DEUTSCHES ELEKTRONEN-SYNCHROTRON DESY

DESY 67/19
Juni 1967

Quark Model and High Energy Production Processes

by

H. Satz
Deutsches Elektronen-Synchrotron DESY,
Hamburg

2 HAMBURG 52 · NOTKESTIEG 1

Quark Model and High Energy Production Processes

H. Satz, Deutsches Elektronen-Synchrotron (DESY)

Summary: The additivity assumption for quark constituents in hadronic reactions is applied to high energy production processes. It is shown that this assumption together with a statistical model for quark-quark production reactions leads to a simple picture which successfully describes the essential aspects of non-annihilation production reactions.

The quark model[1], with the additional assumption[2,3] that the scattering amplitude $T(s,t)$ of an elastic hadronic reaction for large s and small t is simply the sum of the individual two-body scattering amplitudes of the constituent quarks, has recently led to a number of interesting relations for high energy total and diffraction cross-sections. It was shown, however, that the experimental agreement with the thus obtained sum-rules for the case where baryon-antibaryon scattering is involved can be considerably improved if the additivity assumption is made only for the non-annihilation part of the total cross-section[4]. This seems to us an indication that perhaps one should consider an additive quark picture for certain classes of inelastic processes (no baryon-number exchange) rather than for the elastic scattering amplitude.

The aim of this note is to pursue such a line of thought further; for simplicity we shall here consider only pions, nucleons, and antinucleons. For production reactions the additive quark picture turns out to lead to predictions of a rather dynamical nature which so far agree quite well with the experimental situation and which can be subjected to further experimental tests.

Consider then, as an example, the pion-proton reaction

$$\pi^- P \longrightarrow P\, 2\pi^- \pi^+ \pi^0 \qquad (1)$$

To maintain as simple as possible a picture, we neglect any resonance effects. Denoting the basic quark-antiquark triplets with (p,n,λ), $(\bar{p},\bar{n},\bar{\lambda})$, we have the quark contents $P=(ppn)$, $\pi^+=(p\bar{n})$, $\pi^-=(\bar{p}n)$, $\pi^0=(p\bar{p}-n\bar{n})/\sqrt{2}$. Our assumption will be that at high energy the amplitude for a pion-proton reaction consists of the sum of terms corresponding to collisions between one (virtual) quark in the proton and one in the pion, this collision leading to the creation of a number of quarks and antiquarks, with conservation of additive quantum numbers. Two of the emitted quarks recombine with the "spectator" quarks to form again a proton and a pion, while the other produced quarks "arrange" themselves into some allowed hadronic final state (see fig. 1). The situation in the case of proton-proton or non-annihilation proton-antiproton reactions is quite analogous.

Denoting the energy- and momentum-transfer between initial and final proton (pion) by $w_1, t_1 (w_2, t_2)$, we have, corresponding to fig. 1, a contribution of the form

$$f_i^P (t_1, w_1)\ f_j^\pi (t_2, w_2)\ T(q_i q_j \longrightarrow q_i q_j\ \pi^+ \pi^- \pi^0) \qquad (2)$$

to the amplitude for (1). Here $f_i^P(t_1, w_1)$ is determined by the wave-function of the i-th (bound) quark inside the proton, and $f_j^\pi(t_2, w_2)$ similarly for the pion; the collision amplitude for the (virtual) quarks is denoted by $T(q_i q_j \rightarrow q_i q_j \pi^+ \pi^- \pi^0)$, where we have already written the excess quarks in recombined form. Note that this picture includes as well the coupling of quarks different from the initial ones with the "spectators", leading to reactions as illustrated in fig. 2, where the spectator of the pion recombines such as to form a π^0 instead of the initial π^-. (figures 1 and 2 correspond respectively to an exchange of no charge and of charge one at the lower vertex).

Let us now study some of the consequences of the additivity assumption for inelastic reactions. One immediate result is the concept of "leading particles": since only one of the quarks in each of the collision partners interacts, an equidistribution of CMS energy among the incident quarks implies that the two final particles arising by recombination of spectators with two produced quarks will carry much more energy than any particles created in the quark-quark collision. A high energy hadron-hadron collision thus yields two (or including resonances, perhaps three or four) fast particles plus an ever increasing number of "slow" ones. It is easy to see that because of additive quantum numbers these leading particles can differ from the incident ones only by a charge difference $\Delta Q = \pm 1$ (similarly also for strangeness); e.g. in π^- - P interaction the leading pion is either a π^- or a π^0 (in the general case, resonances such as ρ^- and ρ^0 are also possible). This occurrence of leading particles, here quite naturally a consequence of the additivity assumption, has been the main source of difficulty in statistical model descriptions of non-annihilation high energy collisions[5,6], which in contradiction to experiment yield an asymptotic inelasticity (the fraction of available kinetic energy going into particle production) of unity. The maximum value of the inelasticity K in our model is reached if both of the quarks which recombine with the spectators have negligible kinetic energy compared to that of the system of produced quarks, i.e., if essentially no energy is taken back to the spectators. We thus have

