# The search for quarks

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The results of numerous experiments on the search for quarks and other fundamental particles are reviewed. In the first section, various composite models of elementary particles are described: the Sakata model, the quark model, and models with two or three fundamental supermultiplets. The second section deals with the experiments on the search for quarks, polyquarks and fundamental particles with integral charges which have been carried out with accelerators. Special attention is given to the most recent highest-precision results obtained at IHEP (Serpukhov) and at CERN. The results of the accelerator experiments are analyzed by means of the phase-space model and a phenomenological model which takes into account the basic features of the dynamics of the strong interactions. No quarks of mass $\lesssim 5$ GeV have been detected in the accelerator experiments, and the upper limits on the possible production cross sections of these particles have been estimated to be $10^{-37}-10^{-39}$ cm$^2$. In the third section, the results of searches for quarks in cosmic rays and searches by physico-chemical methods are systematized. Quarks have not been detected in these experiments, and works reporting the observation of fractionally charged particles have proved to be in error. Various theoretical models of quark production are discussed in the fourth section. The review of the literature goes up to September 1972.

## CONTENTS

## I. FUNDAMENTAL PARTICLES

### 1. Introduction

The stormy development of high-energy physics during the past two decades, which has been associated with the construction of large accelerators, has resulted in the discovery of a host of new elementary particles, which now number about 200. The majority of these particles are short-lived strongly interacting particles—the so-called resonances. Since the number of elementary particles now exceeds the number of chemical elements, the very concept of an elementary particle as a certain basic structural element of matter has lost its original meaning. There has arisen the major problem of achieving a clear-cut systematization of this diversity of particles, which in a certain sense would be reminiscent of the periodic system of elements.

Theoretical ideas in this direction have developed along two paths. On one hand, there have been investigations of the symmetry properties of the strong interactions, which can lead to a grouping of particles into familites with similar properties. Thus, it has been established that the strong interaction is charge-invariant, i.e., it does not depend on what charge states the particles are in. Charge invariance implies that the strongly interacting particles are grouped into isotopic multiplets, i.e., families of particles which differ from one another only in their electromagnetic characteristics. The members of an isotopic multiplet are the various charge states of one and the same particle. Examples of isotopic families are the proton and neutron, or the $\pi^+$, $\pi^-$ and $\pi^0$ mesons. However, the number of such isotopic multiplets is also very large—about 80.

Later on, it was discovered that the isotopic multiplets are grouped into more complex familites—unitary supermultiplets, whose existence is due to other symmetry properties of the strong interactions, namely unitary or SU$_3$ symmetry. The differences between the members of a single unitary supermultiplet which incorporates several isotopic multiplets are essentially greater than those between the particles which comprise a single isotopic multiplet. However, representatives of different unitary supermultiplets are quite clearly distinguished from one another. An example of a unitary supermultiplet is the octet of baryons with spin and parity $J^P = 1/2^+$—the proton and neutron, the $\Lambda$ hyperon, the $\Sigma^+$, $\Sigma^-$ and $\Sigma^0$ hyperons, and the $\Xi^-$ and $\Xi^0$ hyperons. Unitary supermultiplets of particles with different values of the spin can be combined into still more complex families—the so-called SU$_6$ supermultiplets, etc. Group-theoretic methods play a major role in the study of the symmetry properties of the strong interactions and the structure of the supermultiplets.

On the other hand, there have developed so-called composite models of elementary particles, by means of which attempts have been made to reduce all the diversities of particles to bound states of a minimum number of fundamental or truly elementary particles. The composite models have made it possible to give a transparent explanation of the symmetry properties of the strong interactions as a manifestation of a symmetry of the interactions between fundamental fields. In the first composite model, Fermi and Yang regarded protons, neutrons, antiprotons and antineutrons as fundamental particles. Subsequently, after the discovery of strange particles, there appeared a series of new composite models, the most successful of which was the Sakata model. In this model, the fundamental particles (Φ) are protons, neutrons and Λ hyperons, as well as the corresponding antibaryons. All the mesons are bound baryon-antibaryon states ($\Phi\bar{\Phi}$), while the baryons consist of two fundamental baryons and one fundamental antibaryon ($\Phi\Phi\bar{\Phi}$). With the aid of this model, it was possible to predict the existence of a number of new particles, to give a good description of the structure of the meson unitary suppermultiplets, and to explain many phenomena in the domain of weak interaction physics[1]. However, the Sakata model encountered insurmountable difficulties in the analysis of the baryon unitary supermultiplets, since it led to a completely incorrect structure of the baryon families (see Sec. 4). These difficulties are of a fundamental character and lead to the conclusion that one must either abandon an extremely attractive minimal composite model with three fundamental baryon fields or assign highly unusual properties to these fundamental particles. Gell-Mann and Zweig[2] took the second path when in 1964 they conjectured that there exists a fundamental triad of p, n and λ quarks—particles with fractional electric and baryon charges, from which all the strongly interacting particles are constructed in such a way that baryons consist of three quarks, while mesons consist of a quark and an antiquark.

The quantum numbers of the quarks are shown in Table I. By virtue of the laws of conservation of electric and baryon charges, at least one quark—the lightest one—must be stable.

It is difficult to make any definite predictions about the masses of the quarks. In certain models, reasons have been put forward in favor of a small value for their mass (slightly larger than $M_p/3$). However, in the nonrelativistic model, for which the greatest number of interesting results have been obtained, the quark mass must be quite high. In fact, the condition for the validity of the nonrelativistic approximation for a system of quarks bound by a deep potential well of radius R has the form

$$P/M_Q \approx 1/M_Q R \ll 1.$$

If the range of the interaction between quarks is $R \approx m_\rho^{-1}$, the quark mass is $M_Q \gtrsim 3-5$ GeV. The high accuracy of the mass formulas for relating the masses of the particles of supermultiplets provides grounds for supposing that the quark mass must be even larger, of the order of 10 GeV, although these considerations are naturally not conclusive. It also follows from the mass formulas that the mass of the λ quark must be somewhat larger than the mass of the p and n quarks.

## 2. The quark model

We give below a brief description of the basic features of the quark model. All the details and references to the original papers can be found in the books and reviews[3-9].

TABLE I. Quantum numbers of the quarks.

| Type of quark | $B$ | $q$ | $T$ | $T_3$ | $S$ | $Y$ | $Z = 3/2\langle Y\rangle_{\text{supermult}}$ |
|---|---|---|---|---|---|---|---|
| $p$ | 1/3 | +2/3 | 1/2 | +1/2 | 0 | 1/3 | 0 |
| $n$ | 1/3 | −1/3 | 1/2 | −1/2 | 0 | 1/3 | 0 |
| λ | 1/3 | −1/3 | 0 | 0 | −1 | −2/3 | 0 |

Composite model: baryon–(QQQ), meson–($Q\bar{Q}$).

Notation in Table I and in Tables II and III below: B–baryon number, q–ratio of the charge of the particle to the charge of the proton, S–strangeness, T–isotopic spin, $T_3$–its third projection, Y–hypercharge, Z–supercharge, C–"charm".

**a) Quarks and symmetries of the strong interactions.** In the language of the quark model, isotopic invariance ($SU_2$ symmetry) means the invariance of the strong interaction under transformations of the type (p quark) $\rightleftarrows$ (n quark). If isotopic invariance were a strict conservation law, the masses of the p and n quarks would be identical, as would also the masses of all the hadrons belonging to one and the same isotopic multiplet. However, isotopic invariance is broken by the electromagnetic interactions, which lead to a certain difference between the masses of the individual constituents of isotopic multiplets. This difference is small—of the order of several megaelectron volts.

