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IS IT INDEED IMPOSSIBLE TO FIND QUARKS?

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I. Introduction

During the last ten years, revolutionary changes have taken place in the physics of strong interactions, owing to the discovery of a vast number of short-lived and strongly interacting particles - the so-called resonances. It was established that all strongly interacting particles can be grouped into families - unitary supermultiplets, each of which consists of one or several isotopic multiplets. In order to explain the structure of the supermultiplet Gell-Mann and Zweig proposed /1/ that there was a fundamental triad of p , n and λ -quarks, particles with a fractional electrical and baryon charge, from which are built an entire range of strongly interacting particles, in such a manner that baryons are composed of three quarks and mesons from a quark and anti-quark. In accordance with the laws of conservation of the electrical and baryon charges, at least one, the lightest quark, should be stable.

As for the mass of quarks, it is difficult to make any definite predictions. Several years ago, non-relativistic quark models became very popular, and a large number of interesting theoretical results were obtained by means of these. In these models, the quarks have a very great mass ($\gtrsim$ 3-5 GeV, and, possibly, even greater than 10 GeV). Strongly interacting particles are linked quark states, the link being formed by a deep potential well having a radius R. For the quarks, the conditions of the non-relativistic approximation $P/M_Q \simeq \frac{1}{M_Q R} \ll 1$ are fulfilled. Non-relativistic quark models have made it possible to explain numerous properties of hadrons, and to predict a great number of relationships between the cross-sections of reactions at high energies. The questions examined here are discussed in detail in /2-9/ , where reference is made to other papers.

Apart from the models with heavy non-relativistic quarks, proposals have been made on a number of occasions to the effect that the mass of quarks is small - less than the mass of the nucleon (see, for example /10/). Interest in such models has particularly grown during recent years in connection with experiments involving the inelastic scattering of leptons on hadrons in deeply inelastic region /11/ . In order to interpret these experiments, Feynman proposed a new model describing the structure of hadrons on the basis of a proposal to the effect that they contained several point-like non-structural objects - partons /12/. Real attempts were made to identify these partons with quarks /13 - 15/ . These attempts are of particular interest in the light of the results of the latest experiments with the antineutrino, which point toward the fractional charge of partons /18/. A detailed description of the parton model is given in a number of reviews /16 - 18/ .

If it is considered that partons are quarks with small masses, the question first arises as to why these quarks were not observed hitherto in the great many experiments. There is no satisfactory answer to this question. A very typical exposition of the situation is that given by R. Feynman /15/ : "My quarks have small masses, and they do not fly out of the nucleons owing to certain reasons which I will be able to tell you about in 25 years' time, approximately. The masses of the quarks which I need, are so small that without the slightest doubt, we ought to be able to observe them. Thus, it is possible that all of this is nonsense, and the experiment will very soon show the truth. If the entire conception is correct, then it is very, very exciting, since we have a paradox, and finding a paradox is the hope of physics. This is the true way of bringing about a revolution".

In this situation, we wish to make a critical analysis of the experiments in which a search was made for particles with a fractional charge, from the standpoint of the possible existence of light quarks, which might be retained in nucleons by certain completely unusual forces of the barrier type, and would require large momentum transfers in order to be ejected from the nucleons.*) One should not be surprised at the unusual or rather unlikely

*) The possibility that many unusual processes take place in the region of large momentum transfers has been discussed on a number of occasions in the literature (see, e.g. /19-21).

nature of such proposals, since the whole situation is paradoxical. In our opinion, it is now necessary to examine all possible new experimental ways of finding quarks which have not been covered in earlier experiments.

II. Short Review of the Results of Quark Searches

When the Gell-Mann/Zweig hypothesis was put forward concerning the existence of quarks, a large number of experiments were performed to find them. Below, we list the main results of these experiments (a more complete review of the data is given in[9]).

1. The Search for quarks in accelerators

In not one of the many experiments in accelerators [22-29] were any quarks found. Table 1 shows the upper limits of the differential cross-sections of quark formation, or the upper limits for their fluxes (in relation to the fluxes of normal particles), directly as found in the experiments. From this, it is possible to make certain estimates for the upper limits of the quark production total cross-sections. These estimates depend, however, on the generation model for these particles. Figure 1 shows the upper limits for the total cross-sections obtained in the phase-space model (the angular distribution of the particles produced is isotropic in the centre-of-mass system, whilst their momentum spectrum corresponds to the Lorentz-invariant phase volume).

2. The Search for Quarks in Cosmic Rays

The search for quarks in cosmic rays was marked by dramatic moments when individual groups considered that they had succeeded in finding particles with fractional charges. However, the results of the subsequent more accurate measurements showed that these effects did not exist. In this way, when experiments were carried out with cosmic rays no quarks were observed. The data obtained from a number of experiments provided the following values for the upper limits for the possible fluxes of single quarks in the atmosphere at a depth D: $I\ (0°)_{90\%,\ q\ =\ 1/3} = 0.8 \times 10^{-10} cm^{-2} ster^{-1} sec^{-1}$ ($D = 740\ g/cm^2$) ; $I\ (0°)_{90\%,\ q\ =\ 2/3} = 1.6 \times 10^{-10} cm^{-2} ster^{-1} sec^{-1}$ ($D = 750\ g/cm^2$) /30,31/. From this, it is possible to obtain the upper limits for the possible quark production cross-sections using various assumptions concerning their absorption in the atmosphere, or the dependence of the quark production cross-section having a specific mass M_Q on the energy of the primary protons. The results of these estimates /9,32/, for a quark mass $M_Q = 1$ GeV are between 10^{-31} and 10^{-34} cm^2 , for $M_Q = 5$ GeV : between 10^{-30} and 10^{-33} cm^2 and for $M_Q = 10$ GeV: between 10^{-29} and 10^{-32} cm^2 .

