Hadrons and quarks in high energy collisions[1)]

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1. INTRODUCTION: SURVEY OF RECENT DEVELOPMENTS

1.1. Experimental developments

Much has happened in particle physics in the last five years, in particular in our experimental knowledge of weak interactions and of hadrons, i.e., of particles which experience the strong interaction. Regarding the former, the great event has of course been the experimental discovery in 1973 of a new type of weak interaction, the so-called neutral-current weak interaction.[1]

Concerning the hadrons, the notion that they are composite objects containing quarks confined by some type of gluon field has gained great support from its success in giving a simple and unified description of many phenomena, ranging from hadron spectroscopy and purely hadronic reactions to deep inelastic lepton-hadron scattering [2] and e^+e^- annihilation into hadrons.[3]

New metastable hadrons were discovered and their properties are explainable by postulating a new hadronic quantum number called charm, analogous to strangeness. The resulting picture is basically simple in terms of quarks. In addition to the three usual quarks (often denoted by u for "up", d for "down" and s for "strange"[2)]) one introduces a fourth quark, c for "charmed".[4]

The existence of charm turns out to be related in a deep way to the properties of the neutral-current weak interaction, in particular to its property to conserve strangeness. The weak couplings of the four quarks give a very elegant explanation for this, as was in fact predicted theoretically before the experimental discovery of charm.[5]

In addition to these developments which fit in a rather coherent picture of particles and interactions, one must mention various experimental facts and indications showing that this picture is still incomplete. The two main categories of phenomena of this type are:

i) the evidence for the production of what seem to be new leptons of mass ~1.9 GeV in e^+e^- annihilation at center-of-mass energy around 4 GeV and above,[6] and of $\mu^+\mu^-$ resonances of mass ~9.5 GeV in 400 GeV proton-nucleus collisions; [7] (ii) the existence of very narrow meson resonances in the 2 GeV mass range which seem to be explainable as narrow baryon-antibaryon states or through related extensions of the quark model.[8] Finally, one should mention the abnormal hadronic collisions producing secondaries with high transverse momentum.[9] Although they are usually regarded to be due to the action of point-like constituents of the hadrons, they have not yet been studied and understood sufficiently well to lead to any definite conclusion on the validity or otherwise of this interpretation.

1.2. Theoretical developments

Progress has also been important on the theoretical side, although the work on which it is based was done over a long period of some 25 years, starting with the formulation of the first non-abelian gauge field theory in 1954.[10] As far as established theoretical results are concerned (as opposed to theoretical speculations or models), the most important ones are undoubtedly the concept of spontaneous symmetry breaking and the fact that it provides a mechanism to generate masses for the gauge fields,[11] the proof of renormalizability for nonabelian gauge theories,[12] and the discovery that these theories are asymptotically free,[13] i.e. that the effective coupling strength approaches zero for processes with increasing momentum transfers (for spacelike four-momenta).

This remarkable renaissance of quantum field theory was paralleled by a vast amount of speculative work, to which it gave a theoretical basis. The most frutiful developments concern unified gauge theories for weak and electromagnetic interactions.[14,15] For the weak interactions such theories found support from their prediction of neutral currents with coupling strengths compatible with the ones observed in high energy neutrino reactions, and from the elegant way in which they incorporate the charm quantum number. No fully satisfactory scheme is yet known, however, and impor-

[1)]This paper was first issued in English as a CERN preprint dated 17 May, 1977 from which it was translated into Russian for Usp. Fiz. Nauk by I. M. Dremin. The present English text has been supplied by the author as document CERN/DG-3 dated 20 October, 1977, and is not being published in English elsewhere.

[2)]The Russian translator pointed out that s is often associated with the word "sideways".

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tant experimental results are still missing. One class may become available in the near future; it concerns the parity violation effects induced by the neutral-current weak interaction in optical transitions of atoms. The other, more crucial experiments concern the predicted existence of bosons mediating the weak interactions, with masses probably in the range 50 to 100 GeV. The standard Weinberg-Salam model,[14] with the mixing angle θ_W fixed by the measured rate of neutral current interactions ($\sin^2_W \simeq 0.24-0.37$) predicts $m_{W^\pm} \simeq 60-75$ GeV, $m_{Z_0} \simeq 80-100$ GeV for the masses of the charged and neutral intermediate bosons respectively. These predictions are model dependent but the masses are probably too high for the intermediate bosons to be produced with existing accelerators.

For the strong interactions many theorists favor a scheme where quarks interact with gluon fields of non-abelian gauge type, both the quarks and the gluon fields carrying a new set of SU(3) quantum numbers introduced long ago[15] and now called color. This scheme, usually referred to as Quantum Chromodynamics, has the property of asymptotic freedom and is therefore a good candidate to account for the phenomenological success of the quark model. There is in addition a widespread hope that it could explain quark confinement, but so far without much theoretical foundation.

2. INTERNAL STRUCTURE OF HADRONS AS PROBED BY LEPTONS

2.1. Deep inelastic lepton-nucleon scattering

After its initial success for the classification of hadrons, the quark model achieved new results of surprising simplicity in providing a common description of deep inelastic collisions of electrons, neutrinos and antineutrinos with nucleons:[3)]

$$\begin{aligned} &e+N\to e+N^*,\\ &\nu_\mu+N\to\mu^-+N^*,\\ &\bar\nu_\mu+N\to\mu^++N^*.\end{aligned} \tag{2.1.1}$$

Consider a collision where the lepton deposits an energy Q_0 and a momentum $\vec{Q}$ onto the nucleon N which gets into an excited state N^* of effective mass W (Fig. 1). Measuring the distribution of the scattered lepton in angle and energy gives information on the following space-time correlation function between currents

$$A_{\mu\nu}=\int d^4x\exp(iQ_\lambda x^\lambda)\langle j_\mu(x)\,j_\nu(0)\rangle_N. \tag{2.1.2}$$

The quantity $j_\mu(x)$ is the current density operator relevant to the lepton-hadron interaction considered in (2.1.1), i.e., the electromagnetic current for the electron scattering processes, or the charged weak current for the neutrino and antineutrino scattering processes $\nu_\mu+N\to\mu+N^*$. The expectation value $\langle j_\mu(x)\,j_\nu(0)\rangle_N$ is taken for the initial nucleon state.

The deep inelastic region of scattering is the region where both $Q^2=-Q_\mu Q_\mu\equiv|\vec{Q}|^2-Q_0^2$ and W^2 are large

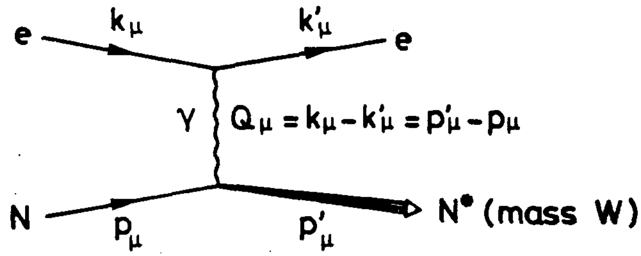

FIG. 1. Kinematics of inelastic electron-nucleon scattering. The particle exchanged is a virtual photon γ.

compared to $m_N^2\sim 1$ GeV^2; it begins already at Q^2, $W^2\gtrsim 3$ GeV^2 (we take units with $\hbar=c=1$ and denote the nucleon mass by m_N, we also note that Q^2 is always positive for kinematic reasons). The first important experimental finding, made initially at SLAC for electrons and at CERN for neutrinos, is that $A_{\mu\nu}$ does not decrease when Q^2 and W^2 become much larger than m_N^2. From Eq. (2.1.2) this means that $\langle j_\mu(x)j_\nu(0)\rangle_N$ has a distribution in space-time which cannot be smooth and must have some form of sharp ridges. The simplest interpretation is to say that the charge pertaining to the current $j_\mu(x)$ is distributed in grains of size much smaller than $m_N^{-1}\simeq 2\times10^{-14}$ cm. Under this interpretation the most natural assumption is to identify these grains with the quarks and to see to what degree the resulting very simple picture can account for the facts. We proceed with a brief review of where one stands today in this line of analysis (we do not consider other lines, e.g. the one based on generalizations of vector meson dominance).

2.2. Valence quarks in deep inelastic scattering

The most elementary assumptions one can now make are the following:

A1. The current $j_\mu(x)$ in Eq. (2.1.1) is the one produced by the so-called *valence quarks*; these are the quarks which according to the original quark model are the constituents of the nucleon (two u quarks and one d quark for the proton, two d and one u for the neutron—for mesons the valence quarks would be a quark and an antiquark).