In analogy with this, the unitary symmetry $SU_3$ amounts to invariance under the transformations (λ quark) $\rightleftarrows$ (p, n quarks). If $SU_3$ symmetry were exact, all kinds of quarks would have the same mass. The same would hold for the masses of the individual constituents of unitary supermultiplets. It turns out that $SU_3$ symmetry is broken much more strongly than isotopic invariance. The characteristic difference between the masses within supermultiplets is several hundred megaelectron volts. This means that there exists an $SU_3$-symmetric super-strong interaction, which gives the main contribution to the quark mass and to the binding energy of a system of these heavy fundamental particles when they form composite states—the hadrons. In addition, there exists a medium-strong interaction, which breaks $SU_3$ symmetry and is responsible for the difference between the masses of the isotopic families which combine into $SU_3$ supermultiplets.

In the nonrelativistic quark model, important results have been obtained under the assumption that the so-called $\underline{SU_6 \text{ symmetry}}$ holds. According to this assumption, the super-strong interaction is not only independent of the types of quarks, but is also independent of the orientation of their spins. Thus, the Hamiltonian of the super-strong interaction is invariant with respect to the unitary group of six-dimensional transformations $SU_6$. The medium-strong interactions break this symmetry1) and may depend on the spin indices as well as the $SU_3$ indices of the quark fields.

**b) Supermultiplet structure.** The mathematical apparatus of group theory is used to establish the structure of the supermultiplets.

1) $\underline{SU_3 \text{ supermultiplets}}$. The mesons are bound states of the quark-antiquark system. The structure of the meson supermultiplets can be written symbolically as a direct product of fundamental triplets of quarks and antiquarks: $\{3\} \times \{\bar{3}\} = \{8\} + \{1\}$. In other words, the mesons form $SU_3$ octets and singlets. The baryons, which consist of three quarks, are grouped into $SU_3$ singlets, octets and decuplets (the corresponding symbolic notation is $\{3\} \times \{3\} \times \{3\} = \{1\} + \{8\} + \{8\} + \{10\}$).

2) $\underline{SU_6 \text{ supermultiplets}}$. In accordance with $SU_6$ symmetry, the mesons and baryons are grouped into still more complex $SU_6$ supermultiplets. In this case, the mesons form an $SU_6$ singlet (with zero total quark spin) and an $SU_6$ 35-plet, which includes an $SU_3$ singlet with total quark spin 1 and $SU_3$ octets with spins 0 and 1: $[6] \times [\bar{6}] = [1] + [35]$ or, indicating separately the $SU_3$ indices and the spin indices, $[\{3\}_{1/2}] \times [\{\bar{3}\}_{1/2}] = [\{1\}_0] + [\{1\}_1 + \{8\}_0 + \{8\}_1]$. The baryons are represented as $[6] \times [6] \times [6] = [20] + [56] + [70] + [70] = [\{1\}_{3/2} + \{8\}_{1/2}]$

$+ [\{8\}_{1/2} + \{10\}_{3/2}] + [\{1\}_{1/2} + \{8\}_{1/2} + \{8\}_{3/2} + \{10\}_{1/2}] + [\{1\}_{1/2} + \{8\}_{1/2} + \{8\}_{3/2} + \{10\}_{1/2}]$. The baryon $SU_6$ supermultiplets are characterized by the following symmetry properties of the unitary and spin parts of the wave function with respect to interchange of the quarks: the 56-plet is symmetric, the 20-plet is antisymmetric, and the 70-plet corresponds to a mixed symmetry.

c) **Classification of boson and baryon states.** The classification of the hadronic states encounters serious difficulties, owing to the lack of definitive data on the spin and parity of the majority of the known resonances. For this reason, we know at the present time the full composition of only a few supermultiplets.

1) Mesons. The $(Q\bar{Q})$ system in the state with orbital angular momentum $L = 0$ gives a nonet (an $SU_3$ singlet and an $SU_3$ octet) of pseudoscalar mesons ($^1S_0$, i.e., $J^P = 0^-$) and a nonet of vector mesons ($^3S_1$, i.e., $J^P = 1^-$). These particles form an $SU_6$ singlet and an $SU_6$ 35-plet, the latter containing $SU_3$ octets of pseudoscalar and vector mesons and a vector $SU_3$ singlet.

The other mesons correspond to excited states of the $(Q\bar{Q})$ system with orbital angular momenta $L = 1$ ($^3P_2$, $^3P_1$, $^3P_0$ and $^1P_1$), $L = 2$ ($^3D_3$, $^3D_2$, $^3D_1$ and $^1D_2$), etc. At the present time, only the nonet of tensor mesons with $J^P = 2^+$ ($^3P_2$) is completely filled, and also possibly the nonet of mesons with $J^P = 1^+$ ($^3P_1$).

Thus, the simple quark model gives a good prediction of the grouping of the mesons into nonets and the structure of the $SU_3$ and $SU_6$ supermultiplets. It also permits a definitive prediction of the following combination of meson quantum numbers: parity $P = (-1)^{L+1}$, G-parity $G = (-1)^{L+S+T}$, and C-parity and CP-parity of neutral mesons $C = (-1)^{L+S}$, $CP = (-1)^{S+1}$ (here S and L are the total spin and orbital angular momentum of the system of quarks, and T is the isotopic spin of the meson).

2) Baryons. The (QQQ) system in the state with $L = 0$ makes it possible to describe the octet of the ordinary baryons with $J^P = 1/2^+$ and the decuplet with $J^P = 3/2^+$, provided that a 56-plet is chosen for the unitary and spin parts of the wave function. We shall henceforth call these baryons the fundamental 56-plet. Baryon resonances with negative parity must belong to $SU_6$ 70-plets.

3) Exotic resonances. The possible existence of exotic resonances, which can be explained only in terms of more complex quark structures, is of great importance. Examples of exotic resonances would be baryon systems of the type (QQQQQ), such as baryons with strangeness $S > 0$ or isotopic spin $T > 3/2$, and meson states of the type (QQQQ), which do not satisfy the conditions $|S| \leq 1$, $T \leq 1$, $|Q| \leq 1$ or which are characterized by combinations of spin, parity and charge parity which cannot exist for a single fermion-antifermion pair. At the present time, there is no reliably established exotic resonance. The experimental situation regarding the search for exotic resonances is reviewed in[10].

d) **Main achievements of the quark model.** Let us enumerate very briefly the principal successes of the simple nonrelativistic quark model:

1) The model gives a good description of the structure of the meson supermultiplets and, what is especially significant, the structure of the baryon supermultiplets.

2) One obtains mass formulas which are in good a agreement with experiment and which define a relation among the masses of the various isotopic families that constitute the supermultiplets. One obtains relations among the electromagnetic mass differences of hadrons for the isotopic families belonging to the fundamental 56-plet; these relations are also in agreement with experiment, but they have not been verified to high accuracy.

3) There are predictions for a number of electromagnetic properties of hadrons, many of them being in good agreement with experiment (the magnetic moments of the neutron and other baryons, the relations $G_E^{(P)}(q^2) = G_M^{(P)}(q^2)/\mu_P = G_M^{(N)}(q^2)/\mu_N$ and $G_E^{(N)}(q^2) = 0$ for the form factors of nucleons, the widths of the radiative decays of vector mesons and, in particular, the width $\Gamma(\omega \rightarrow \pi^0\gamma)$ and a number of other relations).

4) In the quark model, the weak decays of hadrons are due to the decays of one of the quarks of which they are composed. The total hadronic weak current, being the sum of the quark currents, transforms according to the octet representation of the group $SU_3$ (without the quark model, this statement is postulated). A number of predictions are obtained for the leptonic decays of baryons, selection rules such as $\Delta Q = \Delta S$ and $\Delta T = 1/2$ are explained, and the relation $F_A(q^2)/G_A = G_E^{(P)}(q^2)$ is established between the weak axial form factor and the electric form factor of the proton. All these predictions are in accord with experiment, although in many cases they have not been verified to sufficient accuracy.

