, or in other words the statistical mechanics of relativistic fields and their associated particles. It began to attract considerable attention when it was realized that the modern field theories of particles and interactions have interesting links with cosmology, more precisely with the evolution of the early universe which is believed to have been filled with matter and radiation at very high temperature. In 1972 Kirzhnits and Linde [15] pointed out that the electroweak theory predicts a thermodynamic phase transition at sufficiently high temperatures, because in the Higgs mechanism the expectation value $\langle \Phi \rangle$ of the scalar field is then no longer fixed by the minimum of $V(\Phi)$ and will in general vanish, corresponding to restoration of the symmetry. In the actual theory the transition temperature cannot be estimated reliably, but is expected to lie in the range $T \sim 50$–500 GeV (by T we mean the temperature multiplied by the Boltzmann constant, $T = 1$ GeV corresponds to 1.16×10^{13} K). In the high-temperature phase (which in the standard Big Bang model of the expanding universe prevailed at times $\lesssim 10^{-12}$ s) all gauge bosons are predicted to be massless and additional scalar bosons appear instead of the longitudinally polarized states of the massive gauge bosons. Cosmological effects of the electroweak phase transition are generally believed to be unimportant.

Also QCD and strongly-interacting matter are predicted to behave quite differently at high temperatures than in laboratory situations studied so far, corresponding mostly to $T \simeq 0$ MeV or, in exceptional cases, to perhaps $T < 10$ MeV in quasi-thermal excitations of heavy nuclei (compound-nucleus states). The condensates $\langle g^2 G_{\mu\nu} G^{\mu\nu} \rangle$ and $\langle \bar{q}q \rangle$ are expected to "melt away" at high T, with the vanishing of $\langle \bar{q}q \rangle$ restoring chiral symmetry (except for possible quark-mass effects). In addition, a more spectacular transition is expected to occur, usually called the *deconfinement phase transition* first considered by Collins and Perry in 1975 [16].

Under normal conditions, hadronic matter is composed of well separated hadrons, each hadron being a composite of QCD partons, quarks, antiquarks and gluons (see the end of section 2.1), with a typical size of order 1 fermi $= 10^{-13}$ cm. At temperatures $T \sim 100$ MeV, blackbody radiation contains a substantial fraction of hadrons, especially pions which are the lightest hadrons (mass ~ 140 MeV$/c^2$). As T increases further, the density of these hadrons grows rapidly, and when it reaches about 1 fermi^{-3} it is expected that the hadrons somehow coalesce, allowing the partons to form a so-called *quark–gluon plasma* in which they circulate rather freely over distances $\gg 1$ fermi. This is the *deconfinement phase transition* which is clearly predicted by lattice QCD calculations and is generally expected to occur at a temperature in the range $T \sim 150$–250 MeV. The corresponding time in the early expansion of the universe is of order 10^{-6}–10^{-5} s. We shall return in section 5 to the problems related to possible effects of field-theoretical phase transitions in the early universe.

In addition to the temperature, there is a second variable which, for large values, is expected to have a drastic effect on hadronic matter. It is the baryon-number density which in QCD is one third of the net quark density (density of quarks minus density of antiquarks), or the corresponding chemical potential μ. Even at low T it is expected that hadronic matter will turn into a quark–gluon plasma when μ becomes sufficiently large, and this presumably happens in the collapse of heavy stars [16]. It is conceivable that a cold quark–gluon plasma ($T \sim 10$ MeV) could exist in the core of neutron stars. There are also more extreme speculations on abnormal, stable or metastable states of cold nuclear matter containing a large number of strange quarks [17].

Contrary to the electroweak phase transition mentioned earlier, the QCD deconfinement phase transition will perhaps become accessible to laboratory experiments in the near future. The hope exists that small, short-lived droplets of quark–gluon plasma could be formed in heavy-ion collisions at relativistic centre-of-mass energies, and much discussion is going on concerning the possibility to detect their occurrence and thereby determine some of their properties [18].