A2. The quarks are treated as free Dirac particles of spin $\frac{1}{2}$ and their masses are neglected. According to the standard quark model, the currents for the u and d quarks are

$$j_\mu^{em}=e\left\{\tfrac{2}{3}\bar u\gamma_\mu u-\tfrac{1}{3}\bar d\gamma_\mu d\right\}, \tag{2.2.1}$$

$$j_\mu^{cw}=\frac{G}{\sqrt2}\cos\theta_C\bar u\gamma_\mu(1-\gamma_5)\,d+\text{herm. conjugate} \tag{2.2.2}$$

The superscript em refers to the electromagnetic current, cw to the charged weak current, and the notation u, d is used for the Dirac wave functions. The coupling constants are

$e=\sqrt{4\pi\alpha}$, $\alpha=1/137$ — Sommerfeld constant
$G=10^{-5}/m_p^2$ = Fermi constant (m_p = proton mass)
$\cos^2\theta_C=0.95$, θ_C = Cabibbo angle

The approximation then consists, for electron-nucleon scattering, in calculating by means of (2.2.1) the elas-

[3)]Also the muon scattering process $\mu+N\to\mu+N^*$ falls in this category, but it is entirely similar to $e+N\to e+N^*$.

tic processes (Fig. 2)

$$e+u\to e+u,\quad e+d\to e+d. \tag{2.2.3}$$

For the neutrino and antineutrino cases, one calculates by means of (2.2.2) the two-body processes

$$\nu_\mu+d\to\mu^-+u,\quad \bar{\nu}_\mu+u\to\mu^++d. \tag{2.2.4}$$

To carry out these calculations one must specify the four-momenta of the quarks for a given four-momentum of the nucleon. Here again one uses a very simple approximation:

A3. The four-momentum of the nucleon being P_μ, the four-momenta of the quarks $q_1, q_2, \ldots$ are approximated by $x_1 P_\mu, x_2 P_\mu, \ldots$ where the numbers $x_1, x_2, \ldots$ can vary in the interval $0 < x_i < 1$. That this makes sense when the mass W of the final hadronic system N^* is very large can be seen by going to the coordinate system where N^* is at rest and noting that the four-momentum of the incident nucleon is there very large

$$|\mathbf{P}|,\ P_0 \gg m_N \quad \text{c} \quad P_0-|\mathbf{P}| \approx \frac{m_N^2}{2P_0}\approx 0.$$

Also the four-momenta of the quarks are then large and it is reasonable to neglect their mass, their binding energy and their transverse momentum in the nucleon. The quark four-momenta then have the same direction as P_μ in four-momentum space and can be written as $x_i P_\mu$.

Under these assumptions, the distributions of the outgoing leptons in the reactions (2.2.3–4), —and therefore (by assumption A2.) those in the original reactions (2.1.1)—, can be entirely calculated in terms of the probability distributions $p_i(x_i)$ for the momentum fractions x_i of the valence quarks in the nucleon. For the differential cross section $d\sigma/dQ^2$ one has simply

$$\frac{d\sigma}{dQ^2}=\sum_i \int \frac{d\sigma_i(x_i)}{dQ^2}\,p_i(x_i)\,dx_i, \tag{2.2.5}$$

where the $d\sigma_i(x_i)/dQ^2$ are the cross sections for the processes (2.2.3–4) calculated for incident momentum $x_i P_\mu$ of the quark. The distribution in W^2 can be calculated by noting that W^2/Q^2 fixes the value of the momentum fraction x of the particular quark which is scattered. Indeed, one has by definition

$$W^2=(Q_\mu+P_\mu)^2 \quad \text{or} \quad 2Q_\mu P_\mu = Q^2+W^2,$$

where the nucleon mass term has been neglected (remember that Q^2 is defined as $-Q_\mu Q_\mu$). On the other hand, the processes (2.2.3–4) with masses neglected give

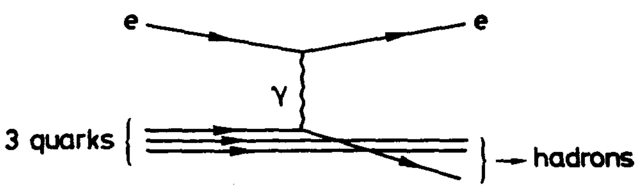

FIG. 2. Illustration of approximation A2 for deep inelastic electron-nucleon scattering.

$$(Q_\mu+xP_\mu)^2=0 \quad \text{or} \quad 2xQ_\mu P_\mu = Q^2.$$

Hence

$$x=\frac{Q^2}{Q^2+W^2} \quad \text{and} \quad \frac{dx}{dW^2}=-\frac{x}{Q^2+W^2}. \tag{2.2.6}$$

This gives for the double differential cross section expressing the distribution of the outgoing lepton

$$\frac{d^2\sigma}{dQ^2\,dW^2}=\frac{x}{Q^2+W^2}\sum_i \frac{d\sigma_i(x)}{dQ^2}\,p_i(x), \tag{2.2.7}$$

with the sum running over the three valence quarks and with x determined by the first equation (2.2.6).

It is remarkable that the simple valence quark scheme just described is capable of accounting to a considerable extent for the experimental data, and this is why deep inelastic scattering has provided strong additional support to the quark model. The scheme works quite well for

$$x=\frac{Q^2}{Q^2+W^2}\geqslant 0.25 \ \text{when}\ W^2\leqslant 3Q^2. \tag{2.2.8}$$

Its most striking success is that it accounts simultaneously for the double differential cross section $d^2\sigma/dQ^2dW^2$ of all three reactions (2.1.1), with the same probability distributions $p_i(x)$ for which reasonable shapes are found. The scheme has shortcomings, however, which will now be summarized.

S1. The main shortcoming occurs at $x \lesssim 0.25$ where the cross sections are too large to be described in terms of the three valence quarks. What happens is that the data at small x are incompatible with (2.2.7) when one takes into account the normalization of the probability distributions

$$\int_0^1 p_i(x)\,dx=1. \tag{2.2.9}$$

In fact the behavior of the data for fixed Q^2 and increasing W^2 (i.e. $x\to 0$) suggests that if one wants to describe them with an equation of the shape (2.2.7) one should have $p_i \propto x^{-1}$ at small x, in contradiction with (2.2.9).

S2. The second shortcoming of the scheme is that the electron scattering data, which are more accurate than the neutrino data, require the introduction of a weak Q^2-dependence in the probability distributions $p_i(x)$. This so-called *scaling violation* is confirmed by the very high Q^2 data obtained at Fermilab in deep inelastic muon scattering $\mu+N\to\mu+N^*$ which measures the same hadronic properties as the electron process $e+N\to e+N^*$.

These shortcomings will be discussed in the next subsection.

2.3. Scaling violation and further nucleon constituents

That the simple valence quark scheme of subsection 2.2 could not be more than a first approximation was not only shown *a posteriori* by the experimental facts, but was also expected on theoretical grounds. This holds in particular for assumption A2 which cannot be strictly correct, since the most striking property of quarks is of course that they have never been produced as free particles, and they must therefore be assumed to remain confined in hadrons by a very strong *confinement force*. This contradicts assumption A2 and implies that shortcoming S2 is bound to exist. What is remarkable is not that *scaling violation* occurs, but that it is a rather small effect and that it appears to be the same in electron and neutrino reactions. Quarks behave approximately as free particles for the short space and time intervals which are probed in deep inelastic processes, the confinement force becoming important only over larger space and time intervals. The main manifestation of the confinement force is therefore expected to occur in what happens to the hadronic system N^* at a later time, i.e., after the lepton has excited it by hitting a quark q_i of the initial nucleon: the confinement force must prevent q_i from escaping as a single quark and must force it to combine with newly created quarks and antiquarks so that N^* is composed only of ordinary hadrons (with quark composition $q\bar{q}$ for mesons, qqq for baryons and $\bar{q}\bar{q}\bar{q}$ for antibaryons). We shall return to the scaling violation after discussing the shortcoming S1 which is quantitatively more important.

The simplest interpretation of S1 is that leptons interact with more than the three valence quarks and that these additional effects are concentrated at small values of

$$x=\frac{Q^2}{Q^2-W^2}. \tag{2.3.1}$$

The conventional view is that the nucleon contains in addition to the valence quarks a set of quark-antiquark pairs, each pair being approximately in a singlet state so as to save the main rule of the original quark model that the quantum numbers of the hadrons are carried by the valence quarks. For deep inelastic scattering the quarks and antiquarks in this so-called *sea of quark-antiquark pairs* are again treated according to assumption A2, and the fact that the additional scattering is concentrated at small x implies that each of them carries only a small fraction xP_μ of the nucleon momentum Eq. (2.2.6) can be applied to each of them). Eq. (2.2.7) is now to be read differently. The sum should run over each type of quark (u, d, s, c) and each type of antiquark ($\bar{u}, \bar{d}, \bar{s}, \bar{c}$), and each term contains the distribution $p_i(x)$ for the corresponding type of quark or antiquark. For the strange and charmed quarks, eqs. (2.2.1–2) are to be supplemented by

$$j_\mu^{em}=e\left[\frac{2}{3}\bar{c}\gamma_\mu c-\frac{1}{3}\bar{s}\gamma_\mu s\right], \tag{2.3.2}$$

$$j_\mu^{cw}=\frac{G}{\sqrt{2}}\,[\sin\theta_C\bar{u}\gamma_\mu(1-\gamma_5)\,s+\cos\theta_C\bar{c}\gamma_\mu(1-\gamma_5)\,s$$
$$-\sin\theta_C\bar{c}\gamma_\mu(1-\gamma_5)\,d]$$
$$+\text{ herm. conjugate}. \tag{2.3.3}$$

The assignments for the charmed quark are those of Ref. 5 and successfully account for the properties of charmed particles so far discovered. They are less well established, of course, than those for the familiar u, d and s quarks.