5) The quark model makes it possible to derive a large number of relations among the cross sections for strong processes (selection rules for t-channel exchange, the relation $\sigma_t(pp) = (3/2)\, \sigma_t(\pi p)$, the Treiman-Johnson relations, and a number of others), which are confirmed by experiments with a satisfactory accuracy.

Many of the successful predictions of the theory which we have enumerated are specific consequences of the quark model and could not be derived in a symmetry theory. From a number of data (mass formulas, radiative widths of hadrons, etc.), we can infer that the behavior of the quarks in hadrons is universal in character; the λ quarks are heavier than the p and n quarks by the same amount, and their interactions and magnetic moments are renormalized in the same way in both baryons and mesons. From the data on form factors, it evidently follows that the radii of the quarks are much less than the radii of the hadrons: $r_Q \ll r_{had}$.

## 3. Difficulties that arise in the quark model

The quark model is sufficiently simple and transparent, and it makes it possible to give a good explanation of a large number of existing experimental data. However, we must note that this model also encounters a number of very great difficulties:

a) It is so far an open question whether quarks are real particles which can exist in the free state or whether they are some kind of "quasi-particles" which can appear only in composite systems, i.e., in essence are nothing but a mathematical abstraction. Numerous experiments involving both accelerators and cosmic rays, as well as physico-chemical investigations, have failed to establish the existence of stable particles with fractional charges. However, it is possible that the mass of these particles is too large and that they will still be found in future experiments at much higher energy.

b) If quarks are fermions, the following difficulty is encountered in describing the fundamental 56-plet of baryons. The complete wave function of the (QQQ) system must be antisymmetric. Since the unitary and spin part of the wave function of the 56-plet is symmetric, its spatial part must be antisymmetric and cannot correspond to the two S-waves. In all reasonable models of the forces which act between quarks, it is very difficult to explain this for the ground state.

c) The saturation of the forces which act between quarks is a complicated problem. It is very important to ascertain whether, in addition to systems consisting of three quarks or a quark and an antiquark, there can exist other stable or quasi-stable states: exotic resonances, diquarks or polyquarks with charges 4/3, 5/3, etc.[11].

d) A number of data imply that quarks preserve their individuality within composite hadrons and that they are "point-like" ($r_Q \ll r_{had}$). It is not yet clear how these properties of quarks can be reconciled with the notions that they possess an immense binding energy and must be surrounded by a meson "cloud."

e) If fractionally charged quarks are the fundamental components from which the entire diversity of hadrons is constructed, there arises the question as to why the fundamental hadrons have fractional charge, while the leptons have integral charge. It has been suggested[12] that perhaps the leptons are also constructed from "leptonic quarks" with fractional charges. These "leptonic quarks" could be produced either directly in electromagnetic interactions or in the decays of the "hadronic" quarks. However, the hypothesis that "leptonic quarks" exist is rather arbitrary in character.

## 4. Fundamental particles with integral charges

**a) Supercharge and "charm."** As we saw in Sec. 3, the most natural course in explaining the $SU_3$ and $SU_6$ symmetries of the strong interactions and especially the correct structure of the baryon and meson supermultiplets is to introduce a single triplet of truly elementary or fundamental particles—the quarks, which must then possess fractional electric and baryon charges. The fractional quark charges are associated with the requirement of a correct description of the structure of the baryon supermultiplets within the framework of a minimal model of three fundamental fields. This circumstance can be best illustrated with the aid of the concept of supercharge[6, 9].

Supercharge is the name given to a quantity proportional to the mean value of the hypercharge in a supermultiplet:

$$Z = (3/2)\ \langle Y\rangle_{\text{supermult}}$$

Just as the hypercharge is equal to twice the mean electric charge of an isotopic multiplet ($Y = 2\langle q\rangle_{\text{isomult}}$), the supercharge is equal to three times the mean electric charge of a supermultiplet ($Z = 3\langle q\rangle_{\text{supermult}}$).

Supercharge is an additive quantum number: the supercharge of any system of particles is equal to the sum of their supercharges. For the fundamental Sakata-type triplet of baryons with integral charge P, N, Λ2), we have Z = +1 (for the triplet of antibaryons, Z = −1). Composite baryons in this model are constructed from two fundamental baryons and one fundamental antibaryon, and the supercharges of all baryon supermultiplets must be Z = +1 (antibaryon supermultiplets have Z = −1). At the same time, Z = 0 for the fundamental baryon supermultiplets which are observed empirically (the baryon octet with $J^P = 1/2^+$: P, N, Λ, $\Sigma^+$, $\Sigma^0$, $\Sigma^-$, $\Xi^-$, $\Xi^0$; the baryon decuplet with $J^P = 3/2^+$: $\Delta^{++}$, $\Delta^+$, $\Delta^0$, $\Delta^-$, $\Sigma^{*+}$, $\Sigma^{*-}$, $\Xi^{*0}$, $\Xi^{*-}$, $\Omega^-$). A Sakata-type model with integral charges of the fundamental baryons is therefore incompatible with experiment3).

Thus, there are two ways in which a composite model of elementary particles can be successfully constructed.

1) One can assume that there exists a fundamental triplet of superneutral baryons with Z = 0, from which all the remaining baryons are constructed. This was done in the quark model of Gell-Mann and Zweig. In fact, for the fundamental triplet of baryons, of which two form an isodoublet with S = 0 and one an isosinglet with S = −1 (this requirement allows the simplest description of the isotopic properties of the ordinary and strange baryons), we have $Z = 3\langle q\rangle_{\text{triplet}} = [(\Sigma_i B_i) - 1][1/2]$. Thus, it follows from the requirement Z = 0 that B = 1/3, and we obtain a triplet of quarks with fractional charges.

2) One can introduce a more complicated system of fundamental particles, for example in accordance with the "eightfold way" of Gell-Mann and Ne'eman[13], in which the fundamental particles are the entire octet of the "ordinary" baryons with Z = 0: P, N, Λ, $\Sigma^+$, $\Sigma^0$, $\Sigma^-$, $\Xi^0$, $\Xi^-$. The theory of $SU_3$ symmetry was first constructed in just this way. However, in the "eightfold way" one must postulate many selection rules which appear in a natural way in the minimal model with three baryon fields; moreover, it is not clear why $SU_3$ symmetry should appear for the model with 8 fundamental fields. As is well known, these difficulties subsequently led one of the founders of the "eightfold way," Gell-Mann, to the quark hypothesis. It is also possible to introduce several supermultiplets of fundamental particles, which must have non-zero supercharge. The existence of several fundamental supermultiplets makes it possible to construct all the superneutral particles which exist in nature. However, there must also exist in this case supercharged particles, both fundamental and composite, which have not yet been observed.

It should be noted that the concept of supercharge may have a very profound meaning. For example, it is possible that supercharge is strictly conserved; in that case, the lightest of the supercharged particles must be stable. Schemes are possible in which violation of supercharge is induced by the superweak, weak, electromagnetic or medium-strong interactions.

In certain models in which supercharge is conserved, at least in the strong and electromagnetic interactions, there was proposed a somewhat different definition of this quantum number, which is related to a generalization of the Gell-Mann-Nishijima formula for the charge q, hypercharge Y and isotopic spin projection $T_3$. The generalized formula for the charge is of the form

$$q = T_3 + (Y/2) + (C/3); \tag{1}$$

here C is a new quantum number which is very similar to supercharge and known as "charm"[14]. If the relation (1) holds, the existence of fundamental particles with integral electric charges not exceeding unity and fractional baryon number becomes possible. Two types of such triplets with B = 1/3 are possible:

$$C = 1:\ \{q = 1,\ T_z = 1/2,\ S = 0\},\ \{q = 0,\ T_z = -1/2,\ S = 0\},$$
$$\{q = 0,\ T_z = 0,\ S = -1\};$$

$C = -2$: $\{q = 0,\ T_z = 1/2,\ S = 0\}$, $\{q = -1,\ T_z = -1/2,\ S = 0\}$,
$\{q = -1,\ T_z = 0,\ S = -1\}$.