3. Multiple production of particles in quantum chromodynamics

As mentioned already, the confinement property of QCD has a profound effect on the particle-production process in high-energy collisions, making it a many-body problem of a totally novel type. In this section we attempt to describe in pictorial terms the essentials of this process as it is understood at present in the framework of QCD, concentrating on features which are common to the main theoretical models currently used to describe the data. Figure 1A represents the incident state of a meson–nucleon collision. The meson contains a quark labelled 1 and an antiquark (open circle), the nucleon contains three quarks labelled 2, 3, 4 (these five partons are presumably surrounded by clouds of quark–antiquark pairs and gluons). The shaded areas represent the volumes of the two incoming hadrons. They are supposed to be occupied by colour fields (the gauge fields of QCD) and have diameters of order 1 fermi. We have drawn them as if they were spherical, neglecting Lorentz contraction. The arrows indicate the motion.

Figure 1B depicts what is conjectured to be the situation a few fermi$/c$ after the beginning of the collision (1 fermi$/c = 1/3 \times 10^{-23}$ s) in the large majority of cases, the so-called *soft collisions* which produce only particles with low transverse momenta (low p_{T}). Presumably through parton-exchange processes the incident hadrons have picked up colour charges as they traversed each other, and a

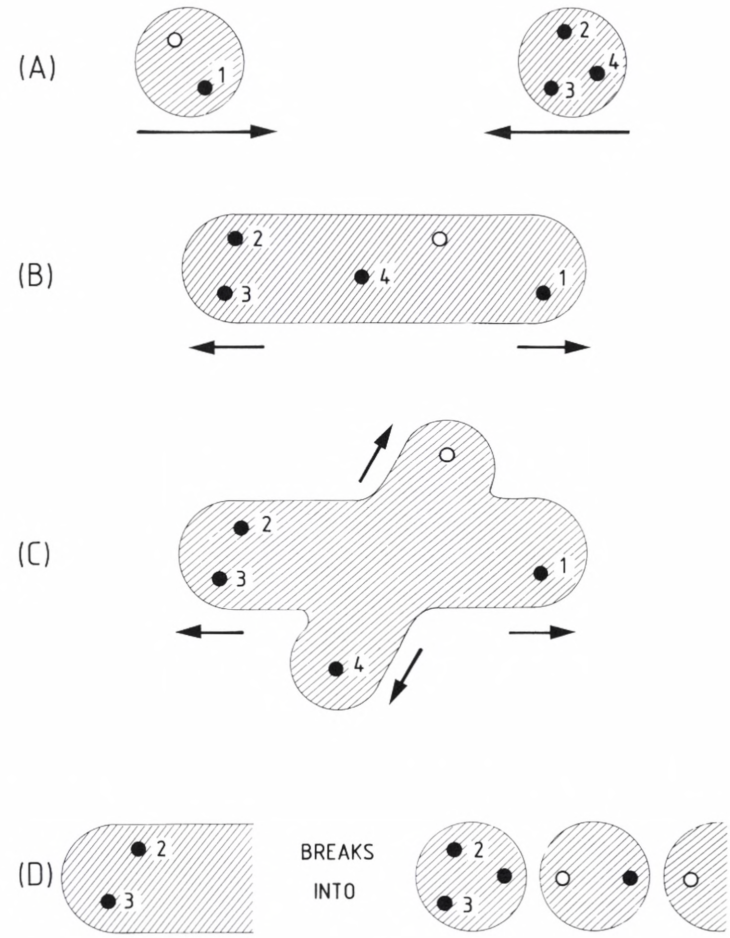

Fig. 1. Time development o a high-energy meson–nucleon collision. (A) initial state; (B) early state after soft collision; (C) early state after hard collision; (D) hadronization (see text for details).

colour-field region has formed between them (shaded area). It stretches out more and more but is believed not to expand significantly in the transverse direction, so that it forms a so-called *flux tube* of width ~ 1 fermi. By the Gauss theorem it contains a longitudinal colour electric field of constant flux as the opposite colour charges at the ends remain constant. The corresponding tension can be estimated to be ~ 1–2 GeV/fermi. The data suggest that one parton of each incident hadron gets "held back" and is located rather centrally in the tube whereas the others (quarks 1, 2 and 3 in fig. 1B) are located near the ends. As the tube stretches it breaks up, and this is believed to take place as illustrated in fig. 1D, by creation of additional quark–antiquark pairs in the colour field and regrouping of all partons into colourless hadrons, which then form the final state of the collision. This last phase of the collision is called *hadronization*.

