A CRITICAL ANALYSIS OF THE QUARK STATUS

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SUMMARY

A world analysis of the experiments to search for quarks shows that the general belief that quarks do not exist is not based on such good experimental grounds. For example, the extensive searches so far performed in strong interactions are limited to small p_T values; the electromagnetic case is even worse, while quarks production in weak interactions is at present an unexplored field. Intuitive arguments on a plausible proton breaking mechanism are presented in order to emphasize the serious limitations of the experiments performed so far, and to stimulate further searches in the right direction.

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The basic motivation of the "confinement" theories is the well-known fact that quarks have been reported not to exist up to masses as high as 10 GeV and even higher¹⁾. Purpose of this paper is: to point out that an analysis of the quark experiments performed so far shows that all these searches have a common serious bias; to propose an intuitive model of the proton breaking mechanism which could explain why quarks have not been observed in past experiments; and to suggest further investigations.

So far, quark searches have been carried out extensively in strong interactions¹⁾; a few experiments²⁾ have been performed using electromagnetic probes, but an analysis of all these experiments shows that the transverse momentum of the searched quark has always been very limited³⁾. The results of this analysis are reported in Fig. 1. Here all published experiments with magnetic analysis, i.e. those where it was possible to measure the transverse momentum (p_T) of the produced particles, are reported. Sixteen experiments have been performed with $p_T \leq 0.1$ GeV/c and 22 with $p_T \geq 0.1$ GeV/c, but out of the 38 experimental searches none was sensitive to transverse momenta above 1 GeV/c. In experiments with 0° beams without magnetic analysis, the geometric acceptance of the apparatus places a p_T limit of ≤ 1 GeV/c.

So, if in order to break a proton it was necessary to give to one of its constituents a transverse momentum greater than 1 GeV/c, the above-quoted experiments would lose their significance. One experiment not included in this list is that of Fabjan et al.⁴⁾, because no magnetic analysis was available in this search. However, these authors⁴⁾ state that their experiment was sensitive to the highest possible value of p_T of the produced quark (for example as high as 20 GeV/c) because the set-up was placed at 90° in the (pp) c.m.s. and the total energy ranged from $\sqrt{s} = \sqrt{2080}$ GeV to $\sqrt{s} = \sqrt{3844}$ GeV. On the other hand, these results are also presented in terms of the ratio ϕ , flux of quarks over flux of π 's, which is reported to be of the order of 10^{-9} . In order to clarify the relevance of this experiment in the general belief that quarks do not exist, it should be pointed out that the value of 10^{-9} for ϕ , applies to p_T values below 1 GeV/c, while the sensitivity of this experiment to $p_T \approx 20$ GeV/c would correspond to the above ratio ϕ , worsened by at least ten orders of magnitude.

As is well known, since many years indirect experimental evidence [deep inelastic scattering effects and SU(3) multiplets] support the idea that the proton is made of super-elementary point-like objects. Fractional^{5,6)} or integral⁷⁾ values have been proposed for their charge states. Their mass should be as low as a few hundred MeV⁸⁾, but they have never been observed; as mentioned above, impressive mass limits above the 10 GeV level have been published¹⁾. The conventional way out of this puzzle is either to say that the "quarks" are mathematical entities^{9,10)}

deprived of physical meaning, or that quarks indeed exist and make-up hadrons; but they are, for example, bound by forces which increase with distance, i.e. they are confined¹¹⁾ inside the particles of which they are the basic constituents.

We wish to propose a completely different point of view, based on the known basic features of strong, electromagnetic, and weak interactions, and on an intuitive model of the proton "breaking" mechanism, which we believe is very plausible on physical grounds. If this model is accepted, the conclusion is that searches for quarks so far have not been made in the right experiments.

It is well known that strong interactions are "strong" but very "soft". Electromagnetic interactions are weaker but harder. Weak interactions are the hardest we know. Nevertheless, all previous attempts to break the proton have been mainly concentrated in the field of strong interactions. Figure 2 shows the present limits on quark production in strong interactions at CERN ISR^{4,12)}.

The highest value of c.m. energy so far investigated is $\sqrt{s} = 62.2$ GeV. At this energy the observation of one event¹²⁾ with $Q = +(1/3)e$, provides with 90% confidence level the following upper limit on the flux of quarks compared with the flux of pions:

$$\frac{\phi_Q = +(1/3)e}{\phi_{\pi^\pm}} \leq 1.78 \times 10^{-9} .$$

Notice that the enormous amount of total energy, 62.2 GeV, available in the (pp) c.m. system, is associated with the complex of hadronic cloud and point-like constituents which make up the proton. In the (pp) collision the total energy available to each single component of the proton complex is obviously very much smaller than 62.2 GeV.

The same difficulty exists for high transverse momentum phenomena induced by hadronic probes.

From an intuitive point of view it is perfectly plausible that, in order to break the proton, a high p_T should be given to one of its constituents, at once in a single action as illustrated in Fig. 3.