Many other possibilities also exist. It is obvious that we must have at least two "charmed" fundamental multiplets in order to construct composite models of the ordinary elementary particles.

**b) Composite models involving several supermultiplets of fundamental particles with integral charges.** There exists a large number of composite models involving several supermultiplets of fundamental fields. One of the simplest systems of fundamental particles consists of a unitary triplet of baryon fields $R_p$, $R_N$, $R_\Lambda$ and a unitary baryon singlet M. The quantum numbers of the fundamental particles and the schemes for constructing "composite hadrons" are shown in Table II. Many other models involving two unitary fundamental multiplets are considered in[15], which gives references to earlier papers.

Of the models involving several fundamental supermultiplets, those of greatest interest seem to be the schemes with three unitary triplets[3,16,17], in which one can avoid the difficulties associated with the symmetry of the wave function of the ground state of the baryon $SU_6$ 56-plet.

One of the possible resolutions of this problem is the assumption that there exist not one, but three unitary triplets of quarks ($p^{(\alpha)}$, $n^{(\alpha)}$, $\lambda^{(\alpha)}$, where $\alpha = 1, 2, 3$). Each baryon consists of one quark of each of the triplets; thus, all three quarks are different and the difficulties with the Pauli principle do not arise.

In essence, this possibility is equivalent to the assumption that the quarks are not fermions, but parafermions of the third order, so that they are not governed by the Pauli principle.

These three families of quarks can be the ordinary quarks with fractional charge and differ from each other in having different values of some new quantum number. However, the introduction of three triplets of fundamental particles makes it possible to get rid of the fractional values of the electric charges. We shall consider below a model with three triplets due to Bogolyubov et al.[3,16]. Similar schemes were also proposed in[17].

In this model, there exist three fundamental triplets of particles with spin 1/2: $P_\eta$, $r_\eta$, $S_\eta$ ($\eta = 1, 2, 3$ is a unitary index). Their quantum numbers are shown in Table III.

If we denote the electric charge and hypercharge of the quarks by $q_0$ and $Y_0$, we have the relations $q_P + q_r + q_S = 3q_0$ and $Y_P + Y_r + Y_S = 3Y_0$. The systems $(P_\alpha r_\beta S_\gamma)$ are therefore characterized by the same values of the quantum numbers as the states of three ordinary quarks. In this model the baryons have the structure $(P_\alpha r_\beta S_\beta)$, while the mesons have the structures $(\bar{P}_\alpha P_\beta)$, $(\bar{r}_\alpha r_\beta)$, $(\bar{S}_\alpha S_\beta)$ or linear combinations of them. In this way, all the basic results of the quark model may be preserved. There is considerable arbitrariness in the choice of the quantum numbers in the model of three fundamental triplets. Thus, the condition $B_P + B_r + B_S = 1$ must be satisfied for the baryon numbers. One can therefore choose not only $B_P = B_r = 1$, $B_S = -1$, as in Table III, but also $B_P = 1$, $B_r = B_S = 0$, etc., or $B_P = B_r = B_S = 1/3$.

TABLE II. Quantum numbers of the fundamental particles in the model with a unitary triplet and a unitary singlet of baryons.

| Type of baryon | $B$ | $q$ | $T$ | $T_3$ | $S$ | $Y$ | $Z = \frac{3}{2}\langle Y\rangle$ supermult |
|---|---|---|---|---|---|---|---|
| $R_p$ | 1 | 1 | 1/2 | 1/2 | 0 | 1 | 1 |
| $R_N$ | 1 | 0 | 1/2 | −1/2 | 0 | 1 | 1 |
| $R_\Lambda$ | 1 | 0 | 0 | 0 | −1 | 0 | 1 |
| $M$ | 1 | 0 | 0 | 0 | 0 | 0 | 0 |

Composite model: ordinary (superneutral) particles—mesons $(R\bar{R})$, $(M\bar{M})$ and baryons $(R\bar{R}M)$; supercharged particles—mesons $(R\bar{M})$, $(M\bar{R})$ and baryons $(M\bar{M}R)$, $(R\bar{R}R)$.

TABLE III. Quantum numbers of the fundamental particles in the model with three triplets [16]

| Type of baryon | $B$ | $q$ | $T$ | $T_3$ | $S$ | $Y$ | $C$ |
|---|---|---|---|---|---|---|---|
| $P_1$ | 1 | 1 | 1/2 | +1/2 | 0 | 1 | 0 |
| $P_2$ | 1 | 0 | 1/2 | −1/2 | 0 | 1 | 0 |
| $P_3$ | 1 | 0 | 0 | 0 | −1 | 0 | 0 |
| $r_1$ | 1 | 1 | 1/2 | +1/2 | −1 | 0 | 3/2 |
| $r_2$ | 1 | 0 | 1/2 | −1/2 | −1 | 0 | 3/2 |
| $r_3$ | 1 | 0 | 0 | 0 | −2 | −1 | 3/2 |
| $S_1$ | −1 | 0 | 1/2 | +1/2 | +1 | 0 | −3/2 |
| $S_2$ | −1 | −1 | 1/2 | −1/2 | +1 | 0 | −3/2 |
| $S_3$ | −1 | −1 | 0 | 0 | 0 | −1 | −3/2 |

Composite model: ordinary particles—baryons $(P_\alpha r_\beta S_\gamma)$ and mesons $(\bar{P}_\alpha P_\beta)$, $(\bar{r}_\alpha r_\beta)$, $(\bar{S}_\alpha S_\beta)$ or linear combinations of them; "charmed" particles may exist.

**c) Higher symmetries.** The introduction of several families of fundamental baryon fields gives us great freedom in constructing composite models of elementary particles. In this way, we can dispense with the fractional electric charge of the fundamental particles and also overcome certain difficulties of the quark model, such as the problems connected with the symmetry of the wave functions of the fundamental 56-plet of baryons. Fundamental particles with integral charge may be stable or comparatively long-lived, but can have an extremely short lifetime corresponding to an interaction which violates unitary symmetry. We must assume that there exist composite particles of a new type—"supercharged" or "charmed" particles, for which there are also different possibilities for the lifetime, depending on the degree of conservation of this new quantum number.

If there exist two or several supermultiplets of fundamental particles, there arises the question as to whether there are symmetries higher than the unitary $SU_3$ symmetry. In fact, in the quark model the distinction between the p, n and λ quarks had to vanish in the limit of $SU_3$ symmetry. If we have a model with a fundamental triplet R and singlet M, the distinction between the components of R vanishes in the limit of $SU_3$ symmetry, but the distinction between R and M remains. But perhaps there exists a super-strong interaction for which the distinction between the particles R and M vanishes if all the remaining interactions are included. In that case, $SU_4$ symmetry must be realized in nature. An analogous situation can occur for the other schemes with several unitary supermultiplets.

Nevertheless, it seems to us that, if we abandon the model with three quarks of fractional charge and go over to more complicated models with several families of fundamental particles, the theory will become more artificial and less attractive. However, the question as to whether one or another model is correct is basically an experimental question; consequently, experimental searches for quarks, fundamental particles with integral charges, "charmed" particles, etc. are of great significance and rank among those fundamental experiments without which it is not possible to construct a theory of the strong interactions.