At all stages the processes involved are characterized by energy–momentum transfers < 0.1–1 GeV$/c$, for which perturbative QCD calculations are not valid. We have so far no reliable way to calculate these processes. The present state of theory is that various phenomenological models have been developed in close contact with the abundant experimental material. Two of them, the Lund model [19] and the dual-parton model [20] are now quite elaborate and play an important role in experimental work. They have shown considerable predictive power at various stages, but in other respects have been and continue to be guided in their development by unforeseen experimental facts. While fitting in the qualitative picture sketched above, these models differ considerably in the assumed detailed specification of the early collision phase (fig. 1B) and the hadronization phase (fig. 1D).

As mentioned in section 2.1, we know since 1973 that in a fraction of high-energy hadron collisions, particles of high p_T are produced. These so-called *hard collisions* have been studied extensively, mainly at the CERN Intersecting Storage Rings and the Proton-Antiproton Collider. Although very rare, they form a clearly distinct class of collisions characterized by the occurrence of the high-p_T particles in two lateral jets on opposite sides of the longitudinal (i.e. incident) direction. Their existence and properties were predicted by QCD and brilliantly confirmed by experiment. In our pictorial description they are examplified by fig. 1C. Their characteristic is the occurrence of a hard collision (i.e. a collision with energy–momentum transfer $\gg 1$ GeV$/c$) between one parton of one incident hadron and one parton of the other (quark 4 and the antiquark in fig. 1C). The other partons fly through. The former two partons create the lateral jets and the other partons create the two longitudinal jets of fig. 1C, all four jets then breaking up by hadronization as depicted in fig. 1D. The new element is now that the hard collision of the two first partons can be calculated reliably from QCD because perturbative methods apply at large momentum transfers and indeed these calculations are successful in accounting for the high-p_T data.

Similarly, perturbative QCD calculations are very successful in accounting for hard collisions involving leptons (deep-inelastic scattering of electrons, muons and neutrinos on nucleons; high-energy electron–positron annihilation into hadrons). In all cases, nevertheless, the non-perturbative aspects connected with hadronization (fig. 1D) must be included by means of phenomenological models of the type mentioned above. Vice-versa, these models are being developed to the point where they are able to deal with the various types of collisions, soft and hard.

In principle, the non-perturbative properties of QCD should all be calculable numerically by lattice field-theory methods, but for scattering and particle-production processes this prospect is a long way off. The situation is very much better for hadron spectroscopy, vacuum condensates and QCD at positive temperature.

4. *Quantum chromodynamics vacuum condensates*

In this section we sketch how one can estimate the values of the quark and gluon vacuum condensates of QCD, $\langle \bar{q}q \rangle$ and $\langle g^2 G_{\mu\nu} G^{\mu\nu} \rangle$ (see section 2.2). The general idea can be described as follows. Consider the Feynman diagrams which are

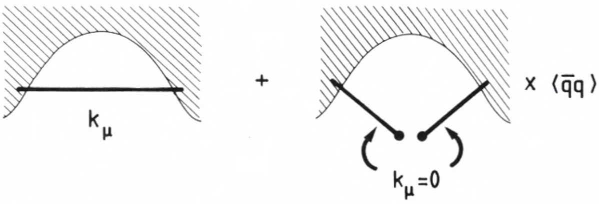

Fig. 2. Contribution of the quark condensate to a Feynman diagram (see text).

relevant for the perturbative calculation of a physical quantity, and suppose this quantity to be such that the integrands of the Feynman integrals pertaining to the diagrams vary little when the four-momentum k_μ of any line varies over an interval $|k_\mu| \sim 0.1$ GeV. This happens when large momentum-transfers or large masses are involved. The effect of the condensates can then be incorporated in the calculation by adding for each line a "condensate contribution", as illustrated in fig. 2 for a quark line. In the figure the diagram on the left represents the perturbative contribution and the one on the right the additional term. In the latter, the cut line of the diagram is given by $k_\mu = 0$ and the multiplicative factor is the condensate $\langle \bar{q}(x)\ q(x') \rangle$ at $x \simeq x'$. This is justified under the assumption that the diagram contribution is constant for k_μ varying around $k_\mu = 0$ over the range of the condensate in momentum space. The latter range is believed to be $\ll 1$ GeV. The contribution of the gluon condensate is added similarly by cutting gluon lines, the multiplicative factor being $\langle g^2 G_{\mu\nu}(x)\ G^{\mu\nu}(x') \rangle$ at $x \simeq x'$ up to a numerical factor.