A simple and popular choice of the functions $p_i(x)$ is in terms of two distributions, $P_{\rm val}(x)$ for valence quarks and $P_{\rm sea}(x)$ for sea quarks and antiquarks. It reads

$$p_u=2P_{\rm val}+P_{\rm sea},\quad p_d=P_{\rm val}+P_{\rm sea}\quad\text{for protons}$$
$$p_u=P_{\rm val}+P_{\rm sea},\quad p_d=2P_{\rm val}+P_{\rm sea}\quad\text{for neutrons}$$
$$p_{\bar{u}}=p_{\bar{d}}=p_s=p_{\bar{s}}=p_c=p_{\bar{c}}=P_{\rm sea}\quad\text{for protons and neutrons}$$

One may also prefer to put $p_c=p_{\bar{c}}=0$, as was of course done before the discovery of charm. Only $P_{\rm val}$ is subject to a normalization condition:

$$\int_0^1 P_{\rm val}(x)\,dx=1,$$

which ensures that the number of valence quarks in the nucleon is 3. The total number of q and $\bar{q}$ of given type in the sea is given by

$$2\int_0^1 P_{\rm sea}(x)\,dx.$$

Very reasonable fits to the data are obtained with the above choices. They reveal that $P_{\rm sea}$ is concentrated toward small x and grows like x^{-1} for $x\to 0$, corresponding to a non-vanishing value of $d^2\sigma/dQ^2dW^2$ in this limit. They also show that the *total amount of four-momentum carried by all quarks and antiquarks in the nucleon*, which is given by XP_μ with

$$X=\sum_i\int xp_i(x)\,dx=3\int xP_{\rm val}(x)\,dx+n\int xP_{\rm sea}(x)\,dx,\quad n=6\ \text{ or }\ 8$$

is of the order of half the nucleon four-momentum P_μ, i.e. $X\simeq 0.5$, and *most of it is contributed by the valence quarks*.

This is an important finding. Even when all the deep inelastic scattering is attributed to quarks and antiquarks in the nucleon, —and we shall argue below that this assumption is rather extreme—, these q and $\bar{q}$ do not account for more than half of the nucleon contents. The usual conjecture in this respect is to say that *the other half of the nucleon consists of gluons*, i.e. of quanta of the mesonic "glue field" supposed to confine the quarks. Such gluons are assumed not to have any direct interaction with leptons, i.e. not to contribute to the currents j_μ^{em} and j_μ^{cw}, so that they give no contribution to the cross sections $d^2\sigma/dQ^2dW^2$.

One has thereby constructed a picture of the nucleon which, on the face of it, requires three sets of constituents, namely the valence quarks, the quark-antiquark sea and the gluons. One should remember, however, that gluons and quarks must interact, since the former confine the latter. Consequently, the presence of an important gluon component in the nucleon implies the presence of virtual $q\bar{q}$ pairs by the virtual transitions

$$\text{gluon}\leftrightarrow q\bar{q}.$$

Hence the above picture can be reformulated by saying that *the nucleon basically consists of the three valence quarks and a cloud of gluons, the latter contributing to lepton scattering by quark-antiquark pair creation* (Fig. 3).

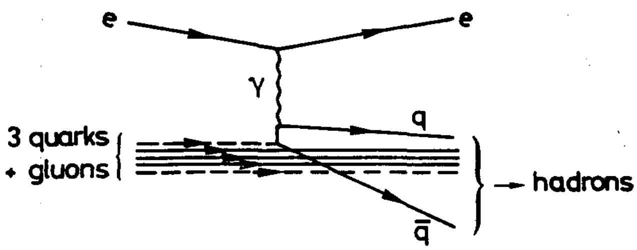

FIG. 3. Contribution of quark-antiquark pairs to deep inelastic electron-nucleon scattering. The dashed lines represent gluons.

This formulation also avoids an artifical feature of the more conventional picture which claims that all $q\bar{q}$ effects in deep inelastic lepton scattering are due to $q\bar{q}$ pairs pre-existing in the nucleon. For example, the latter picture is not easily maintained for diffraction dissociation processes of the type

$$\left.\begin{array}{l} e \to e + \gamma_{\text{virt}}, \quad \nu \to \mu + W_{\text{virt}}, \\ \gamma_{\text{virt}} + N \to V + N, \quad W_{\text{virt}} + N \to V + N, \end{array}\right\} \qquad (2.3.4)$$

in which the virtual photon γ or weak intermediate boson W dissociates diffractively into a meson state V. From our knowledge of diffraction dissociation we expect that the process (2.3.4) will occur at non-vanishing but small $x = Q^2/(Q^2 + W^2)$ even when Q^2 is large, and that it will produce meson states V in a mass range $m_V \lesssim Q$. It is obviously more natural to say that the hadron V is composed of a $q\bar{q}$ pair which has been created out of the virtual photon or weak intermediate boson by a diffractive process in the nucleon gluon field, rather than to claim that the $q\bar{q}$ of the V pre-existed in the nucleon as part of the latter's sea of quarks and antiquarks.

We now turn to the question of *scaling* in deep inelastic lepton nucleon scattering. In our elementary formulation it is the question of the validity of Eq. (2.2.7) with the sum running over all types of quarks and antiquarks and with the $p_i(x)$ independent of Q^2. Experimentally, one finds that for increasing Q^2 the $p_i(x)$ slowly increase for small x (roughly $x \lesssim 0.2$) and slowly decrease for larger x. It is remarkable that this form of scaling violation is qualitatively predicted by Quantum Chromodynamics, the variations with Q^2 at fixed x being logarithmic. It can also be understood on the basis of intuitive arguments. At small x the lepton scattering involves virtual $q\bar{q}$ pairs, and it is natural that more such pairs get active as one probes smaller dimensions by increasing Q^2. At larger x the valence quarks do most of the scattering, and their number is fixed. But for a given x their scattering strength is expected to decrease as Q^2 increases. This can be made plausible in two essentially equivalent ways. Due to its interaction with the gluon field, the quark has a form factor which decreases as Q^2 increases. One can also say that larger Q^2 probe smaller dimensions, hence "barer" components of the quark. The barer the component, the smaller is its four-momentum, the rest of the four-momentum residing in the gluon cloud of the quark. The net effect is that the bare valence quarks appear at smaller x for larger Q^2. Since for a given Q^2 their distribution $p_i(x)$ is a decreasing function of x, it implies that $p_i(x)$ decreases for increasing Q^2 at fixed x. This way of reasoning also suggests that for increasing Q^2 the assumption A3 presumably gets violated to a certain degree, in the sense that the components of the quark momentum transverse to the nucleon may no longer be negligible.

This ends our discussion of the quark-gluon picture of internal hadron structure as derived from the study of deep inelastic lepton scattering on nucleons. Before turning to problems of the strong interactions, we briefly consider another way of studying hadrons with leptons, which has recently revealed an extraordinary fruitfulness.

2.4. Electron-positron annihilation into hadrons

The process $e^+e^- \to$ hadrons, which had been known for some time to give very useful information on the neutral vector mesons, has become at higher energies an unbelievably rich source of new experimental facts. This occurred at center-of-mass energies above 3 GeV, accessible with the e^+e^- storage rings SPEAR at SLAC and DORIS at DESY. In addition to the J/ψ vector meson of mass 3.095 GeV and width 69 ± 15 keV, also found at Brookhaven,[4] the SPEAR ring led to the discovery of many other particles, including charmed mesons[4] and, very probably, a new lepton.[6]

We here briefly mention some general features of e^+e^- annihilation into hadrons which are of direct importance for the quark-gluon picture of hadron structure. The basic assumption relating these annihilation processes to quarks is closely similar to assumption A2 of subsection 2.2. It can be formulated as follows:

A4. e^+e^- annihilation into hadrons proceeds through a first step where the e^+e^- pair annihilates into a quark-antiquark pair, the quark and antiquark behaving as free Dirac particles (Fig. 4).

This assumption is subject to the limitations already mentioned for A2 at the beginning of subsection 2.3. In particular, once the quark and antiquark have been created and separate from each other, the action of the confinement force must become very strong and produce additional $q\bar{q}$ pairs so as to ensure that the final state be composed only of hadrons (mainly mesons).