$$K^{\max}_{\pi P} = 5/12 \qquad K^{\max}_{PP} = 1/3 \qquad (3)$$

for pion-proton and proton-proton collisions, respectively. As the CMS energy $W \longrightarrow \infty$, with a statistical picture applied to the quark-quark production process, the energy of the produced quarks increases with $W^{1/2}$, while the spectator quarks each retain W/2 or W/3 (pions or protons); hence in the asymptotic limit the above values of $K^{\max}$ are actually attained:

$$K = K^{\max}(1 - \text{const.}/W^{1/2}) \quad \text{as } W \longrightarrow \infty \qquad (4)$$

The average experimental value[5)] from cosmic ray data (essentially PP collisions) is $\sim 1/3$.

The observed average multiplicity $\overline{N}$ as a function of the CMS energy W increases roughly as $AW^{1/2}$, with constant A, in accord with the statistical model. Experimentally, however, the coefficients A in PP processes and A' in $P\overline{P}$ annihilation reactions differ, since in annihilation there are no leading particles and thus the entire energy is available for production. For the same reason the statistical model in its original version is quite applicable for pure annihilation. Applying the statistical picture in non-annihilation (here PP collisions) only to the quark-quark interaction, we obtain as high energy limit

$$\overline{N}^{\text{annih.}}_{PP}/\overline{N}_{PP} = W^{1/2}/(W/3)^{1/2} = \sqrt{3} = 1.7 \qquad (5)$$

and similarly $\overline{N}^{\text{annih.}}_{PP}/\overline{N}_{\pi P} = 1.6$. The experimental value of this ratio is roughly 1.5, both for pions and for protons as incident particles[7)].

A statistical picture for the quark-quark reaction moreover leads (simply by combination probabilities) to a higher yield of pions than of proton-antiproton pairs[8)], as in fact observed.

We note further that the above mentioned selection rules for leading particles predict different energy spectra for π^+ and π^0 in reaction (1), but similar ones for π^- and π^0. An experimental test of this result (although perhaps somewhat difficult because π^0-neutron separation problems and resonance effects) would be of great interest.

In view of the rather promising results of our considerations, we propose the following simple framework for high energy inelastic collisions: non-annihilation production is described by an additive quark picture as discussed, with a statistical model for the quark-quark (and for the quark-antiquark) production reaction occurring therein.

The "form factors" $f_i^x(t,w)$ we take as independent of quark and particle indices i and x, i.e. we assume similar wave-functions for all (non-strange) quarks both in pions and nucleons. The transition probability of (1) we consider to be the incoherent sum of the individual quark-quark contributions possible, i.e. we take the relative phases between the various contributing amplitudes to be random. Finally we would take the amplitude $T(q_i q_j \rightarrow q_i, q_j, X)$ to be independent of quark indices and final state charge configuration of X, provided the isospins (Clebsch-Gordan coefficients) are properly taken into account.

Besides the already discussed consequences such a picture yields many more predictions. The pion-proton differential cross-section e.g.for reaction (1) is given by

$$\partial^5\sigma/\partial t_1 \partial t_2 \partial w_1 \partial w_2 \partial M \sim |f(t_1,w_1)|^2 |f(t_2,w_2)|^2 \Omega_3(M) \qquad (6)$$

where $\Omega_3(M)$ is the three-particle phase space for fixed mass M of the three non-leading pions. Moreover the momentum transfer distribution $\partial\sigma/\partial t$ for the proton and for the leading pion should be the same. Experimental data on these questions are presently becoming available and in fact support our predictions[9].

The model further gives rise to the "global" asymptotic sum rule

$$\sigma_{in}^{\pi P} = 2/3\ \sigma_{in}^{PP} \qquad (7)$$

which is well satisfied, as one would expect from the experimental agreement with the corresponding sum rule for total cross-sections[10], together with the diffraction results. Finally the model implies sum rules relating specific (fixed particle number) $\pi^{\pm}$-nucleon, nucleon-nucleon, and non-annihilation nucleon-antinucleon production cross-sections; e.g., relations between (1) and the corresponding nucleon or antinucleon induced reaction, etc. Their derivation and test will however be discussed separately.

In conclusion we find that a quark model for inelastic reactions, coupled with statistical considerations, leads to a picture for non-annihilation production processes which contains the essential aspects of these reactions and which moreover leads to some previously not obtainable numerical predictions in good agreement with experimental data. - As in previous applications[2,3],we have here simply assumed the additivity of the constituent quark reactions; the justification for such an assumption unfortunately remains an open question. However, we find its success in various aspects of hadronic reactions to be a strong indication of more than mere coincidence.