The theoretical basis for this method, called the operator product expansion, goes back to a fundamental paper of K. Wilson in 1969 [21]. Then years later, Shifman, Vainshtein and Zkharov [14] showed how it could be used to determine the vacuum condensates by the study of correlation functions between currents. One considers sum rules for correlation functions in cases where large momentum-transfers are involved, which occurs for currents containing heavy quarks. The operator-product expansion expresses the correlation function in terms of vacuum condensates as explained above (fig. 2). Using the sum rule one can estimate the value of the correlation from experimentally known resonances and one can guess it for higher-mass contributions, so that the values of the condensates can be extracted. Many studies of this type have been carried out in recent years. Individual papers often give rather precise values for the vacuum condensates, but they show considerable variations from paper to paper. We quote below more conservative estimates which we took from Shuryak's review [10]: $\langle \bar{q}q \rangle \sim -(0.010\text{–}0.015)\ \text{GeV}^3$ for u and d quarks, and $\langle g^2 G_{\mu\nu} G^{\mu\nu} \rangle \sim 0.1\text{–}0.8\ \text{GeV}^4$.
The condensate $\langle \bar{q}q \rangle$ for s quarks (strange quarks) is believed to be comparable to its value for u and d.

5. *Field-theoretical phase transitions and the early universe*

In the last few years the possible role of field-theoretical phase transitions in the early expansion of the universe has given rise to an outburst of studies which, although very speculative, are undoubtedly of great interest and have strongly increased the contacts between astrophysicists and particle physicists. We shall briefly review the two main lines of work. References and additional information can for example be found in the surveys of Abbott [22] and Brandenberger [23].

5.1. The hadronic phase transition

Most probably the main effect of the transition from quark-gluon plasma to hadron gas in the early universe has been to stop or strongly slow down the cooling for a few microseconds when the transition temperature $T_c \sim 200$ MeV was reached, i.e. at an age of the universe which was itself a few microseconds. During this time interval, the energy needed to drive the continued expansion ($\mathrm{d}E = -p\ \mathrm{d}V$, $E =$ energy in volume V, $p =$ presure) was provided by the apparently large latent heat of the deconfinement transition, whereby both temperature and pressure remained constant or almost constant. This process modified the time evolution of the expansion, but it probably had no after-effects in the present universe if it took place adiabatically (no entropy production).

More interesting possibilities occur if one assumes that the transition was irreversible despite the fact that its time scale ($\sim 10^{-6}$ s) was very long compared to hadronic times ($> 10^{-23}$ s). One can speculate that the transition showed strong supercooling followed by violent release of the latent heat. As pointed out by Witten [24] such violent processes with a microsecond time scale could produce gravitational waves which for present observers, by the red shift due to the expansion, would lead to a characteristic time of the order of one year. In favourable cases this gravitational remnant of the hadronic phase transition could be detectable through its effect on pulsars.

Another type of effect, not requiring such violent processes, could be the appearance of an inhomogeneous distribution of nucleons in space as a result of the transition. During the latter, growing regions of space were occupied by hadron gas and shrinking regions by quark–gluon plasma. Due to the high mass of the nucleon (~ 940 MeV$/c^2$) compared to the transition temperature (~ 200 MeV), the net quark number (i.e. the small relative surplus of quarks over antiquarks which at that time was of order 10^{-9}) was probably concentrated in the plasma regions more than in the gas regions, giving spatial inhomogeneities in the nucleon distribution when all plasma had disappeared. Most probably these inhomogeneities were smeared out long before nuclei began to be synthetized, in which case they had no after-effects. It is conceivable, however, that they were stable enough to survive until the epoch of nucleosynthesis and to affect the cosmic abundance of light elements [25]. Witten has also speculated that they could have caused the production of nuggets of "strange quark matter", if such matter would be stable [24]. De Rújula has reviewed how such nuggets could be searched for [26].

Further progress on these problems will profit from the results of future experiments on relativistic ion collisions if these experiments reveal manifestations of the hadronic phase transition and provide facts concerning its characteristics.