3. The Physico-chemical search for quarks

If stable particles with a fractional charge existed, then they should have been generated continuously in the atmosphere by cosmic radiation, been decelerated to thermal velocities and accumulated in the matter around us during the whole period of the Earth's existence (1.5×10^{17} seconds).

Let us assume that the entire flux of these particles created in the atmosphere, and falling upon 1 cm^2 of the Earth's atmosphere, is stopped in several tens of nuclear interaction lengths ($2 - 4 \times 10^3\ g/cm^2$). Then, for a quark flux $I_Q\ (0°) = 2 \times 10^{-11}$ particles $cm^{-2}\ sec^{-2}\ ster^{-2}$ the equilibrium concentration of these particles should be 10^{-20} quarks/nucleon. In fact, thanks to mixing, and a number of other factors, the expected concentration should, in the majority of materials, be significantly lower /33,34/: in sea water - 10^{-29} to 10^{-21}; in atmospheric dust - 10^{-25} to 10^{-22}; in hard rock - 10^{-25} to 10^{-21}; in meteorites - 10^{-20} quark/nucleon *). The results of the experiments in which a search

*) It was pointed out that because of the effect of the Earth's electric field, the quark storage time in water and, possibly, air is reduced to about a year. If this is so, the expected concentration of quarks in these materials is further reduced by 10^9 times (see, for example, /35/).

was made for small admixtures of quarks in the surrounding material, are set out in Table 2. In these experiments the quarks were not discovered, and upper limits were determined for their possible concentrations.

It should be pointed out that the results of papers /35,36 and 40/, as well as the data for water in paper /38/, are based on the methods for enriching matter with quarks, and are valid only for certain assumptions. There is considerable doubt /43/, also, about the reliability of the estimates made in /39/. Consequently, the search for quarks in the surrounding matter does not, as will be seen from Table 2, impose any new limitations on the value of the quark production cross-section compared with the direct data obtained in cosmic radiation.

III Possible methods of searching for quark production in hadron processes with large momentum transfers

If quarks have small masses ($\not< M_p$) and are linked together with certain very strong interactions of the barrier type, it seems natural to try to discover them in processes with large momentum transfers, i.e. "to knock out" the quarks from the range of action of these constraining barrier forces.

In this case, if quarks are produced in hadron-hadron interactions, then we should be concerned with very large transverse momenta. In effect, the transverse and longitudinal momentum transfers in strong interactions differ very strongly from each other, and it is only when the transverse momentum transfer increases that we begin to study the deeper spatial regions of the hadrons. When the momentum is transferred in a longitudinal direction, the quark may not fly out of the region where other quarks are in motion, i.e. it is not formed in a free state.

If we consider, from this viewpoint, all of the experiments on accelerators (except for experiments /29/ on colliding beams), we note that they were aimed at finding quarks which fly out at small angles and with low momentum transfers. In this way, these experiments, in spite of the very low upper limits for the quark production differential cross-sections obtained in them, and particularly in papers [27 and 28], may prove to be completely insensitive to the mechanism we are considering for quark production in processes with large transverse momenta.

On the other hand, a search for quarks was carried out in colliding proton beam experiments [29] in various conditions, including conditions involving large transverse momenta. These experiments are, however, characterized by a much lower sensitivity than those carried out on the usual type of accelerator.

In experiments to find quarks in cosmic radiation, it has also been possible to record particles with a fractional charge and being produced with large transverse momenta. Indeed, such particles separate, with a higher probability, from the shower core in which they may have been produced. Consequently, as far as these are concerned, it is not so important to study the shower tracking of the quark by the usual particles, which may have rendered the apparatus used for experiments [30 and 31] insensitive to the recording of particles with a fractional charge. For small quark masses, the results of cosmic experiments provide the limitations on the production cross-section of these particles, which are comparable to the data obtained with colliding proton beams, (see Figure 1).

The possibility of obtaining, in strong interactions, large transverse momentum transfers deserves separate examination. Views have been expressed that the cross-sections of processes with large transverse momenta caused by a strong interaction, fall as a function of exp $(-bP_{\perp}{}^{2})$ where $b \approx 3 - 4\ (\mathrm{GeV/c})^{-2}$ and that when $P_{\perp} > 3$ GeV/c a fundamental part is played by electromagnetic processes which gradually diminish as P grows, but not exponentially. [44 and 45].

The latest result [46] obtained in colliding proton rings indicate that at large energies the production of particles is observed with large transverse momenta with cross-sections which, apparently, exceed the electromagnetic cross-sections by two orders of magnitude. If this is so, then the processes of strong interaction may be an effective source for quark production in reactions with large transverse momenta. Similar experiments should, therefore, be carried out with an extremely high sensitivity. Let us examine several possible lines of research.