## II. QUARK SEARCHES WITH ACCELERATORS

### 1. The search for quarks of charge q = 1/3 and q = 2/3 with proton accelerators

a) **Quark production reactions and kinematic conditions of the experiments.** In experiments with modern large accelerators, quarks and fundamental particles could be produced when a target is bombarded by a primary proton beam of high energy. Searches for these new particles have been carried out in secondary beams with a given momentum emerging at a definite angle with respect to the direction of motion of the primary protons. In experimental searches for new long-lived particles, the following two methods have been used to identify them:

1) For particles with fractional charge (quarks)—measurement of the charge by repeated determination of the ionizing power of the particles in scintillation counters or track devices (bubble chambers, streamer chambers, etc.).

2) For particles with both integer and fractional charge—measurement of the mass by determination of their velocity (at fixed momentum) by means of Cerenkov counters and by time of flight.

The simplest quark production processes in nucleon-nucleon collisions are the following reactions:

a) quark-antiquark pair production

$$N+N\to N+N+Q+\overline{Q}, \qquad (2)$$

$$\to N+N+Q+\overline{Q}+nA, \qquad (2')$$

where A denotes other hadrons;

b) the "dissociation" of one of the nucleons into three quarks

$$N+N\to N+2Q_1+Q_2, \qquad (3)$$

$$\to N+2Q_1+Q_2+nA \qquad (3')$$

(in the case in which the proton dissociates, $Q_1$ are positive p quarks with charge q = 2/3 and $Q_2$ is a negative n quark with charge q = −1/3; in the case in which the neutron dissociates, $Q_1$ are n quarks and $Q_2$ is a p quark).

In Fig. 1 we show the thresholds for the production of quarks in reactions (2) and (3) as a function of their mass for collisions of protons with nucleons at rest. It is clear from the figure that in experiments with the proton synchrotron of the Institute of High Energy Physics at Serpukhov (proton energy 70 GeV) quarks can be produced with masses $M_Q \leq 4.8$ GeV (reaction (2)) and $M_Q \leq 3.5$ GeV (reaction (3)). With the CERN accelerator (proton energy 28 GeV), quarks can be produced with masses less than 2.7 and 2.1 GeV, respectively.

As we mentioned above, quark searches with accelerators have been carried out in beams of secondary particles with a given momentum and at a definite angle with respect to the primary beam. It is important to select the conditions of the measurements (i.e., the angle and momentum of the secondary particles) so as to maximize the expected yield of quarks. Data on the production of strongly interacting particles in nucleon-nucleon interactions show that the yields of these particles fall off very rapidly with increasing momentum transfer. Thus, for the production of pions, kaons and antiprotons by protons with an energy between 19 and 70 GeV, the differential cross sections at small momentum transfers are of the form $(d^2\sigma/dp\,d\Omega) \propto \exp(bt)$, where $b = 4-5\ (\mathrm{GeV}/c)^{-2}$, $-t = (\text{4-momentum transfer})^2 = (p\theta)^2$, p is the momentum of the secondary particle, and $\theta$ is its production angle. Experimental quark searches should therefore be made in the region of very small production angles.

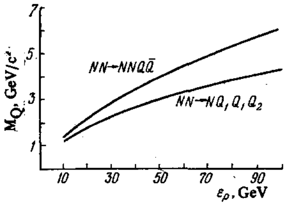

FIG. 1. The production thresholds for quarks in the reactions $NN\to NNQ\overline{Q}$ and $NN\to NQ_1Q_1Q_2$ as functions of their mass, for collisions of protons with nucleons at rest.

The choice of the optimum secondary momentum is to a great extent determined by kinematic considerations. If a particle which is produced has a mass M and is at rest in the center-of-mass system (c.m.s.), its momentum in the laboratory system (l.s.) is equal to $\beta_c\gamma_c M$ (where $\gamma_c = (1-\beta_c^2)^{-1/2}$, and $\beta_c$ is the velocity of the c.m.s. with respect to the l.s.). This situation applies just at the threshold for production of the particle. In the general case, the particles in the c.m.s. are characterized by a certain momentum spectrum, and their angular distribution is symmetric with respect to the "forward" and "backward" directions. Therefore half of the particles have a momentum greater and half have a momentum less than $\beta_c\gamma_c M$ in the l.s. The kinematics of the Lorentz transformation is such that the angular distribution of particles produced in the forward cone in the c.m.s. is compressed into the small-angle region when transformed to the l.s., while the angular distribution of particles produced in the backward cone in the c.m.s. turns out to be distributed over a wide angular range in the l.s. Therefore, for particles of mass M produced at small angles in the l.s., the maximum in the momentum spectrum turns out to be displaced to the region of momenta greater than $\beta_c\gamma_c M$. The data on $\overline{p}$ and $\overline{d}$ production by 70 GeV protons show that the shift is small in this case, amounting to several gigaelectron volts[18].

More detailed calculations of the momentum spectra of quarks in the l.s. can be made only under definite model-dependent assumptions about the production mechanism of these particles. For example, we can make the simplest assumption that the angular distribution of quarks is isotropic in the c.m.s. and that their momentum spectrum corresponds to the Lorentz-invariant phase space. The results of calculations for a primary proton energy 70 GeV are shown in Fig. 2. They show that the most favorable kinematic conditions for the search for particles with high masses occur when the momentum of these particles is 25–30 GeV/c for reaction (2) and approximately 20 GeV/c for reaction (3).

The phase-space model, in which the particles are distributed isotropically in the c.m.s., does not at all reflect the dynamics of the strong interactions, which, as experiment shows, produces a considerable narrowing of the angular distribution of particles and changes their momentum spectrum. As an example, we may compare the momentum spectra of antiprotons and antideuterons calculated according to the phase-space model and measured experimentally (Fig. 3). We see from Fig. 3 that the maximum in the momentum spectrum of strongly interacting particles is shifted toward smaller momenta when compared with the calculations according to the phase-space model. Since the maximum in the momentum distribution exceeds $\beta_c \gamma_c M_Q$ for particles of mass $M_Q$, for the primary proton energy 70 GeV the maximum in the momentum spectrum of secondary particles must lie in the range $6.2M_Q < p_{max} < 27$ GeV/c. Therefore the optimum conditions for the search for heavy particles with $M_Q \geq 3$ GeV correspond to a choice of the secondary momentum in the interval 20–27 GeV/c and are not very crucial in relation to the assumptions about the mechanism for their production. The optimum experimental conditions for other primary proton energies can be chosen from the conditions for 70 GeV by means of the "scale transformation" ($p_{second}/p_{prim}) \approx$ const.

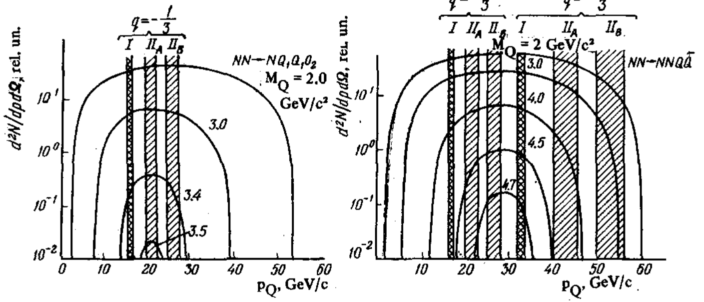

FIG. 2. The expected yields of quarks in the reactions (2) and (3) for a primary proton energy 70 GeV, calculated in the phase-space model. $M_Q$ and $p_Q = |q|p$ are the quark mass and momentum. The crosshatched areas correspond to the momentum intervals in the experiments [19] carried out at IHEP with p = 50 (I), 64.5 ($II_A$) and 80 GeV/c ($II_B$).