5.2. The possibilities of very early phase transitions

Great efforts have been made since the early seventies to go beyond the electroweak theory and to find more comprehensive field theories unifying the electroweak interactions with QCD (the so-called grand unification programme) and also with general relativity (supergravity programme). Despite numerous attempts, these endeavours have not been successful so far, and many theorists are now turning to another possible line of unification, the so-called superstring theories which in pre-QCD days grew out of the dual theories of strong interactions. It is much too early to evaluate the prospects of this new approach [27].

Theoretical developments of unified field theories can potentially make crucial contributions to our understanding of some very puzzling cosmological problems by offering possible solutions in terms of the behaviour of matter at temperatures in the range 10^{10}–10^{19} GeV (10^{19} GeV corresponds to the Planck temperature where gravity can no longer be treated classically). Thus, one of the earliest predictions of grand unified theories [28] was that the baryon number B would not be strictly conserved, giving rise to the possibility that the net baryon number now observed in the universe would have originated during the expansion when the temperature was somewhere in the range mentioned above, the earlier state of the universe being symmetric between matter and antimatter ($B=0$). This would imply that the present value of the net baryon number relative to the photon number in the cosmic background radiation could be calculated from particle physics and general relativity, a possibility which would have seemed totally out of reach twenty years ago.

Another idea which attracted an enormous interest in the last five years is that a field-theoretical phase transition at a temperature T_0 in the above range could have had a deep effect on the early expansion of the universe. The simplest example is a period of "inflation", i.e. of exponential expansion [29], as would happen if for a period the energy–momentum tensor were dominated by a vacuum energy-density of order T_0^4 (in units where $h=c=1$). The great interest of this possibility is that such a period of abnormal expansion would permit causal contact between various regions of the universe to have extended very far at early times, providing an elegant explanation for the high degree of isotropy observed in the cosmic background radiation. It would also explain why the present universe is very flat, any initial curvature having been stretched out by the early expansion.

It is true that it has so far not been possible to put forward a convincing theoretical scheme realizing the above aims. The constraints imposed by theoretical coherence and compatibility with known properties of particles and cosmology turn out to be very severe [23]. Also the hope to observe B violation experimentally in the form of proton decay has so far not been fulfilled. But success may still be forthcoming and the speculative work done so far has greatly widened our outlook on early cosmology.

6. Concluding remarks

We have tried in this lecture to illustrate the domains of particle physics where the theoretical problems and methods have much in common with many-body and condensed-matter physics. The multitude of diverse physical systems accessible to experimentation in condensed-matter physics, and the numerous concepts developed for their theoretical understanding provide a rich store of ideas and analogies to the particle physicist. This can help him to overcome the great handicap that in his own discipline the experimental facts are very hard to come by and are often extremely incomplete. On the other hand, particle physics brought us such truly fundamental advances as non-Abelian gauge theories, electroweak unification with the heavy weak bosons, and quantum chromodynamics with the confinement principle for the field quanta. As our understanding of these novel schemes deepens, possibly with further progress toward unification, we can expect that they will slowly have an impact on the rest of physics, just as the concepts and techniques of Abelian field theories have gradually invaded most of condensed-matter physics.

In closing, I would like to thank the organizers of the Bohr Centenary Symposium for having recreated the stimulating and delightful atmosphere which so many of us fondly remember from our stays in Copenhagen in Bohr's days.

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Discussion, session chairman H. Bethe

Cook: Is the implication of the EMC effect that it is more appropriate to describe the heavy nuclei as made out of quarks than made out of nucleons?

Van Hove: Some would like to put it that way, but there is no consensus. People have taken simple views, like saying that there are pions in the nucleus that give you additional quark–antiquark pairs. Other people have said: The building blocks are closely packed nucleons, and their quark content can therefore be different from what it is in free nucleons. Prof. Bleuler and his collaborators have shown that even low-energy nuclear phenomena can be understood in terms of the color properties of the quarks.

Bang: A comment: There are still simpler ways to explain the EMC effect than the ones you mentioned. Taking the energy–momentum distribution of the nucleons properly into account can explain the effect. I refer to the work of Akulinichev and Vagradov.

Nielsen: Do you say that there is experimental evidence that the strings, which are pulled out when quarks are moving away from each other, are pulled out hot, but don't get their entropy from this?

Van Hove: Yes. The experimental evidence is obtained by applying the Lund model to the multiplicity distribution measured at the highest energies of the $p\bar{p}$ collider. It is observed that the Lund model does not give the necessary multiplicity and entropy creation in the important central region.