One feature of e^+e^- annihilation data supporting this picture is that, at the highest energies measured (the SPEAR data extend to center-of-mass energy ~8 GeV), the hadrons produced have a momentum distribution

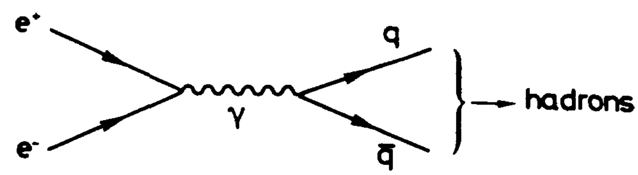

FIG. 4. The mechanism of assumption A4 for e^+e^- annihilation into hadrons. γ is a virtual photon.

which, in each collision, has an elongated shape often referred to as *jet structure*. This is as expected if the hadrons are produced with limited values of their momentum components perpendicular to the direction of the $q\bar{q}$ pair originally created in the annihilation. The distribution of the angle θ between the latter direction (which is also the jet direction) and the incident direction of the e^+e^- pair is compatible with the simple form

$$\frac{d\sigma}{d\cos\theta} \sim 1+\cos^2\theta. \quad (2.4.1)$$

This is the form calculated for annihilation through a single virtual photon

$$e^+e^- \to \gamma_{\rm virt} \to \text{hadrons}. \quad (2.4.2)$$

A second consequence of assumption A4 is that the ratio of the total annihilation cross sections into hadrons and muon pairs

$$R=\frac{\sigma(e^+e^-\to \text{virt} \to \text{hadrons})}{\sigma(e^+e^-\to \text{virt} \to \mu^+\mu^-)} \quad (2.4.3)$$

should have at high energy the value

$$R=\sum_i Q_i^2, \quad (2.4.4)$$

where the sum rules over all types of quarks and the Q_i are their electric charges. Experimentally R is ~2.5 for center-of-mass energies $2.5 \lesssim E_{\rm cm} \lesssim 3.5$ GeV and is ~5.5 at $E_{\rm cm} \gtrsim 4.5$ GeV, i.e., above the threshold region for production of charmed particles and new leptons (the value $R\sim 5.5$ contains the contribution of the new leptons). These values cannot be understood if the types of quarks are only u, d, s, and c (with charges $-\frac{1}{3}$, $\frac{2}{3}$, $-\frac{1}{3}$ and $\frac{2}{3}$ respectively), because one has then $R=2(-\frac{1}{3})^2+(\frac{2}{3})^2=\frac{2}{3}$ below the threshold and $R=\frac{2}{3}+(\frac{2}{3})^2+1=2\frac{1}{9}$ above (in the latter value we have included the new leptons as one term in (2.4.4) with $Q=1$).

The usual interpretation for the higher R values is in terms of the additional SU(3) quantum number of *color*.[15] It says that each of the so-called quark "flavors" u, d, s, c has three color states. This gives $R=3\times\frac{2}{3}=3$ below and $R=3\times 1\frac{1}{9}+1=4\frac{1}{3}$ above the threshold, the latter value again including one unit for the new lepton contribution. We see that the u, d, s quarks with color give a satisfactory R value below the threshold, but that the addition of just the c quark with color and one new lepton is insufficient to account for the increase of the R value through the threshold region, a discrepancy which is not yet resolved.

These considerations illustrate how informative e^+e^- annihilation turned out to be for uncovering aspects of hadron physics which are very hard to extract from the more conventional collision processes involving hadrons as incident particles. In fact, the development of hadron physics in the last twenty years has revealed a remarkable degree of complementarity between hadron-hadron collisions, lepton-hadron collisions and e^+e^- annihilation in providing the experimental information on which our present conceptions of hadron structure are based. The extensive body of knowledge now existing on hadron spectroscopy and hadron dynamics resulted mainly from the experimental work on hadron-hadron reactions, and led to the SU(3) classification of hadrons and to the formulation of the quark model. It took the work on deep inelastic electron-nucleon and neutrino-nucleon scattering to extract a more precise picture of the structure of nucleons and of the properties to be attributed to the quarks. As to e^+e^- annihilation, it turned out to be by far the most effective way of producing the heavy hadronic states related to the new quantum number of charm, and the only way so far to produce the new lepton of mass 1.9 GeV.

3. STRONG INTERACTIONS

3.1. General considerations

The new concept of a composite structure of hadrons with quarks and gluons as constituents leads to far-reaching consequences for strong interaction physics. The strong interactions as they are classically observed in reactions between hadrons are presumably manifestations of the same strong force which also confines quarks and gluons in the hadrons themselves. The general picture which many physicists now regard as the most plausible one for the strong interactions can be described by invoking analogies and differences with electrodynamics. They are summarized in Table I and commented upon below under the specific but unproven assumption that the SU(3) group of color is an invariance group of the strong interactions.

Property I goes back to the original work of Greenberg[15] in which quarks are attributed two sets of quantum numbers, $q=q_{f\gamma}$, one f related to what is now called flavor ($f=u, d, s, c$) and the second γ related to what is now called color ($\gamma=1,2,3$). Hadrons are either mesons, baryons or antibaryons, according to the three ways of making color singlets:

$$\text{mesons:} \quad \sum_{\gamma} q_{f\gamma}\bar{q}_{f'\gamma},$$

$$\text{baryons:} \quad \sum_{\gamma\gamma'\gamma''} \varepsilon_{\gamma\gamma'\gamma''} q_{f\gamma} q_{f'\gamma'} q_{f''\gamma''},$$

$$\text{antibaryons:} \quad \sum_{\gamma\gamma'\gamma''} \varepsilon_{\gamma\gamma'\gamma''} \bar{q}_{f\gamma} \bar{q}_{f'\gamma'} \bar{q}_{f''\gamma''},$$

with: $\varepsilon_{\gamma\gamma'\gamma''}$ fully antisymmetric and $\varepsilon_{123}=1$.

The small distance part of II is supposed to be related to the asymptotic freedom property of the gluon field, i.e. of the strong analogue of the photon field. This property holds for the non-abelian gauge field of

TABLE I.

Strong interactions (Chromodynamics)	Electromagnetic interactions (Electrodynamics)
I. *Color*, a set of eight charge operators Q_a with the commutation rules of the SU(3) Lie algebra.	*Electric charge*, a single charge operator Q.
II. *Confinement force* between systems which do not have all Q_a zero, should be weak at small distances and grow strong at larger distances.	*Coulomb force* between systems which have non-zero charge Q, depends as $1/R$ on the distance R between the systems.
III. *Hadronic system*, is a color singlet, i.e. has all Q_a zero.	*Electrically neutral system* ($Q=0$).
IV. *Strong force* between hadronic systems.	*Van der Waals force* between electrically neutral systems.

Yang-Mills type[10] belonging to the SU(3) group of color. The gluon field has then eight components, one for each charge Q_a. The large distance part of II is related to the crucial question of confinement on which very little is known. Confinement could be absolute but need not be; in fact, we shall argue below that, due to the low value of the meson masses, even a moderately strong confinement force might suffice to make single quark production very unlikely (see subsection 3.5).

Properties III and IV make it clear how complicated the strong interaction dynamics of hadrons is likely to be. Just as interatomic and intermolecular interactions are intricate manifestations of electrodynamics, requiring *ad hoc* concepts and approximations to become physically understandable, strong interactions between hadrons are likely to be complicated and indirect manifestations of the basic strong interaction laws. The theoretical schemes developed to describe them (Regge model and Reggeon field theory, dual resonance model and dual theory) cannot be expected to reveal the basic laws in any straightforward way. Rather than trying to transform these essentially phenomenological schemes into full-fledged theories, hadron physics now tends to concentrate more on bridging the gap between the new concepts of quark-gluon structure and what is observable in hadronic reactions. This is clearly attempted in most studies of high transverse momentum collisions, although without too many conclusive results so far (see subsection 3.4). The same trend becomes also apparent in recent work on high energy hadron-hadron collisions of the normal, low p_T type, which will be our next topic.