1. Colliding Beam Tests

The luminosity of the CERN proton rings is about 10^{30} cm^2/sec. This means that if the apparatus has a solid angle of about 1 steradian, over 500 hours of measurement it is possible to reach the top limits for the total quark production cross-section (1.5 - 3) $\times 10^{-35} cm^2$, i.e. to advance by roughly three orders of magnitude in comparison with the result already achieved on colliding beams /29/.

2. Further experiments in cosmic radiation

Further experiments in cosmic radiation can enable existing limits to be reduced, but not more than by a few times.

3. Physico-chemical experiments

It would appear that physico-chemical research offers good prospects if it enables reliable limits to be attained for quark concentrations at a level of 10^{-25} - 10^{-27} quark/nucleon in various elements, and, above all, in mountain rock.

4. Experiments on conventional accelerators

In these experiments, it is not possible to attain such large values for momentum transfers as in colliding beam experiments, but in the region of accessible transverse momenta it is possible to advance to substantially lower limits as regards the quark production cross-sections. We shall give summary estimates for the sensitivity of similar experiments when applied to two variants of experiments on the 70 GeV accelerator at IHEP- on an inner proton beam and on an ajected beam of π^--mesons with momenta of about 40 - 50 GeV/c.

In experiments with an internal target irradiated by a proton beam, the search for quarks may be made in a special channel of secondary particles corresponding to a large angle of emergence and a large transverse momentum. In this case, in order to increase the relative aperture of the experiment, the channel must let a wide range of particles pass through. The relative aperture of the channel $\Delta\Omega \cdot \Delta P_Q$ may attain a value of $\sim$ 250 - 500 microsterad x GeV/c. Over a period of 500 hours of measurement at an internal beam intensity of 10^{12} p/cycles and a target efficiency of 0.5 ($\sim 1 \times 10^{17}$ proton interactions in the target) it is possible to reach the next limits in the differential cross-sections of quark production in nucleon-nucleon collisions: $d^2\sigma_Q/drd \simeq (2.5 - 5) \times 10^{-39}$ cm^2/ster x GeV/c, which corresponds to estimates for total cross-sections of $\sim 10^{-38}$ cm^2. The sensitivity of these experiments will exceed the sensitivity of experiments on colliding beams by more than three orders of magnitude. The kinematic limit for transverse momenta in experiments with an internal beam at the IHEP accelerator (Serpukhov) is about 5 GeV/c. In the experiments at the NAL accelerator (Batavia), it is increased by about twice.

It should be noted that although in proton beam experiments a very high intensity is used ($\sim 10^{12}$ particles/cycle), we lose a factor of about $\sim 10^5$ owing to the small acceptance angle of the channel. Furthermore, there is a certain indeterminacy in the experiment owing to the question of the choice of the optimum kinematic conditions for quark discovery. Consequently, it is possible to set up experiments on an ejected beam of π - mesons with an energy of 40 - 50 GeV/c (the kinematic limit for the transverse momentum is $\sim$ 4 GeV/c). If the intensity of the beam of π - mesons is $\sim 3 \times 10^6$ particles/cycle, and the thickness of the secondary target is about 2 nuclear interaction lengths, then the upper limit for the total quark production cross-sections with a large transverse momentum which may be achieved over 500 hours of measurement on the accelerator (and with recording of the quarks in the entire range of large angles of emergence) will be $(1.5 - 3) \times 10^{-37}$ cm^2. These experiments are fairly difficult, since it is necessary to record quarks in an accompanying shower, and the background conditions may be fairly difficult. It would appear that it is precisely these conditions that will limit the intensity of the π -meson beam, which in principle may be made an order of magnitude higher. The advantage of this method is, however, that there are no indeterminacies in the choice of the kinematic conditions of the experiment, and the possibility of observing, in a single event, two or three particles with a fractional charge.

It is also necessary to examine the physico-chemical quark investigation method on an accelerator. If, during a period of one year a large tray containing water is irradiated with an ejected proton beam so that it slows down all the strongly interacting particles which are produced, including, also all the quarks (the tray should contain about 10^3 litres, i.e. 10^{30} nucleons; the number of protons that have interacted is $\sim 2 \times 10^{18}$), and if, in effect, as a result of the enriching processes the sensitivity of the search for quarks in the water can be raised to 5×10^{-27} quarks/nucleon /36/, then it is possible in this experiment to reach the upper limit for the quark production cross-section in nucleon-nucleon interactions which is about 10^{-40} cm^2 (or even lower, if the degree of enrichment can be increased). A disadvantage of this method is of course the imprecise situation concerning the enrichment of the specimen with particles having a fractional charge. However, if the experimenters are lucky, and succeed in finding quarks, this indeterminacy does not reduce the value of the experiment.

IV. On the Search for quarks in deeply-inelastic lepton processes with large momentum transfers

Experiments with deeply inelastic lepton-hadron interactions open up new possibilities for finding quarks in processes with large momentum transfers.