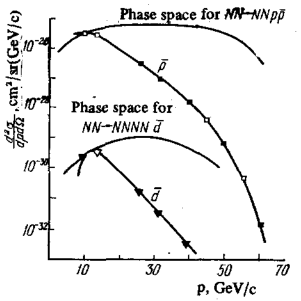

FIG. 3. Experimental spectra for the production of antiprotons and antideuterons by 70 GeV protons on Al nuclei and the results of calculations in the phase-space model for the reactions NN → NN$p\bar{p}$ and NN → NNNN$\bar{d}$ (the phase-space curves are normalized to the experimental data at p = 10 GeV/c).

**b) Experimental searches for quarks.** Since it was first hypothesized that quarks exist, numerous experimental searches for them have been carried out with accelerators. Since the theoretical predictions for the cross sections for producing these particles differ among themselves by many orders of magnitude and are very uncertain (see Sec. IV), there have been experimental searches that are distinguished by a very high sensitivity. However, quarks have not been seen in a single one of these experiments. In Table IV we show the corresponding estimates of upper bounds on the differential cross sections for quark production in nucleon-nucleon collisions. Particularly low values of these bounds have been established by measurements carried out in 1968–69 at IHEP[19] and at CERN[24].

The experimental arrangement for the quark search carried out at IHEP is shown in Fig. 4. To separate fractionally charged particles, the ionization of the particles was measured in a large number of spectrometric scintillation counters. Moreover, use was made of a time-of-flight spectrometer, allowing the determination of the masses of heavy particles, and a gas Cerenkov counter to suppress the background of light particles (muons, pions, kaons and antiprotons). The setup also incorporated a magnetic spectrometer with wide-gap optical spark chambers for further analysis of the registered events.

The conditions under which the quark search was carried out are shown in Table IV and in Fig. 2. It should be noted that in the main exposure the magneto-optical channel[26] was adjusted to the momentum p = 80 GeV/c, corresponding to the momentum of quarks with charge q = −1/3, $p_Q = |q|p = 26.7$ GeV/c. The use of the channel with the momentum p = 80 GeV/c is of special interest. Since the energy of the accelerated protons which bom-

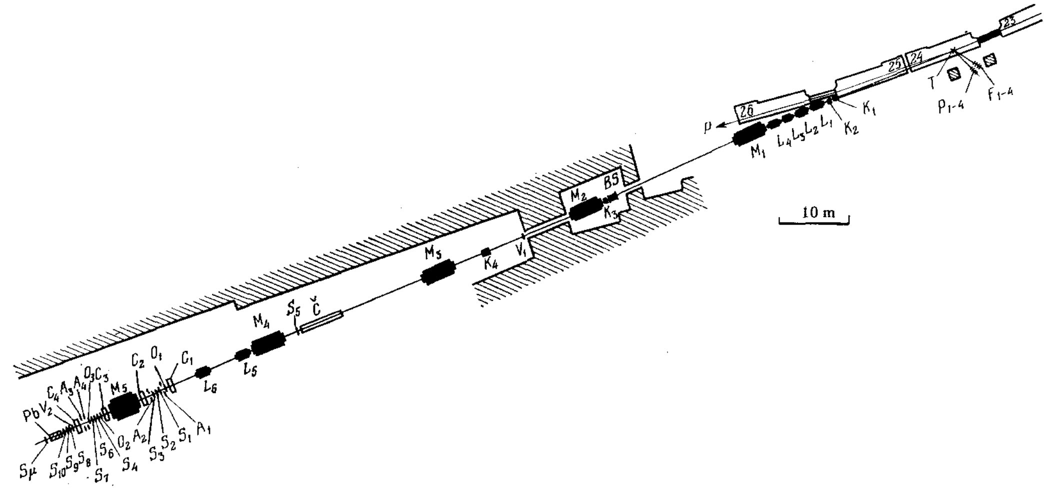

FIG. 4. Arrangement of the IHEP quark search experiment. p—beam of accelerated protons; T—target; $K_1$-$K_4$—collimators; $M_1$-$M_5$—bending magnets; $L_1$-$L_6$—quadrupole lenses; BS—beam shutter; $S_1$-$S_{10}$—spectrometric scintillation counters (to measure the ionization of particles); $0_1$-$0_3$, $A_1$-$A_4$—analyzing and guard counters to eliminate edge effects in the spectrometric counters; $V_1$, $V_2$, $S_5$—counters to measure the time of flight; C—threshold Cerenkov counter; $C_1$-$C_4$—wide-gap spark chambers of the magnetic spectrometer; the counter $S_\mu$ and lead absorber served to provide information on the interaction of quarks with matter if they were to be detected; $F_1$-$F_4$ and $P_1$-$P_4$—monitors.

TABLE IV. Searches for quarks with charge 1/3 and 2/3 with proton accelerators

| Reference | Exper. method | Proton energy | Length of channel. π | ϑ, mrad | p, GeV/c | $N_\pi$ | Target | q | $p_Q$, GeV/c | $d^2\sigma_Q/dp\,d\Omega\|_{90\%}$, cm²/sr × GeV/c | $M_{Q\max}$, GeV |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 20 | Bubble chamber | 31 | ~10⁻⁷ sec | 120 | 8.5 | 8·10⁶ | W | +1/3<br>+2/3 | 2,83<br>5,7 | $n_Q/n_\pi\|_{90\%} \leqslant 4\cdot10^{-6}$<br>$n_Q/n_\pi\|_{90\%} \leqslant 8\cdot10^{-6}$ | 2,0<br>2.5 |
| 21 | The same | 27.5 | 140 | 76 | 20 | [illegible]·10⁵ | Cu | −1/3<br>−2/3 | 6,7<br>13.4 | $2,2\cdot10^{-36}$<br>$\sim1.1\cdot10^{-35}$ | 2.5<br>2.5 |
| 22 | The same | 21 |  | 77 | 16 |  | Cu | −1/3<br>−2/3 | 5.3<br>10.6 | $10^{-35}-10^{-34}$<br>$(2\div5)\cdot10^{-34}$ | 2.0<br>2.2 |
| 23 | Scintillatio counters | 21 | 40 | 0 | — | 3·10⁷ μ | Be | ±1/3 |  | "Leptonic quarks"*) | 2 |
|  |  |  |  | 314 | 4.5 | 10⁶ | Be | [illegible]1/3 | 4.5 | $n_Q/n_\pi < 10^{-10}$<br>$n_Q/n_\pi\|_{90\%} \leqslant 10^{-[illegible]}$ | 2 |
| 19 | Scintillation counters, Cerenkov counters, wide-gap spark chambers | 70 | 125 | 0 | 50 | 0,8·10⁹ | Al | −1/3<br>−2/3 | 16.7<br>33.3 | $1.4\cdot10^{-3[illegible]}$<br>$7.7\cdot10^{-3[illegible]}$ | 4.4<br>4.8 |
|  |  |  |  | 0 | 67.5 | 0.8·10⁹ | Al | −1/3<br>−2/3 | [illegible]<br>45.0 | $3,8\cdot10^{-37}$<br>$2.4\cdot10^{-37}$ | 4.7<br>4,2 |
|  |  |  |  | 0 | 80 | No-back ground channel | Al | −1/3<br>−2/3 | 26.7<br>53.3 | $7.1\cdot10^{-38}$<br>$4.1\cdot10^{-38}$ | 4.8<br>3.3 |
| 24 | Scintillation counters, Cerenkov counters, streamer chambers | 27 | 90 | 0<br>6,5 | 32,7<br>22 | The same<br>2.3·10[illegible] | Be<br>Be | −1/3<br>−2/3 | 10.9<br>14.7 | $7.2\cdot10^{-3[illegible]}$<br>$5,2\cdot10^{-3[illegible]}$ | 2.7<br>2,4 |
|  |  |  |  | 44 | 20 | 5,6·10[illegible] | Be | ±1/3<br>±2/3 | 6.7<br>13.3 | $2.6\cdot10^{-3[illegible]}$<br>$1.3\cdot10^{-3[illegible]}$ | 2,5<br>2,5 |

[1] ϑ is the angle of emission of the secondary particles; p is the momentum of the secondary particles; $p_Q = |q|p$ is the momentum of quarks with charge q; $M_{Q\max}$ is the limiting value of the mass of the quarks produced in collisions of a proton with a nucleon at rest under the kinematic conditions of the given experiment. Quark searches were carried out in the range of masses from 0 to M, exceeding $M_{\max}$ by several GeV, in order to exploit the possible broadening of the range of masses due to the Fermi motion of the nucleons in the target nucleus. $N_\pi$ is the flux of pions (or other particles) passing through the apparatus; $d^2\sigma_Q/dp\,d\Omega|_{90\%}$ and $n_Q/n_\pi|_{90\%}$ are the upper limits of the differential cross sections and the ratios of the yields of particles (at fixed momentum $p_Q$) at the 90% confidence level (on the nucleon).