If the interaction between the two quarks is of a hadronic nature, the large p_T value could be the result of many small p_T^i , with $p_T = \sum_i p_T^i$, and $p_T^i \ll p_T$, as illustrated in Fig. 4. In a proton-proton collision, with a high transverse momentum proton observed in the final state, it is not clear so far on what firm basis it would be possible to conclude that the single exchange process of Fig. 3 is responsible for the observed high p_T proton and not the multiple one illustrated in Fig. 4, or even the more complicated one of Fig. 5, where the many p_T^i 's are exchanged between different quark lines. Each p_T^i may never be sufficient to break a proton; thus after the series of p_T^i exchanges, the final state is again a bound system of

quarks and hadronic cloud, and the emerging proton shows a large $p_T = \sum_i p_T^i$. This is obviously not restricted to the proton case. Quite generally, if in a hadron-hadron collision we observe a high p_T particle, either a pion or a proton or a hadron of any sort, the transverse momentum carried out by the observed particle is by no means sure to be the result of a single high p_T transfer process; rather it is likely to be the result of many small p_T^i exchanges, building up a high p_T process.

A good evidence that a high p_T can be transferred in a single action (Fig. 3) between two quarks of two protons would be a jet-structure in purely hadronic collisions. This jet-structure has so far not been clearly established in terms of a single transfer process being responsible for the observed "jet-like event"¹³⁾. On the other hand, quarks have neither been searched for so far in jet-like events, nor in high p_T events³⁾. But even if this were the case, there would still be the problem of being sure that these events correspond to a high p_T single transfer process between the super-elementary constituents of the two interacting hadrons (Fig. 3). In fact, once again we should emphasize that strong interactions are strong but very "soft". Therefore the observation of a high p_T event produced in hadronic interactions does not imply that the high value of p_T observed is associated with a single exchange process.

For this to be true, a "hard" probe is essential. Electromagnetic and weak interactions provide hard probes. A high p_T process produced by a weak probe is sure to be associated with a single momentum transfer, multiple exchanges being excluded by the values of the coupling constants. Figures 6 and 7 illustrate the case of a weak-boson exchange; the same qualitative features are expected if instead of a weak boson, a photon is exchanged between two quarks. In the field of electromagnetic interactions, evidence for jet-like structure has been reported at SPEAR in (e^+e^-) annihilations¹⁴⁾, but no quark search has so far been performed in these jet-like events.

Efficient probes for penetrating the hadronic cloud, without being q^2 -degraded, are the non-strong ones. The weak boson is certainly the best we know today. Thus a basic process of proton-breaking could be via a W-exchange mechanism, as illustrated in Fig. 6. Another way to provide a point-like constituent of a hadron with a large p_T , is via a direct neutrino-quark contact point-like interaction, as shown in Fig. 8. The neutrino is certainly a very efficient probe for penetrating the hadronic cloud of a proton without being q^2 -degraded. A very good way of breaking the proton would thus be via high-energy neutrino interactions. These arguments can obviously be extended to the domain of electromagnetic interactions, with a point-like lepton-quark coupling, or with a single hard photon exchange. Evidence for single hard photon exchange between the electron and a quark are the well-known deep inelastic phenomena. But no quark search has been made in association with deep inelastic effects at SLAC.

As mentioned above, so far quark searches have been carried out extensively only in strong interactions; but the search for quarks in the "hard" component of these interactions (high p_T and jet-like events) is many orders of magnitude less sensitive than the soft part, which is the only one investigated. The search in electromagnetic interactions provides much lower values of the quark mass limit and refers to an even lower value of the transverse momentum; here again no quark searches have been made in association with the observed jet and deep inelastic events.

Quark production in neutrino interactions is an as yet unexplored field.

If the reason for quark absence so far is not "absolute confinement" but the nature of the proton breaking mechanism, which would require a big bang to be given to one of the super elementary constituents, then the quark limits in all previous experiments lose their significance.

We would like our proposal to be put to experimental test, with an intensive search for quarks in high-energy neutrino interactions¹⁵⁾, in electromagnetic interactions, and also in the "hard" tails of the strong interactions.

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Figure captions

- Fig. 1 : Showing the values of p_T for published experiments carried out at well-defined p_T values. Note that 16 measurements have been made at $p_T = 0.1$ GeV/c and none above $p_T = 1$ GeV/c.
- Fig. 2 : Summary of the limits for the ratio flux of quarks over flux of pions, relative to ISR experiments: full points refer to Ref. 4, open circles refer to Ref. 12.
- Fig. 3 : Feynman diagram illustrating the exchange of a large p_T between two quarks.
- Fig. 4 : Feynman diagram illustrating a series of small p_T^i exchanges between two quarks. The p_T^i is never sufficient to break the proton. Thus, after the series of p_T^i , the final state is again a bound system of quarks and hadronic cloud, and the emerging proton shows a large $p_T = \sum p_T^i$.
- Fig. 5 : Feynman diagram illustrating a large p_T hadronic process as result of the exchange of many p_T^i between different quark lines.
- Fig. 6 : Feynman diagram illustrating the interaction between a lepton and a quark via an intermediate weak boson. All p_T is transferred in this process in a single action.
- Fig. 7 : Feynman diagram illustrating multiple exchanges between a lepton and a quark, via an intermediate weak-boson. Each W-line causes a depression factor. Thus the splitting of p_T is very unlikely when a weak coupling is involved.
- Fig. 8 : Feynman diagram illustrating a direct neutrino-quark contact point-like coupling.

Fig. 1

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