Let us examine the interaction of a hadron with a virtual γ -quantum for deeply inelastic μ (e) -nucleon scattering (Figure 2.). In these processes, when there are large momentum transfers, we are dealing with a unique situation, when a virtual photon interacts with one parton (a quark), which momentarily escapes from the region where other partons (quarks)$^{*)}$ are situated. It is convenient to carry out this examination in a system of co-ordinates in which the time component of the momentum transfer $Q_0 = 0$ /15/. Before the collision of the nucleon and photon there is a combination of partons (quarks) with a 4-momentum $P = \{|\vec{p}'|, \vec{p}'\}$ and virtual photon $Q = \{0, \vec{Q}'\}$. Let us introduce an invariant value ω, by which scaling is effected in deeply inelastic μ (e)-nucleon scattering: $\omega = \frac{2PQ}{-Q^2}$. Then $-PQ = \vec{P}' \vec{Q}' =$

$$\frac{\omega Q^2}{2} = \frac{\vec{Q}' \vec{Q}'}{2}\omega \text{ i.e. } \vec{Q}' = -\frac{2\vec{P}}{\omega} \text{ see Fig. 2.}$$

The photon interacts with a parton (quark) which has a momentum of $x\vec{P}'(x < 1)$. After the interaction, the quark energy in the system considered does not change, because the absorbed virtual photon does not carry energy and only transmits the momentum. The momentum of the quark changes by $2P'/\quad$.

As it is only the direction of the momentum that changes and not its value, the interaction condition is $x = \frac{1}{\omega}$. After interaction, the ejected quark recoils with a momentum of $-\vec{P}'x$, and the remaining combination moves forward with a momentum of $P'(1 - x)$. In this way, the quark can separate itself from the remaining combination of hadrons, and as the momentum transfer increases by $q^2 = (2\vec{P}'x)^2$, the probability of such a separation may increase: for a fairly large momentum transfer the quark may be torn out of the range of action of the barrier forces.

The question of the advantages of seeking quarks in the processes of deeply inelastic lepton-hadron interactions, or in hadron-hadron collisions with large transverse momentum transfers, still has not, apparently, been solved. On the one hand, in deeply inelastic lepton-hadron reactions a more distinct picture

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*) The interaction time of a virtual photon with a parton is small compared with the life of the virtual parton state of the nucleon.

may be obtained of the separation of the quark from the hadron structure. On the other hand, however, if it is, in fact, true that it is in hadron-hadron interactionsthat there occurs the mechanism of a transfer of large transverse momenta with cross-sections which exceed the electromagnetic cross-section, then the production of quarks in similar processes may be greater than in lepton-hadron collisions. We believe that independent exploratory experiments are necessary in both these and other processes.

Let us now examine the possibilities of such lepton-hadron experiments.

1. μ N-interactions

Let us carry out some estimates for the case of μ N-interactions in the deeply inelastic region. The differential cross-section of the inelastic process, as we know, is of the form:

$$\frac{d^2\sigma}{d q^2 d\nu} = \frac{4\pi\alpha^2}{q^4} \cdot \frac{E'}{E} W_2(q^2, \nu)\left[\cos^2\frac{\theta}{2} + 2\frac{W_1(q^2, \nu)}{W_2(q^2, \nu)} \sin^2\frac{\theta}{2}\right] =$$

$$= \frac{4\pi\alpha^2}{q^4} W_2(q^2, \nu)\left[1 - \frac{\nu}{E} + \frac{q^2}{4E^2}\left(2\frac{W_1(q^2, \nu)}{W_2(q^2, \nu)} - 1\right)\right].$$

Here, E is the primary energy of the muon; E' is the energy of the muon after scattering; $\nu = E - E'$, θ is the scattering angle of the muon (all in the laboratory system of co-ordinates); $Q^2 = -q^2 = -4\,E\,E' \sin^2\frac{\theta}{2}$ = the square of the 4^x momentum transfer; $W_1(q^2, \nu)$ and $W_2(q^2, \nu)$ are the structural functions of the nucleon.

For further calculations it is assumed that in the whole region under examination q^2, ν :

$$\frac{W_1(q^2, \nu)}{W_2(q^2, \nu)} = \left(1 + \frac{\nu^2}{q^2}\right)\frac{1}{(1 + R)} \approx (1 + \nu^2/q^2)$$

i.e. $R = \sigma_L(q^2, \nu)/\sigma_T(q^2, \nu) = 0$),
and the structural function $W_2(q^2, \nu)$ is of the form

$$\nu W_2(q^2, \nu) = 0{,}32 \left[1 - \exp a(\omega - \omega_{min}) \right]^3$$

where

$$\omega = \frac{2M_p \nu}{q^2} \; ; \quad \omega_{min} = \frac{2M_p \nu_{min}}{q^2} = 1 + \frac{(2M_p + m_\pi) m_\pi}{q^2} \simeq 1 \; ; \quad a = -1{,}35 .$$

(This form of νW_2 agrees well with experimental data concerning deeply inelastic electroproduction /11/ in the q^2 and ν region in which these experiments were carried out). On these assumptions for μ - p -interactions values of $\sigma(q^2 > q^2_{min})$ are obtained.