3.2. Low transverse momentum collisions of hadrons on hadrons

Whereas hadron-hadron collisions at center-of-mass energies E_{CM} up to a few GeV are mostly dominated by the production and decay of a small number of familiar resonances, the situation changes for $E_{CM} \gtrsim 5$ GeV where the most common collisions produce an increasing number of secondaries, all of which have small values of their *transverse momentum* p_T. The latter is defined as the projection of the momentum vector on a plane perpendicular to the so-called longitudinal direction, which is the incident direction taken in the laboratory frame or in the CM frame, both definitions being equivalent (CM = center-of-mass). In contrast, the longitudinal momenta p_L (defined as the projections of the momenta on the longitudinal direction) have a wide distribution extending over the whole range allowed by energy-momentum conservation. A useful alternative for expressing this distribution is in terms of the (longitudinal) *rapidity*, which is a dimensionless variable defined by the equation

$$y = \frac{1}{2} \ln \frac{1+v_L}{1-v_L}, \qquad 3.2.1$$

with v_L the projection of the velocity on the longitudinal direction (remember that $c = 1$ in our units). The rapidity depends on the frame of reference, but it transforms additively

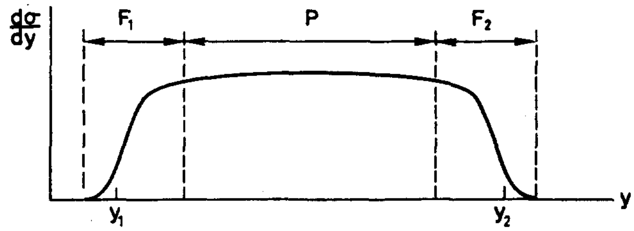

FIG. 5. The general shape of the rapidity distribution of secondaries of proton-proton collisions at very high energy.

$$y \to y + \text{constant}$$

when one starts from the CM frame and applies a Lorentz transformation in the longitudinal direction (the Lorentz transformation from the CM frame to the laboratory frame is of this type).

At very high energy, $E_{CM} \gtrsim 20$ GeV, the rapidity distribution of secondaries takes the qualitative shape depicted in Fig. 5 for the case of proton-proton collisions, where y_1 and y_2 are the rapidities of the incident particles and the three regions marked F_1, P and F_2 have a qualitatively simple behavior. The so-called *fragmentation regions* F_1 and F_2 vary little as E_{CM} increases, both in their shape and in their width $\Delta y \simeq 2$; they are believed to contain secondaries which originate from an approximately energy independent excitation or "fragmentation" of the incident particles. The so-called *plateau region P*, which is absent for $E_{CM} < 20$ GeV, is rather flat and grows slowly in height when E_{CM} increases. Its length is $\simeq y_2 - y_1 - 2\Delta y \simeq y_2 - y_1 - 4$ and grows as $\ln E_{CM}$ + constant at large E_{CM}.

The secondaries in the plateau region are mainly pions and show short-range correlations extending over rapidity intervals of order ~2. A crude description of these correlations can be obtained by assuming that the pions are produced in uncorrelated clusters. There is growing evidence that many of the pions are decay products of familiar meson resonances but it is not known what are the correlations between the latter.

In addition to a few pions, the fragmentation regions usually contain a nucleon if the corresponding incident particle was a nucleon, or a strange hadron if the corresponding incident particle carried strangeness. This is a manifestation of a property known as the *leading particle effect*, which seems to have general validity. It says that the most important quantum numbers of the incident hadrons are usually found back in the corresponding fragmentation regions, ensuring a high degree of overall "neutrality" for the plateau region.

While the inelastic collisions of the above general class account for more than half of the total cross section, there are hadron-hadron collisions of lower multiplicity which have also a large cross section. They are firstly the elastic collisions where both hadrons emerge unchanged except for a small deflection of the direction of flight in the CM system, and secondly the so-called diffraction dissociation collisions where one of the incident hardons, —or less frequently both—, undergoes an excitation which extends to increasingly high masses as the incident energy E_{CM} increases. Also here the secondaries have mostly low p_T.

For these two classes of collisions, the most natural interpretation is in terms of the familiar phenomenon of *diffraction* or shadow scattering. While this is straightforward for elastic scattering, the phenomenon of diffraction dissociation, i.e. *inelastic diffraction*, is of more specific interest for hadron dynamics. The reason is that the inelastic diffraction cross section for hadronic collisions is found experimentally to be quite large in the high energy range ($20 \leq E_{CM} \leq 60$ GeV), where a rather clear empirical separation is observed between diffraction dissociation and the remaining inelastic collisions (the latter are often referred to as *non-diffractive collisions*).

3.3. Quarks and gluons in low p_T collisions

The question of how to account for the main characteristics of low p_T collisions in terms of quarks and gluons is being investigated by many people, and it should be acknowledged that one is far from any consensus on the most promising approach. The subject is typically a "soft" one (as is for example also the study of nuclear reactions), both experimentally—the phenomena are complex and it is hard to say *a priori* what are their most relevant features –, and theoretically—theoretical work usually relies more on guesses than on unambiguous derivations. None of this is very surprising if one accepts the general considerations of section 3.1, nor can one expect to find an easy road to the solution.

On the *experimental side*, it is very likely that comprehensive information is required not only on hadron-hadron collisions, but also on the hadronic systems produced in deep inelastic lepton-hadron scattering and in high energy e^+e^- annihilation. One can indeed expect that a great deal could be learned from comparisons between these processes which involve quarks and gluons in very different manners. Unfortunately, our knowledge of the two classes of lepton-induced processes is still primitive, and it is difficult to reach for them the high values of the hadronically relevant energy variable which are required for proper comparisons to be made.

As an example of such comparative work we mention a study of mean charged hadron multiplicites $\langle n \rangle$ for hadron-hadron, photon-hadron, lepton-hadron and e^+e^- collisions.[16] It concludes that $\langle n \rangle$ tends to become independent of the nature of the incident particles when the hadronic energy is sufficiently high. Although this result is still affected by the limited energy range and the large uncertainty of available data on photon– and lepton-induced collisions, it gives a nice illustration of what can be learned from the type of comparison under discussion. Thus, there are theoretical schemes which predict that $\langle n \rangle$ is twice as large for hadron-hadron than for lepton-induced processes at high energy, and the data may rather soon become good enough to exclude this possibility. Other instructive comparisons deal with the leading particle effect and the distribution of momenta and rapidities of the hadrons produced in the various types of collisions.

If on the experimental side we tend to lack information, the *theoretical situation* is marked by a plethora of models and schemes which all succeed in reproducing more or less the main trends of the data. Many schemes are mathematically involved, all contain a lot of flexibility, and the situation changes too rapidly to make a systematic review worthwhile. We shall try to sketch a few general features according to which the various schemes can be classified.

We start with the most ambitious aim of a genuine *strong interaction theory based on Quantum Chromodynamics* (QCD). The facts that QCD is renormalizable and that it is asymptotically free are of little help in the low p_T situation, all the more so that one does not know how to derive from QCD the confinement property which is empirically the dominant feature of the strong interaction. Since perturbation theory can certainly not be applied in low p_T processes (it is applicable at large Q^2 where asymptotic freedom holds), one needs another approximation scheme. G. 't Hooft has proposed an expansion in $1/N_c$ with $N_c = 3$ denotes the number of colors.[17] It has a remarkable resemblance to the dual loop expansion of dual theory. This bridge between QCD and dual theory can be broadened[18] by making contact with the topological expansion of dual theory,[19] which is a $1/N_f$ expansion with N_f being the effective number of flavors active at low p_T, and the closely related dual unitarization scheme.[20] Despite their formal interest and their ability to incorporate the qualitative properties of the data, such expansion schemes are still subject to many uncertainties and variations, in particular on the way of incorporating the baryons.

At a less ambitious level, many authors have proposed *phenomenological pictures of hadrons and of hadron collisions in terms of quarks and gluons*. This line of work in fact goes back to the original parton models, which adopted a crudely descriptive approach to the empirical facts, in terms of partons which were presumed to be quarks but could also be other objects. The present trend is to attribute an increasingly important role to the gluons in the dynamics of low p_T collisions, either invoking specifically the color property of the single gluons of QCD,[21,22] or at a less specific but perhaps less model-dependent level where hadrons are viewed as composites of valence quarks embedded in a gluon cloud (see subsection 2.3). Despite its generality, the latter concept of "quark-glue structure" of hadrons can lead to a qualitative but simple and intuitive picture of various hadron reactions, as will be reviewed in the remaining part of this subsection.

In view of the property that the main quantum numbers of hadrons are carried by their valence quarks, the *leading particle effect* of common hadronic collisions suggests that in such collisions the valence quarks tend to fly through with smaller loss of incident momentum than the gluon clouds. This leads one to assume that the most important process in such collisions is the strong interaction of the gluon cloud of one incident hadron with the gluon cloud of the other, the color-singlet set of valence quarks of each incident hadron flying through and retaining most of its fraction of incident momentum.