[2] In [25a] a quark search was made in liquid hydrogen bubble chamber using the reaction $\bar{p}p \to \bar{Q}Q$ with 1.3 GeV/c antiprotons. The charge of the particles Q, $\bar{Q}$ is $|q| = 1/3$, 2/3 and 4/3. No quarks were found in the analysis of 60,000 photographs. The limits on the cross sections are not quoted (they are about a microbarn).

[3] After submitting this paper for publication, the first results of the quark search with the CERN colliding proton beams (ISR) with energy 26 GeV + 26 GeV were published [25b]. In this work, no particles with charge q = 1/3 (2/3) were found among 0.6 × 10⁹ charged particles which passed through the apparatus. The following upper limits (at the 90% confidence level) were obtained for the total cross sections for quark production:

| Quark charge q | Range of quark masses, GeV | $\sigma_Q\|$ 90%, cm² |  |
|---|---|---|---|
|  |  | Phase-space model | Model with mean transverse momentum $\langle p_\perp\rangle = 0.4$ GeV/c |
| 1/3 | $2 \leqslant M_Q \leqslant 22$ | $4\cdot10^{-33}$ | $3\cdot10^{-34}$ |
| 2/3 | $2 \leqslant M_Q \leqslant 13-16$ | $(4-10)\cdot10^{-33}$ | $(3-10)\cdot10^{-34}$ |

*The range of the particles in this experiment was 1600 g/cm²; the beam was not analyzed with respect to momentum.

bard the target is equal to 70 GeV, secondary particles are produced at the target with a momentum less than 70 GeV/c. Thus, the experimental quark searches in this exposure were carried out under exceptionally favorable background conditions: The only particles which could pass through the channel were those with a fractional charge, as well as a small number of ordinary particles with integral charge that have scattered on the walls of the collimators, poles of the magnets and lenses or have passed through the shielding (muons). The number of background particles did not exceed several tens per hour.

In all the exposures, the selectivity of the arrangement proved to be much greater than necessary to suppress the background under the conditions of this experiment. Therefore, in the final stages of the analysis no use was made of the information from the spark chambers, Cerenkov counter and some of the scintillation counters. In this way, the efficiency of the set-up was increased somewhat, and no lower limit on the quark mass $M_Q$ was introduced. Even with such a reduction in the number of selection criteria, all of the registered events were rejected by several criteria.

The experimental quark searches carried out with other accelerators have been confined to the range of masses of these particles with energy up to 2.5–2.8 GeV (for collisions of primary protons with stationary nucleons). Therefore we shall give below only a very brief description of these works.

In the principal measurements in the experiments of the CERN group[24], use was also made of a "no-background channel," which was adjusted to a momentum corresponding to an energy greater than the primary energy of the accelerator. To identify fractionally charged particles, the ionization was measured in several scintillation counters and in a streamer chamber. The scheme of the set-up is shown in Fig. 5.

Previous quark searches[20–22] were carried out by means of bubble chambers in which tracks of particles with a small ionization were sought. A fundamental methodological difficulty which had to be faced in these experiments was the background from particles passing through the chamber (after its expansion) on the plateau of sensitivity. These events were characterized by a reduced density of bubbles along the track and could simulate the passage of fractionally charged particles through the chamber. In order to eliminate this background, in[21] the time at which the particles entered the chamber was determined by means of scintillation counters, together with the photographing of the bubble chamber.

In[27,28] searches were made for particles with high masses and charge $|q| \geq 2/3$, i.e., not only quarks but also long-lived fundamental particles with integral charge.

We shall discuss these experiments in greater detail below (Sec. II.3 and Table VII). We shall also consider separately quark searches in electromagnetic processes (Sec. IV.3).

**c) Comparison of the upper bounds on the differential cross sections for quark production with the data on the yields of heavy particles.** In Table V we make a comparison of the upper bounds on the differential cross sections for quark production with the data on the yields of heavy strongly interacting particles—antiprotons, antideuterons and antihelium-3[18,19,30]—for the same values of the momenta and production angles at which quark searches have been made. The effective numbers $N_{\text{"}\bar{p}\text{"}}$, $N_{\text{"}\bar{d}\text{"}}$ and $N_{\text{"}\overline{He^3}\text{"}}$ quoted in the table have the following significance: if quarks had the same production cross sections as antiprotons, antideuterons or antihelium-3, then the number of quarks that would be detected by the set-up during the search experiments would be equal to $N_{\text{"}\bar{p}\text{"}}$, $N_{\text{"}\bar{d}\text{"}}$ or $N_{\text{"}\overline{He^3}\text{"}}$. Thus, these quantities characterize the sensitivity of experiments on the search for fractionally charged particles. We can conclude from Table V that, if the quark mass is less than

TABLE V. Comparison of upper bounds on the differential cross sections for quark production with the data on the yields of heavy strongly interacting particles