In experiments on the IHEP accelerator (Serpukhov) by means of a muon beam with an energy of ~ 30 GeV and an intensity of 10^6 μ/cycle, interacting in an aluminium target having a thickness of 200 g/cm^2 , the following statistics for the events may be obtained over 500 hours of measurements on the accelerator (total muon flux: 2×10^{11}) :

q^2_{min} $(GeV/c)^2$	$\sigma(q^2 > q^2_{min})$ (cm^2)	N° of events c $q^2 > q^2_{min}$	
10	1.6×10^{-33}	2.7×10^4	q^2_{max} =
15	4.4×10^{-34}	7.4×10^3	= 55 $(GeV/c)^2$
20	1.3×10^{-34}	2.2×10^3	
25	3.7×10^{-35}	6.2×10^2	
30	1.0×10^{-35}	1.7×10^2	

Similar experiments on the NAL (Batavia) accelerator will give the following (total flux 2 x 10^{11} muons with an energy E_{μ} = 100 GeV):

q^2_{min} $(GeV/c)^2$	$\sigma(q^2 > q^2_{min})$ (cm^2)	N° of events c $q^2 > q^2_{min}$	
10	6.9×10^{-33}	1.2×10^{5}	
20	1.7×10^{-34}	2.9×10^{4}	
30	6.5×10^{-34}	1.1×10^{4}	
40	2.8×10^{-34}	4.7×10^{3}	q^2_{max} =
50	1.3×10^{-34}	2.2×10^{3}	
60	6.4×10^{-35}	1.1×10^{3}	= 187 $(GeV/c)^2$
70	3.1×10^{-35}	5.2×10^{2}	
80	1.5×10^{-35}	2.5×10^{2}	
90	7.0×10^{-36}	1.2×10^{2}	
100	3.1×10^{-36}	5.2×10	

As the energy of the NAL accelerator increases, as well as that of its muon beam, it will be possible to study, in the appropriate experiments, the region $q^2 > 100\ (GeV/c)^2$.

In this way, it will be possible, in deeply inelastic μ-p interactions, to carry out a sensitive search for quarks in the region of very high momentum transfers.

It should be noted that the search for quarks in μ-p interactions may be carried out in considerably better background conditions than the comparable experiments with a π-meson beam discussed above. In such interactions it is also possible to record the occurrence, in a single interaction event, of two or more particles with a fractional charge.

2. e- p interactions

Experiments to find quarks in deeply inelastic e-p interactions on electron accelerators are of considerable interest in view of the high intensity of the accompanying electron beams. Of particular interest are the data which can be obtained from the 20 GeV SLAC linear accelerator, although experiments there are complicated by the poor time structure of the beam (it is sufficient to say that in the experiments on SLAC only very limited data have been obtained so far concerning the strongly interacting secondary particles which are produced in the deeply inelastic region). For this accelerator, the physico-chemical methods of quark detection may prove particularly promising.

The results of the experiment already carried out at SLAC in order to find quarks [26] are difficult to interpret, but, apparently they are not very sensitive, since even without taking into account the form factors they led to fairly weak restrictions on the quark mass. After adapting the SLAC accelerator to an energy of 40 GeV and to extended beam operation, extremely sensitive experiments will be possible aimed at finding quarks in deeply-inelastic processes with large momentum transfers.

3. Neutrino Experiments

In principle, neutrino experiments with deep inelasticity may, for the range of very high momentum transfers, offer advantages over μ (e)N- experiments, since there is, in the neutrino cross-sections, no dependence on momentum transfers of the $\frac{1}{q^4}$ type, which is characteristic of electromagnetic processes. However, concrete estimates for possible experiments to find quarks in neutrino interactions showed that for a neutrino beam intensity in the energy region of 70 - 200 GeV/c $\sim 10^8$ ν /cycle [47], the muon experiments will have advantages up to $q^2 \approx 90 - 100$ $(GeV/c)^3$.

Conclusion

We consider, therefore, that the experiments to find "light" quarks have still not been terminated, and new efforts are required in this direction before **we can finally** abandon the thought of the possible existence of physical quarks observed in the free state.