This qualitative view is supported by the following empirical fact. The mean fraction of the momentum of an incident hadron carried by its set of valence quarks is known from the deep inelastic lepton experiments to be about $\frac{1}{2}$, and the mean incident hadron momentum fraction estimated to be carried out of a hadron-hadron collision by the leading particles happens to be also $\sim\frac{1}{2}$. In the simplest approximation, one is led to assume that the incident momentum fraction x carried out of the collision by each leading particle is roughly equal to the sum Σx_i of the valence quark momentum fractions x_i in the corresponding incident hadron. Taking the nucleon case and introducing the joint probability distribution $g(x_1x_2x_3)$ of the momentum fractions x_i of the three valence quarks, one can then express the distribution $f(x)$ of the leading particle momentum fraction in terms of g:

$$f(x)=\int_T g(x_1, x_2, x_3)\,\delta(x-x_1-x_2-x_3)\,dx_1\,dx_2\,dx_3. \tag{3.3.1}$$

the integration extending over the region

$$T:\ x_1\geqslant 0,\quad x_2\geqslant 0,\quad x_3\geqslant 0,\quad x_1+x_2+x_3\leqslant 1. \tag{3.3.2}$$

But the valence quark distributions $p_i(x)$ of subsection 2.2 are themselves related to g by

$$p_i(x)=\int_T g(x_1, x_2, x_3)\,\delta(x-x_i)\,dx_1\,dx_2\,dx_3. \tag{3.3.3}$$

One thereby obtains a *remarkable link between the leading particle spectrum of common hadron collisions and the valence quark part* (i.e. the $x\gtrsim 0.3$ part) *of deep inelastic lepton scattering*, and it can be shown[23] that it fits well with the experimental shapes of $f(x)$ and the $p_i(x)$.

We mentioned in subsection 3.2 the three regions observed in the rapidity distribution of secondaries of general inelastic collisions at high energy, namely the two fragmentation regions F_1 and F_2 separated by the plateau region P. A simple relation of these regions to the quark-glue picture sketched above suggests itself naturally. The regions F_1 and F_2 would be the phase space regions mainly populated by the leading particles and the additional mesons which originate from the "hadronisation" of the sets of valence quarks. On the other hand, *the hadronisation of the gluons radiated out of the collision of the two incident gluon clouds would populate the plateau region P.* This gluon cloud collision would presumably be of a type characteristic of nonlinear field theories (QCD is such a theory), the qualitative properties of which were derived long ago under the name of hydrodynamical models of high energy collisions.[24] It is interesting to note that the main difficulty with such models in the past was their inability to reproduce the strong leading particle effects observed experimentally, a difficulty now resolved by the realization that these effects can be attributed to the valence quarks.

The hadronisation of the gluons mentioned above is expected to proceed dominantly by production of low mass $q\bar{q}$ pairs. The most common hadrons in the plateau region will therefore be the familiar mesons, but one expects on statistical grounds (spin multiplicity factor $2J+1$) that the vector mesons will be more abundant than the pseudoscalar ones. This is supported by recent experiments.[25] As to the fact that most hadronic secondaries are produced with low p_T in all three region F_1, F_2, P, it is undoubtedly a manifestation of the very general law of dominance of low over high momentum transfers in strong interaction processes.

The quark-glue picture of hadronic collisions has also interesting consequences for diffraction scattering, elastic and inelastic.[26] The reason is as follows. For a given collision energy and a given impact parameter of the two incident hadrons, their two gluon clouds have a whole spectrum of collision energies and impact parameters, corresponding to the fact that the gluon cloud of each hadron carries a variable fraction x_g of the hadron momentum and has a variable impact vector $\mathbf{b}_g$ with respect to the hadron itself. Consequently, for a given collision energy E_{CM} and impact parameter b of the two incident hadrons, the elastic scattering amplitude of the two gluon clouds has a whole spectrum of values. This in turn implies for the hadrons the existence of *inelastic diffraction* (diffraction dissociation) in addition to ordinary elastic diffraction scattering, the basic formula for the hadron-hadron cross sections at given impact parameter being

$$\sigma_{el}(B, E_{CM})=(\bar{t}_g)^2, \tag{3.3.4}$$

$$\sigma_{inel}(b, E_{CM})=\overline{t_g^2}-(\bar{t}_g)^2. \tag{3.3.5}$$

Here t_g is the imaginary part of the elastic scattering amplitude of the two gluon clouds, its real part being neglected. The bar indicates the average over the variables x_g, $\mathbf{b}_g$ of each gluon cloud in its own hadron, for given values b, E_{CM} of the hadron-hadron collision.

By analyzing the proton-proton data on elastic scattering and diffraction dissociation along the above lines, one is led to interesting conclusions on the *gluon cloud absorptive amplitude* t_g can be approximately described by a gaussian with a flattening at the maximum (i.e. at small β), the unitarity limit of $t_g=1$ (full absorption) being reached at $\beta=0$. The width of the gaussian slowly increases with energy. These features correspond to the following observed properties of proton-proton collisions in the energy range 10 GeV $\lesssim E_{CM}\lesssim 60$ GeV:

i) the total cross section increases (this relates to the widening of the gaussian);

ii) the diffraction dissociation cross section is large (this relates to the x_g, b_g distributions of the gluon clouds in the hadrons and to the fact that t_g is fully absorptive at $\beta=0$);

iii) the proton-proton absorptive amplitude at zero impact parameter ($b=0$) remains practically constant at a value which is smaller than the unitarity limit (that this is so despite an increasing cross section is due to the spread in b_g of the gluon cloud inside the proton);

iv) the proton-proton elastic scattering shows a diffraction minimum at a momentum transfer $\Delta = 1.14$ GeV which is large compared to the mean proton radius R, in the sense that $R\Delta \simeq 5 \gg 1$ (this feature is related to the flattening of t_g at small values of β).

We end this review of quarks and gluons in low p_T hadronic collisions by a brief remark on a further class of such processes, namely the *low multiplicity collisions with exchange of hadronic quantum numbers* (isospin, strangeness, baryon number). Although they have cross sections decreasing with energy, these collisions have been extensively studied. They are usually described by diagrams involving meson or baryon exchange, the quark lines forming a planar diagram (planar means: without lines crossing each other when the diagram is drawn in a plane). It is interesting to note that in all cases of planar quark diagrams the process involves annihilation of a quark and an antiquark present in the incident hadrons, and $q\bar{q}$ creation to build up the outgoing hadrons. It is probably in this fashion that gluons play an important role in such collisions, see also Ref. 21, but little work has yet been done along this line.

3.4. High transverse momentum collisions of hadrons on hadrons

We now come to the abnormal hadron-hadron collisions producing secondaries with high p_T discovered in 1973 at the CERN Intersecting Storage Rings (energy range $20 \lesssim E_{CM} \lesssim 60$ GeV). Whereas the average p_T of secondaries produced in normal collisions is of order 350 MeV/c, secondaries with p_T as high as 8 GeV/c have been seen for $E_{CM} \gtrsim 30$ GeV. At $E_{CM} \simeq 30$ GeV the production cross section of secondaries is about 5×10^7 times smaller for $p_T \sim 5$ GeV/c than for $p_T \simeq 0.5$ GeV/c. The same ratio is only 5×10^6 at $E_{CM} \simeq 60$ GeV due to an increase by a factor 10 of the cross section at $p_T = 5$ GeV/c. The high p_T collisions must therefore be regarded as exceptional processes with a cross section which is small but increases rapidly with incident energy.[9]

Much experimental work has already been devoted to these collisions, mainly at the ISR, and remarkable qualitative features begin to emerge. It appears that a collision in which a very high p_T secondary has been detected also contains a few other secondaries with abnormally high p_T (but considerably lower than the p_T first detected), and that the high p_T secondaries are grouped in two "jets" on opposite sides of the line of flight of the incident particles. The other secondaries seem to have properties largely similar to those of ordinary, low p_T collisions (see Fig. 6). An important fact is that wide distributions are observed for the polar angles θ_1, θ_2 of the two high p_T jets with respect to the line of flight of the incident particles in the CM system. In particular, the jets do not come back to back, i.e. θ_2 is usually different from $\pi - \theta_1$. As to the azimuthal angles θ_1, θ_2 of the two jets, present experimental indications are that the distribution of $|\theta_1 - \theta_2|$ peaks at π, but this needs confirmation.

The two latter properties give support to the type of interpretation most commonly accepted for high p_T collisions. One imagines that they are due to a large-angle elastic (or quasi-elastic) collision between a constituent (perhaps a quark?) of the first incident hadron carrying a variable fraction x_1 of the latter's momentum, and a constituent of the second incident hadron also carrying a variable momentum fraction x_2. After their large-angle collision, these constituents are supposed to produce by "hadronisation" the two high p_T jets on azimuthally opposite sides of the incident direction, their polar angles θ_1, θ_2 reflecting the values of the incident momenta of the constituents, i.e. of the momentum fractions x_1, x_2. After having "lost" the scattered constituents, the incident hadrons would fly through and give rise to the low p_T secondaries of the collision.