Literature

1) M. Gell-Mann, Phys. Lett. 8 (1964) 175
G. Zweig, CERN Reports Th 401, 412 (1964)

2) E. M. Levin and L. L. Frankfurt, JETP Lett. 2 (1965) 65 (Engl. Transl.)
H. J. Lipkin and F. Scheck, Phys. Rev. Lett. 16 (1966) 71

3) J. J. J. Kokkedee and L. Van Hove, Nuovo Cimento 42 (1966) 711

4) J. J. J. Kokkedee and L. Van Hove, CERN Report Th 738 (1967)

5) See e.g. S. Hayakawa in Trieste Seminar 1962 Proceedings, p. 521

6) For a general discussion see H. Satz, Preprint Hamburg 1967: Über die statistische Beschreibung hochenergetischer Vielteilchenerzeugungsreaktionen.

7) V. S. Barashenkov et al., Fortschr. d. Physik 14 (1966)

8) Z. Koba, Phys. Lett 16 (1965) 326

9) G. Drews and H. Nagel (Genova-Hamburg-Milano-Saclay Collaboration on 11 GeV/c π^-), private communication; also R. Sosnowski, report at CERN High Multiplicity Bubble Chamber Events Meeting, April 1967

10) L. Van Hove, Proceedings of the Stony Brook Conference, 1966

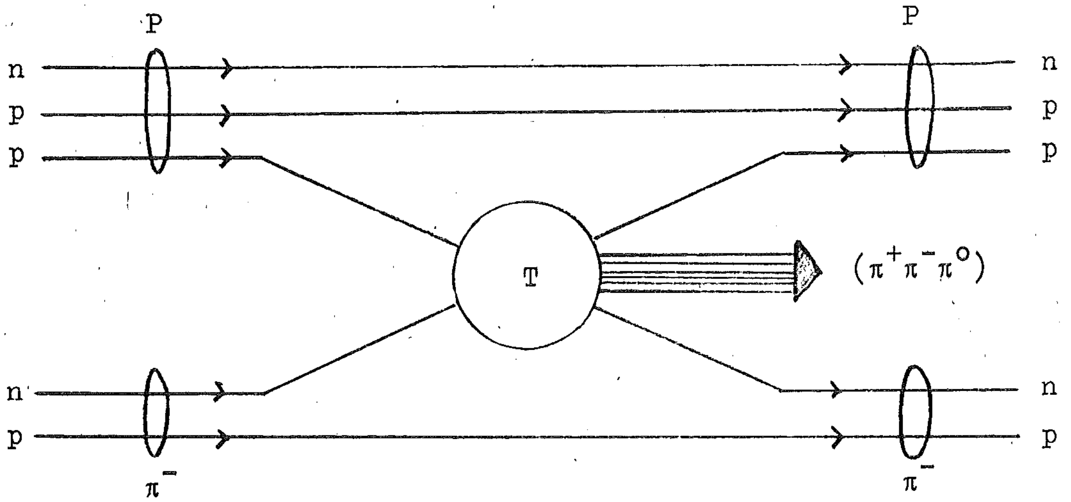

Figure 1

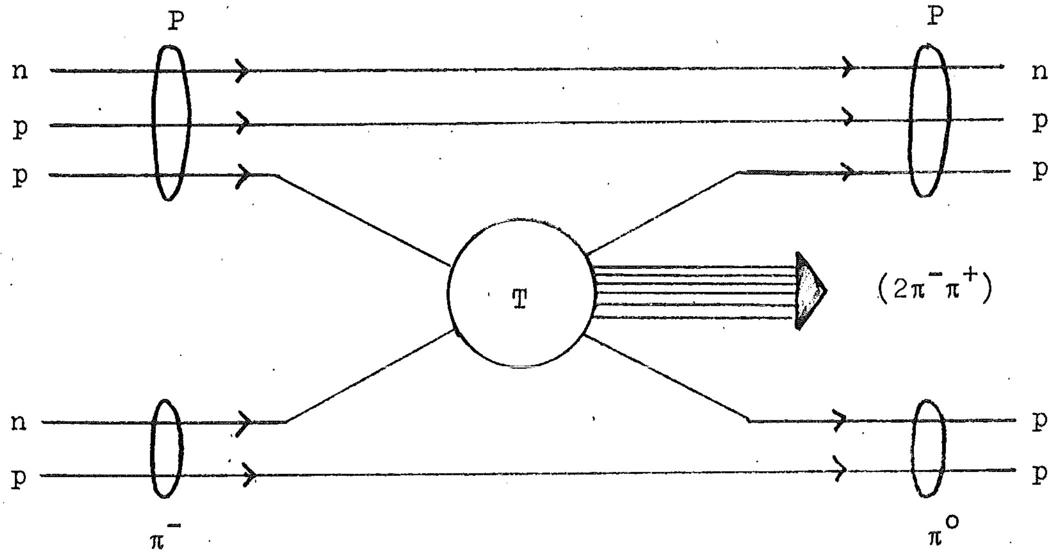

Figure 2