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SEARCH FOR QUARKS WITH A 1/3 AND 2/3 CHARGE, IN PROTON ACCELERATORS

Item	Group	Exper. method	Primary proton energy (GeV)	P (GeV/c)	ϑ (mrad)	Target	q	M_Q max (GeV)	$P_Q = \|q\| P$ (GeV/c)	$P_{Q\perp} = P_Q \sin\vartheta$ (GeV/c)	N_π	$\frac{d^2\sigma_a}{d\Omega dp}\Big\|_{90\%}$ (cm^2/ster. GeV/c)
I.	V.Hagopian et al (1964) /22/	Bubble chamber	3I	8,5	I20	W	+I/3	2,0	2,83	0,34	$3\cdot 10^5$	$5\cdot 10^{-32}$ *)
							+2/3	2,5	5,70	0,68		$2,5\cdot 10^{-32}$ *)
2.	W.Blum et al. (1964) /23/	Bubble chamber	27,5	20	76	Cu	-I/3	2,5	6,7	0,5I	$1,5\cdot 10^5$	$2,2\cdot 10^{-35}$
							-2/3	2,5	I3,4	I,0		$1,1\cdot 10^{-35}$
3.	H.H.Bingham et al. (1964) /24/	Bubble chamber	2I	I6	77	Cu	-I/3	2,0	5,3	0,4I		$4 \div 10\cdot 10^{-36}$
							-2/3	2,2	I0,6	0,82		$2 \div 5\cdot 10^{-36}$
4.	L.P.Leipuner et al. (1964) /25/	Scintillation counters	28	4,5	3I4	Be	-I/3	2	I,5	0,47	10^8	$2\cdot 10^{-36}$ *)
5.	E.H.Bellamy et al. (1967) /26/	Scintillation counters	Electrons 12 GeV	I2,5	0	Cu+Be	-I/3 -2/3		4,2 8,4	0		No quarks with c q = -I/3, M_a < 0.5 GeV; q = -2/3 M_a < 0.75 GeV.
6.	Yu. M. Antipov et al. (1968-69) /27/.	Scintillation counters	70	50	0	Al	-I/3	4,4	I6,7	< 0,08	$0,8\cdot 10^9$	$1,4\cdot 10^{-35}$
							-2/3	4,8	33,3	< 0,I6		$7,7\cdot 10^{-36}$
		Cherenkov counters		64,5	0	Al	-I/3	4,7	2I,5	< 0,I	$0,8\cdot 10^9$	$3,6\cdot 10^{-37}$
							-2/3	4,2	43,0	< 0,2		$2,1\cdot 10^{-37}$
		Wide-gap wire chambers		80	0	Al	-I/3	4,8	26,7	< 0,I3	channel with no background	$7,1\cdot 10^{-38}$
							-2/3	3,3	53,3	< 0,25		$4,1\cdot 10^{-38}$
7.	J.V.Allaby et al. (1969) /28/	Scintillation counters	27	32,7	0	Be	-1/3	2,7	I0,9	< 0,05	channel with no background	$7,2\cdot 10^{-39}$
		Cherenkov counters		22	6,5	Be	-2/3	2,4	I4,7	0,I	$1,3\cdot 10^{10}$	$5,2\cdot 10^{-38}$
		Streamer chamber		20	44	Be	+I/3	2,5	6,7	0,3		$2,6\cdot 10^{-35}$
							+2/3	2,5	I3,3	0,6		$1,3\cdot 10^{-35}$
8.	M.Bott-Bodenhausen et al. (1972) /29/	Colliding proton rings (ISR) Scintillation and Cherenkov counters	Total energy in c.m.s. 44 GeV and 55 GeV (80% of time)		(с.ц.м.)	|q| = 1/3 и 2/3						n_Q/n particles
					$0,9^0$							$0,46\cdot 10^{-8}$
					$2,4^0$							$1,18\cdot 10^{-8}$
					$7,8^0$					may		$0,62\cdot 10^{-8}$
					$12,7^0$					be		$1,38\cdot 10^{-8}$
					$27,1^0$					very		$2,52\cdot 10^{-8}$
					$67,7^0$					great		$5,84\cdot 10^{-8}$

Note : ν is the angle of secondary particle ejection; P is the secondary particle momentum; $P_a = |q| P$ is the momentum of quarks with a charge q; (M_a) max is the limit value for the mass of quarks produced during a collision of a proton with a nucleon at rest in the kinematic conditions of the experiment concerned; the search for quarks was carried out in the range of masses from 0 to M_a, at several GeV higher than (M_a) max, in order to use the possible widening of the range of masses as a result of Fermian movement of nucleons in a nucleus-target; N_5 is the flux of 5 mesons (or other particles) passing through the aperture; 90% = the upper limits of quark production differential cross-sections at a reliability level of 90%.

*Recalculated from experimental results.