Further information comes from the recent study of collisions experimentally selected by the property that the total p_T (vector sum) of several detected secondaries is large.[27] In the range above 3 GeV/c, the distribution of this total p_T is found to have the same shape as for the p_T of a single secondary, but the cross section at given p_T is much larger, by more than a factor 100 at $p_T \simeq 5$ GeV/c (this Fermilab experiment was carried out at $E_{CM} \simeq 20$ GeV). In contrast, previous experiments selected collisions by requiring one single secondary to have a high value of p_T and it was this value of p_T which was used to define the cross section and to plot the p_T distribution. Comparisons between the two types of experiments will clearly be instructive.

Further questions to be investigated concern the actual number of high p_T jets per high p_T collision (is it always 2 or does it vary?), the actual distribution in $|\theta_1 - \theta_2|$, the momentum distribution of the secondaries contained in a high p_T jet (how does it compare with the

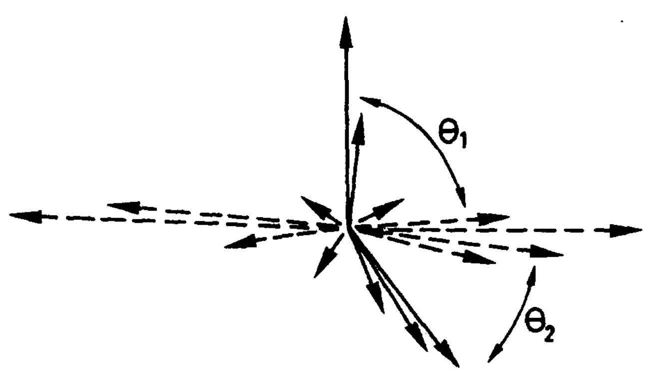

FIG. 6. A high p_T collision in momentum space. The broken lines represent the momentum vectors of the normal, low p_T secondaries. The full lines are those of the high p_T secondaries. The momenta of the incident particles (not shown) are horizontal.

momentum distribution of low p_T secondaries, and with that of the hadronic secondaries in high energy e^+e^- annihilation?), the flow of hadronic quantum numbers in high p_T collisions, etc.

All such information will probably be needed to test the general interpretation of high p_T collisions sketched above and, if it is confirmed, to make it more precise. One may then perhaps get closer to the answer to the obvious question: can the constituents which scatter in such collisions be identified with the quarks? It is now indeed recognized that this question is much more difficult than originally thought, being obscured by many uncertainties concerning quark-quark collisions, the hadronisation of quarks escaping from hadrons, and tl role of gluons in strong interaction processes.

3.5. Further remarks on quark confinement

We end our discussion of the strong interactions by returning to the fundamental question of quark confinement, and we try to comment on it in simple physical terms. Ever since the quark hypothesis was proposed in 1964, experiments to detect single quarks have been going on. Despite many searches, no quark has ever been found to emerge from high energy collisions. One has looked for fractional charges in bulk matter, and a recent publication[28] presents for the first time a positive indication for the existence of fragments of matter with electric charge $\pm\frac{1}{3}$. Obviously, for the quark picture of hadrons to be valid, there must therefore be strong confinement forces to prevent copious production of single quarks, but it may be hazardous to postulate that confinement should be absolute.

The point we want to make is that there is a natural relation between the tendency of quarks to remain confined and the low values of the masses of the most common mesons ($q\bar{q}$ systems). The reasoning goes as follows. Take a hadron H at rest and imagine that one of its quarks, –call it q_0–, receives at time $t=0$ a large amount of momentum and energy in a hard collision process, thereby acquiring a high rapidity $y_0 \gg 1$ with respect to H. At first, the quark q_0 flies rather freely inside the hadron H with a velocity $\tanh y_0$ very close to the velocity of light ($\tanh y_0 \simeq 1$). At a time $t \sim R_0$ with R_0 of the order of the hadron radius, $R_0 \sim 10^{-13}$ cm, q_0 reaches the hadron edge and tries to escape. This is when the confinement force starts to act and presumably becomes rapidly strong. It will decrease the rapidity of q_0 from y_0 to a lower value y_0', as part of the kinetic energy of q_0 is transformed into excitation energy of the gluon field. As soon as this excitation energy grows to a moderate value, say 1 GeV in the rest frame of H, it can be dissipated through creation, near the location of q_0, of a quark-antiquark pair $q_1\bar{q}_2$ with rapidities $y_1, y_2 \sim 1$.

Taking the case where q_1 and $\bar{q}_2$ move in the direction of q_0 with rapidities $y_1 \lesssim 1$ and $\bar{y}_2 > y_1$, we have a situation where the quark q_1 can fill the hole left in H and thereby transform H into a (moderately excited) hadron. As to $\bar{q}_2$ and q_0, they are near each other in space and move in the same direction with rapidities $y_2 \gtrsim 1$ and $y_0' \gg 1$, but y_0' being smaller than y_0. The $\bar{q}_2 q_0$ system can be regarded as a meson of rapidity y_2 in which the quark q_0 has been accelerated to rapidity y_0'. The rapidity y_0'. The rapidity gap $y_0' - y_2$ of $\bar{q}_2 q_0$ is smaller than the original gap between H and q_0. At a time $t \gtrsim 2R_0$ the separation between q_0 and $\bar{q}_2$ will again have grown enough for the confinement force to become strong and reduce the rapidity gap $y_0' - y_2$ to a smaller value $y_0'' - y_2'$, thereby providing enough excitation energy of the gluon field to create a further pair $q_3\bar{q}_4$ with $|y_3 - y_4| \sim 1$. If $y_3 < y_4$, the quark can form a meson with $\bar{q}_2$, and one is left with the pair $\bar{q}_4 q_0$ whose rapidity gap is now only $y_2'' - y_4$. The process can obviously continue until an antiquark $\bar{q}_n$ has been created with a rapidity close to the rapidity left for q_0, so that $\bar{q}_n q_0$ can form a meson. The overall effect is that a *meson jet has been formed in the wake of the quark q_0 which is itself contained in the leading meson of the jet* (Fig. 7).

While the detailed process just sketched for the formation of the meson jet is of course only one among various possibilities (the pair $q_1\bar{q}_2$ could also be formed with rapidities y_1, y_2 up to y_0', and similarly for further pairs), the dynamical principle would always be the same: as soon as quark separation builds up an excitation energy of the gluon field which reaches ~1 GeV in a volume of diameter $\sim R_0$ in some reference frame, this excitation can lead to creation of a low mass $q\bar{q}$ pair with low rapidity in this reference frame. In terms of color, the $q\bar{q}$ pair creation achieves local neutralization of color and thereby reduces the excitation of the gluon field. This general process presumably is active both in deep inelastic lepton-hadron scattering (where one quark of the hadron is hit by the scattering) and in

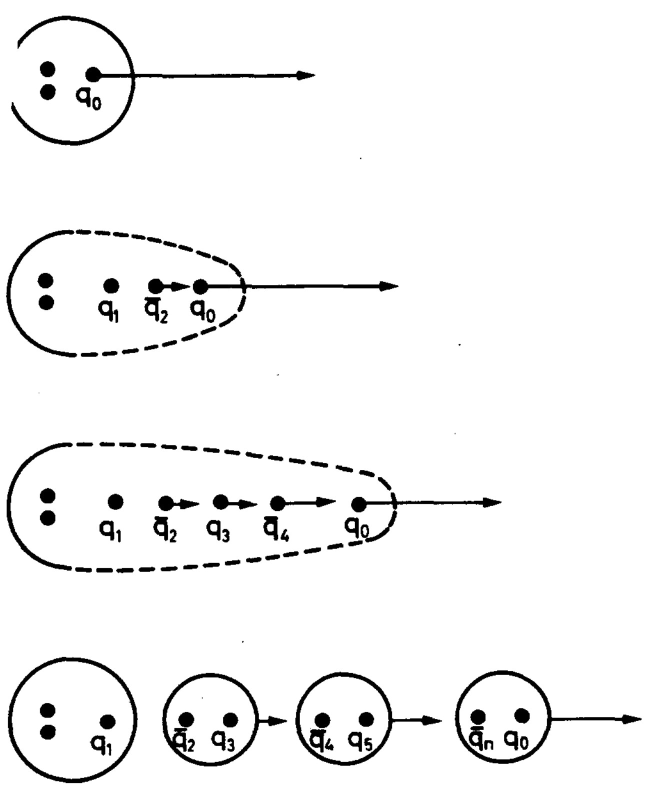

FIG. 7. Quark confinement and formation of a meson jet.

e^+e^- annihilation into hadrons (where the annihilation first produces a $q\bar{q}$ pair with large rapidity separation). It suggests three general properties of the meson jets to which it gives rise:

i) the mesons have a uniform rapidity distribution along the jet axis, except for end effects concentrated in rapidity intervals of order 1 or 2;

ii) only these end effects depend on the quark and hadron (or quark and antiquark) from which the jet initiated;

iii) the mesons produced in the jet are a statistical mixture of low mass $q\bar{q}$ states and the common vector mesons must therefore be more numerous among them than the pseudoscalar ones.