PHYSICO-CHEMICAL SEARCH FOR SMALL CONCENTRATIONS OF QUARKS IN MATTER — TABLE 2

GROUP	METHOD	MATERIAL	UPPER LIMIT FOR QUARK CONCENTRATIONS (FOR 1 NUCLEON)
1	2	3	4
W.A. Chupka et al. (1966) /36/	Enrichment of matter by quarks by various methods (water evaporation, collection of quark-atoms with an electrical field etc.); mass spectrography. The experiment is characterized by a high sensitivity, but its results are not sufficiently reliable and they are difficult to interpret.	Meteorites Air Dust Water	10^{-17} $10^{-30}-10^{-33}$ $3\cdot10^{-27}$ $3\cdot10^{-24}-5\cdot10^{-27}$
G. Gallinaro et al. (1966-68) /37/	Milliken's experiment modified; search for quarks in test specimens with a magnetic suspension device to measure their charge.	Graphite	10^{-18}
V.G. Braginski et al. (1967-1971) /38/	Milliken's experiment modified; search for quarks in test specimens with a magnetic suspension device to measure their charge; a) Diamagnetic test specimen-graphite; to the graphite is added a solution of a stone meteorite and salt from water evaporation; the result for water is based on enrichment during the evaporation and therefore is not sufficiently rèliable, b) Ferrito-magnetic test specimen.	Graphite Water Ion	10^{-18} 10^{-23} 10^{-20}
D.D. Cook et al. (1969) /35/	Electrochemical enrichment of matter by quarks (by 5-7 orders of magnitude), subsequent evaporation and acceleration of quark atoms in a strong electrical field V and measurement of their energy T = qV and, consequently of the charge q with the aid of semi-conductor detectors; as enrichment is based on assumptions concerning the chemical nature of the quark atoms, the results are not sufficiently reliable.	Sea water Mountain rock	10^{-24} 10^{-23}
L. Marshall-Libby et al. (1968) /39/	Negative-charged quarks (and other stable particles) may cause the division of heavy nuclei (U etc.) and lead to very considerable radio-activity. The absence of such pathological activity leads to an upper estimate of the concentration of these particles.	Heavy metals (U)	$2\cdot10^{-30}$ i The reliability of the estimate is subject to considerable doubt /43/
D.M. Rank (1968) /40/	1. The search for quarks with a charge Q = + 2/3 by spectrometric methods; the specimens are first enriched by evaporation and collection of ions by means of an electrical field. 2. Milliken's experiment modified, with oil drops in order to search for quarks with a charge Q = + 1/3; ± 2/3; oil is enriched (by 4-5 orders of magnitude) with quark atoms by means of an electrical field.	Sea water Oil	10^{-18} 10^{-20}
R. Stover et al. (1967) /41/	Milliken's experiment modified; search for quarks in test specimens with a magnetic suspension device to measure their charge.	Ion	$4\cdot10^{-19}$
J. Elbert et al. (1970) /42/	Spectrometer for simultaneous measurement of the mass and charge of ions accelerated in a field of 10^6 eV. The search for quarks was carried out in the particle mass range between $1/3M_p$ to $60M_p$.	Oxygen, Nitrogen, Air, Helium, Hydrogen (from sea water) CO_2 (from lime-stone)	$10^{-14}-10^{-11}$

NOTE : The results of all the experiments based on the method of enriching matter by quark atoms, are based on assumptions concerning their properties and they are therefore not so reliable as direct experiments of the Milliken type. The estimates based on the catalysis of uranium fission are also not reliable.

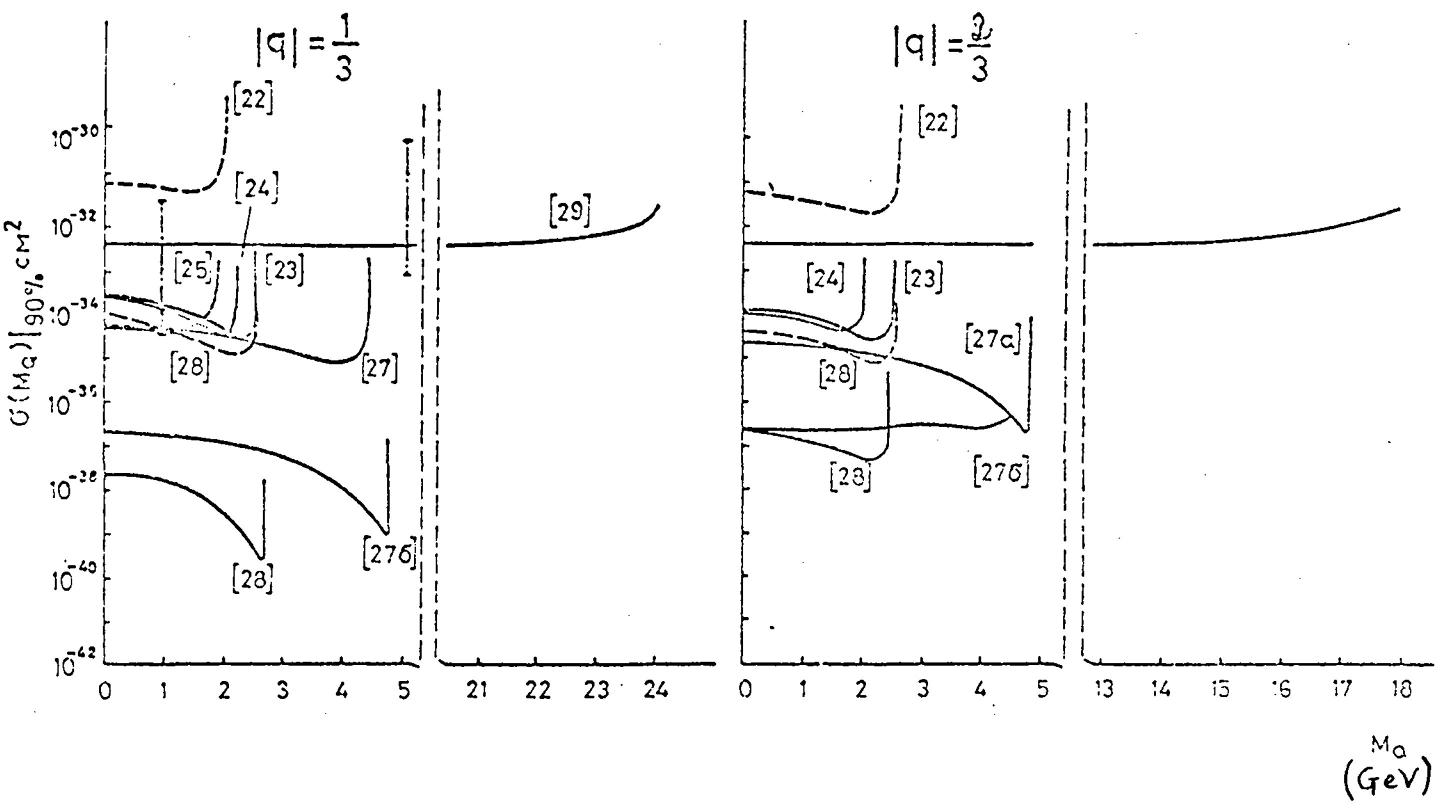

Figure 1.

The upper limits for the total cross-sections for quark production obtained during experiments on accelerators 22-25, 27-29/. The continuous lines: data for quarks with q = - 1/3 and q = - 2/3. Dashed lines - data for quarks with q = + 1/3 and q = + 2/3. (In experiments on colliding beams /29/ the quark charges were not measured). The estimates of the limits for total cross-sections were obtained in the phase volume model. On this drawing are shown estimates /9, 32/ for the upper boundaries of the total cross-sections for the production of quarks with masses of M_Q = 1 GeV and M_Q = 5 GeV, obtained on the basis of experiments in cosmic radiation /30,31/ (chain-dotted lines).

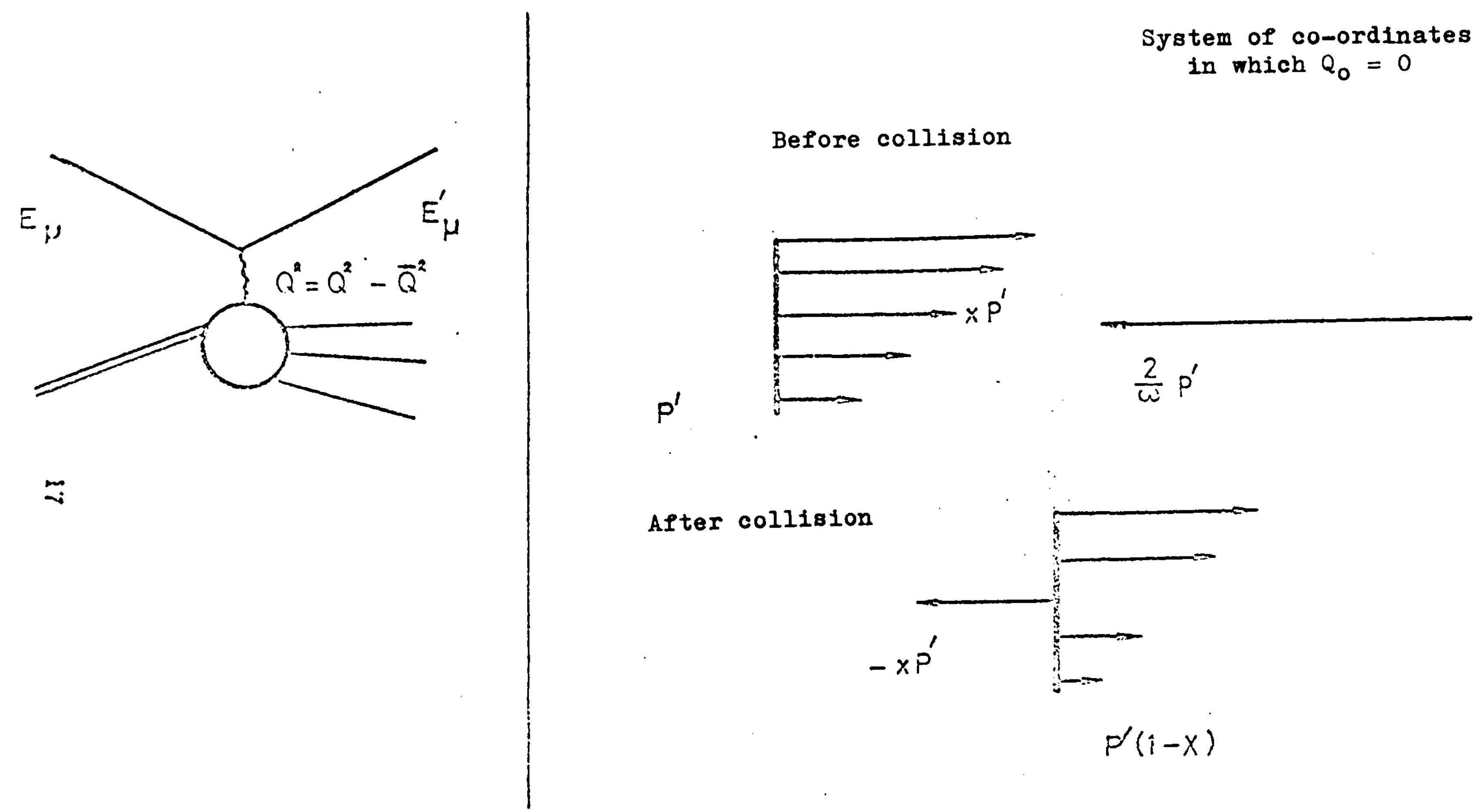

Figure 2. Diagram of the interaction of a hadron with a virtual γ-quantum in deeply-inelastic μ(e) -nucleon scattering (parton model, co-ordinate system for which $Q_o = 0$).