We recall in passing that the last property is also expected, - and indeed observed-, for the mesons produced in the central plateau region of low p_T hadron-hadron collisions (subsections 3.2 and 3.3).

Returning to the problem of quark confinement, we comment briefly on the question of how large the confinement force becomes when a quark is removed from a hadron and separated from it by large distances $R \gg R_0 \sim 10^{-13}$ cm. Depending on whether the confinement potential $V_c(R)$ becomes infinite or remains finite for $R \to \infty$ one will have absolute or limited confinement of quarks. In our way of looking at the confinement problem, the answer to this question hardly matters for what actually happens in most collisions. The reason is that whenever V_c grows to a moderate value of ~ 1 GeV, it is automatically reduced by $q\bar{q}$ pair creation. Furthermore, since the distance R of quark separation will not grow faster than the velocity of light, $dR/dt < 1$, there should always be enough time for this reduction of the confinement potential to take place.

Consequently, under the assumption that $V_c(R)$ remains finite for $R \to \infty$ but becomes large compared to 1 GeV, the probability of producing free quarks in high energy collisions is expected to be extremely small. The only likely way to liberate quarks in the latter case would seem to be through the action of other very energetic effects capable of disturbing the $q\bar{q}$ pair creation mechanism described above. Under the big bang hypothesis such effects might conceivably have occurred in the very early phases of the expansion of the universe, when the densities of matter and energy were very high. The phenomenon of quark separation in such a hot hadronic medium would indeed be very different from what we picture it to be in the vacuum surrounding the microscopic collision volumes where man-made high energy processes take place. If these considerations are correct, it would be in bulk matter rather than in elementary particle collisions that the best chance might exist to find single quarks.

4. CONCLUDING REMARKS

In the preceding paragraphs we surveyed in general terms how high energy reactions involving hadrons are being analysed in terms of the quark-glue picture. This analysis has been remarkably successful in deep inelastic scattering of electrons, muons and neutrinos on nucleons. To these results must be added the impressive achievements of the quark model in hadron spectroscopy. In the latter field, the by now familiar spectroscopy based on the up, down and strange quarks has been supplemented in the last three years by the amazingly successful description of the charmed particles by means of just one additional quark, the charmed quark c. The model turns out to work beautifully both for the "hidden charm" mesons of the ψ family (quark composition $c\bar{c}$) and for the charmed mesons (quark composition $c\bar{q}$ and $q\bar{c}$ with $q = u, d, s$).

Other problems are still open. The description of purely hadronic collisions in terms of the quark-glue picture has not yet reached the stage where one can say which are the dynamical mechanisms at work. Various possibilities are still under investigation, but the trend goes in the direction of attributing an important role to the gluon field in the purely hadronic processes. This may be an interesting line, because hadron spectroscopy and deep inelastic lepton-hadron reactions give much less information about the gluon field than about the quarks. It would indeed be desirable to find a class of experimentally accessible processes where gluons would manifest themselves in some characteristic way, and such a class might exist among hadronic reactions at high energy.[29]

The confinement problem is another unsolved question. To the considerations on quark confinement in the previous section, we add first the remark that there is also a confinement problem for gluons, the nature of which depends on one's theoretical views concerning the gluon field. An additional point to be kept in mind is that the traditional quantum number assignments to quarks (baryon number $\frac{1}{3}$, electric charges $\frac{2}{3}$ and $-\frac{1}{3}$), although the simplest, are not the only ones possible. At the cost of complications, one could assign integer baryon number and electric charge to the quarks, which would make it possible to allow their decay into baryons and mesons. Single quarks could then be produced as heavy unstable baryonic states forming SU(3) triplets. Our considerations of subsection 3.5 could again apply, leading us to expect at least partial confinement, but the search for free quarks would be totally different. It would be the search for a triplet of baryonic resonances rather than for stable states of fractional charge. In this connection, it is interesting that astrophysical arguments have recently been advanced in favor of integer charge quarks.[30]

This reference to astrophysics leads us to our closing remark. With the authors of Ref. 30, we note that if present views on quarks and gluons are correct, they have important consequences for the early phases of the evolution of the Universe under the "hot big bang" theory. This theory says that when the age of the Universe was in the range $t \simeq 10^{-10}$ to 10^{-8} sec, the temperature was $T \simeq (Gt^2)^{-1/4} \simeq 100$ to 10 GeV ($G = 6 \times 10^{-39}$ GeV^{-2} = Newton's gravitational constant) and the density (proportional to T^4) was $\simeq 10^{27}$ to $10^{23} g\,cm^{-3}$, i.e. much larger than the nuclear density of $2.8\times10^{14} g\,cm^{-3}$. Under the quark-gluon model, hadrons would not be expected to exist at such densities, one would rather expect matter to be a hot fluid composed of quarks, antiquarks and gluons with a large number of quarks and antiquarks per cubic Fermi (10^{-39} cm^3). As this early Universe expands, a transition should take place to a phase dominated by baryons, i.e. by 3-quark systems, and the modalities of this transition may be of importance for the well known but difficult questions of finding satisfactory explanations for the formation of galaxies and for matter-antimatter separation. We therefore conclude that the dynamics of quarks and gluons may eventually turn out to matter not only for particle physics, but also for a better understanding of the early evolution and present state of the Universe.

[1]The first observations of neutrino events attributed to the neutral-current weak interaction, performed in the Gargamelle bubble chamber at CERN, were published in F. J. Hasert *et al.*, Phys. Lett. **46B**, 121 and 138 (1973).

[2]We refer to deep inelastic scattering of electrons, muons, neutrinos and antineutrinos by nucleons and nuclei. Surveys can be found in the Proceedings of recent International Conferences on High Energy Physics (in particular the 18th Conference at Tbilisi, USSR, July 1976) and International Symposia on Lepton and Photon Interactions at High Energies (in particular the 1975 Symposium at Stanford, August, 1976).

[3]For surveys see Conference Proceedings in Ref. 2.

[4]The success story of charm began with the discovery at Brookhaven and SLAC of the J/ψ meson of mass 3.1 GeV (quark composition $c\bar{c}$). The original publications are J. J. Aubert *et al.*, Phys. Rev. Lett. 33, 1404 (1974) and J. E. Augustin *et al.*, Phys. Rev. Lett. **33**, 1406 (1974). The first charmed mesons were found at SLAC less than two years later, see G. Goldhaber *et al.*, Phys. Rev. Lett. **37**, 255 (1976).

[5]S. L. Glashow, J. Iliopoulos and L. Maiani, Phys. Rev. **D2**, 1285 (1970).

[6]There is now strong evidence from e^+e^- annihilation experiments for the existence of a new charged lepton of mass 1.9 GeV. It is denoted by $\tau^\pm$. It was first found at SLAC in 1975, see M. L. Perl *et al.*, Phys. Rev. Lett. **35**, 1489 (1975) and **38**, 117 (1976).

[7]In June 1977, a strong enhancement was found at 9.5 GeV in the mass spectrum of $\mu^+\mu^-$ pairs produced in 400 GeV proton-nucleus collisions, see S. W. Herb *et al.*, Phys. Rev. Lett. **39**, 252 (1977). It is believed that it probably consists of two or more very narrow lines which could be interpreted as bound states of a fifth quark and its antiquark (just as the J/ψ meson is a bound state of a charmed quark and its antiquark).

[8]A number of heavy but narrow mesons decaying preferably in baryon-antibaryon pairs have recently been discovered, most of them at CERN. The heaviest one found so far has a mass of 2.95 MeV and a width consistent with the experimental resolution of 20 MeV, see C. Evangelista *et al.*, contribution to the European Conference on Particle Physics, Budapest, July 1977.

[9]See e.g. P. Darriulat's rapporteur talk at the 18th International Conference on High Energy Physics, Tbilisi, July 1976, Proceedings A4-23.

[10]This theory concerned the isospin group SU(2). The classic paper is C. N. Yang and R. C. Mills, Phys. Rev. **96**, 191 (1954).

[11]This mass generating mechanism goes under the name of Higgs mechanism, although it was introduced independently in 1964 by P. W. Higgs and a number of other authors. The mechanism implies the existence of new massive particles called Higgs bosons, not yet discovered experimentally.

[12]The proof of renormalizability was given in the work of G. 't Hooft (1971), and of G. 't Hooft and M. Veltman, B. W. Lee and J. Zinn-Justin (1972).

[13]This was found independently by G. 't Hooft, D. Gross and F. Wilczek, and H. D. Politzer (1973).

[14]The most attractive model for such a unified theory is the one proposed by S. Weinberg (Phys. Rev. Lett. **19**, 1264 (1967) and A. Salam (in Proceedings of 8th Nobel Symposium, Almqvist and Wiksells, Stockholm (1968), as modified by S. L. Glashow *et al.* (Ref. 5) to eliminate strangeness-conserving weak neutral currents and to include the charmed quark.

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