| Proton energy | q | $p_Q$, GeV/c | $\theta_Q$, mrad | Upper bound $\frac{d^2\sigma_Q(p_Q,\vartheta_Q)}{dp\,d\Omega}\Big\vert_{90\%}$, cm²/sr·(GeV/c) | Antiprotons | | Antideuterons | | Antihelium-3($\overline{\mathrm{He}^3}$) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | $\frac{d^2\sigma_{\bar p}(p_{\bar p}=p_Q,\vartheta_{\bar p}=\vartheta_Q)}{dp\,d\Omega}$, cm²/sr·(GeV/c) | Effective number $N_{\text{“}\bar p\text{”}}$ | $\frac{d^2\sigma_{\bar d}(p_{\bar d}=p_Q,\vartheta_{\bar d}=\vartheta_Q)}{dp\,d\Omega}$, cm²/sr·(GeV/c) | Effective number $N_{\text{“}\bar d\text{”}}$ | $\frac{d^2\sigma_{\overline{\mathrm{He}^3}}(p_{\overline{\mathrm{He}^3}}=p_Q,\vartheta_{\overline{\mathrm{He}^3}}=\vartheta_Q)}{dp\,d\Omega}$, cm²/sr·(GeV/c) | Effective number $N_{\text{“}\overline{\mathrm{He}^3}\text{”}}$ |
| E = 70 GeV (IHEP experiment [19] | −1/3 | 16.7 | 0 | $1.4\cdot10^{-35}$ | $1.6\cdot10^{-27}$ | $2.6\cdot10^{8}$ | $1.7\cdot10^{-31}$ | $2.8\cdot10^{4}$ | $\sim 9\cdot10^{-36}$ | 1 |
| | | 21.5 | 0 | $3.6\cdot10^{-37}$ | $7.9\cdot10^{-28}$ | $5.0\cdot10^{9}$ | $5.0\cdot10^{-32}$ | $3.2\cdot10^{5}$ | $\sim 9\cdot10^{-36}$ | 57 |
| | | 26.7 | 0 | $7.1\cdot10^{-38}$ | $2.1\cdot10^{-28}$ | $6.9\cdot10^{9}$ | $1.1\cdot10^{-32}$ | $3.4\cdot10^{5}$ | $\sim 2\cdot10^{-36}$ | 65 |
| | | | | | $\sum N_{«\bar p»}=1{,}2\cdot10^{10}$ | | $\sum N_{«\bar d»}=6{,}9\cdot10^{5}$ | | $\sum N_{«\overline{\mathrm{He}^3}»}=113$ | |
| | −2/3 | 33.3 | 0 | $7.7\cdot10^{-36}$ | $6.0\cdot10^{-29}$ | $1.8\cdot10^{7}$ | $1.8\cdot10^{-33}$ | $5.3\cdot10^{2}$ | — | — |
| | | 43.0 | 0 | $2.1\cdot10^{-37}$ | $6.4\cdot10^{-30}$ | $6.9\cdot10^{7}$ | $1.1\cdot10^{-34}$ | $1.2\cdot10^{3}$ | — | — |
| | | 53.3 | 0 | $4.1\cdot10^{-38}$ | $1.1\cdot10^{-31}$ | $6.2\cdot10^{6}$ | $6\cdot10^{-37}$ | 35 | — | — |
| | | | | | $\sum N_{«\bar p»}=9{,}3\cdot10^{7}$ | | $\sum N_{«\bar d»}=1{,}8\cdot10^{3}$ | | $\sum N_{«\overline{\mathrm{He}^3}»}\sim 0.2-0.3$ | |
| E = 27 GeV (CERN experiment [24] | −1/3 | 10.9 | 0 | $7.2\cdot10^{-39}$ | $1\cdot10^{-28}$ | $5\cdot10^{10}$ | $\bar d/\bar p\sim10^{-6}$ | $\sim5\cdot10^{4}$ | — | — |
| | −2/3 | 14.7 | 6.5 | $5{,}2\cdot10^{-38}$ | $1.5\cdot10^{-29}$ | $6\cdot10^{8}$ | $\bar d/\bar p\sim10^{-6}$ | $\sim5\cdot10^{2}$ | — | — |

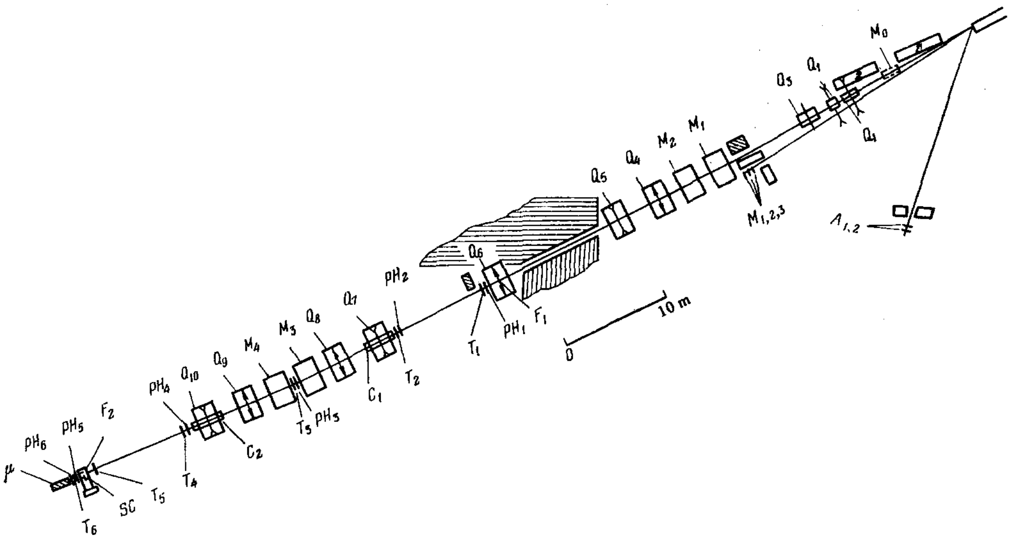

FIG. 5. Arrangement of the CERN quark search experiment [24]. $M_0$-$M_4$—bending magnets; $Q_1$-$Q_{10}$—quadrupole lenses; $F_1$ and $F_2$—beam foci; $T_1$-$T_6$—analyzing scintillation counter; $PH_1$-$PH_6$—spectrometric scintillation counter to measure the ionization of particles; SC—Streamer chamber to measure the ionization; $C_1$, $C_2$—Cerenkov counters; counters $T_1$, $T_5$ and $T_6$ were also used to measure the time of flight; the counter $\mu$, placed behind a layer of absorber (1.5 m of iron), served to provide information on the interaction of the particles; $A_1$, $A_2$—monitors.

4.8 GeV, then for 70 GeV protons quark production should be suppressed by approximately 10 orders of magnitude in comparison with antiprotons, 6 orders of magnitude in comparison with antideuterons, and 2 orders of magnitude in comparison with antihelium-3. The values of the total effective numbers quoted in Table V also enable us to compare the results of the experiments on quark searches carried out at IHEP and at CERN in the range of masses up to 2.5 GeV, where these experiments overlap. It is clear from the table that, if the sensitivity of the CERN experiment is several times higher than that of the IHEP experiment for quarks with charge $q = -1/3$ and mass $M_Q = M_p$, the data obtained at IHEP have a much higher sensitivity for the mass $M_Q = 2M_p$.

d) Estimates of upper bounds on the total cross sections for quark production. Upper bounds on the total cross sections for quark production can be determined from the relation

$$\sigma(M_Q)\Big\vert_{90\%}=\left(\frac{d^2\sigma_Q(p_1,\vartheta_1)}{dp\,d\Omega}\Big\vert_{90\%}\right)_{\exp}\left[\frac{\iint(d^2\sigma_Q/dp\,d\Omega)\,dp\,d\Omega}{d^2\sigma_Q(p_1,\vartheta_1)/dp\,d\Omega}\right]_{\text{theor}};$$

here $(d^2\sigma_Q(p_1,\theta_1)/dp\,d\Omega\vert_{90\%})_{\exp}$ is an estimate of the upper bound on the differential cross section (at the 90% confidence level) obtained experimentally at given values of the production angle $\theta_1$ and momentum $p_1$ of the quarks (see Table IV). In order to determine

$$\left[\frac{\iint(d^2\sigma_Q/dp\,d\Omega)\,dp\,d\Omega}{d^2\sigma_O(p_1,\vartheta_1)/dp\,d\Omega}\right]_{\text{theor}},$$

one must make definite assumptions about the production mechanism of quarks, which would make it possible to perform calculations of their angular and momentum distributions. Such calculations naturally constitute only estimates, since no reliable theoretical models exist. Such estimates are nevertheless useful, since they make it possible to compare from a unified point of view the results of different experimental quark searches carried out under quite diverse conditions, with both accelerators and cosmic rays.

The simplest assumptions about the production mechanism of quarks are made in the phase-space model, already discussed in Sec. II.1, according to which the angular distribution of quarks in the c.m.s. is isotropic and their momentum spectrum corresponds to the Lorentz-invariant phase space. In this way, one can obtain a possible form for the momentum and angular distributions of quarks in the l.s. (see Fig. 2) and determine upper bounds on the total cross sections for the production of these particles in the reactions (2) and (3). The results of these calculations are shown in Figs. 6 and 7.

We have already noted above that the phase-space model does not reflect the dynamics of the strong interactions, which can cause a significant narrowing of the angular distribution of quarks and modify their momentum distributions. Phase-space calculations have the further defect that they have been carried out only for the simplest reactions (2) and (3) with 4 particles in the final states, while the experimental data refer to all quark production processes of the type NN → NNQ$\bar{Q}$(nA) or NN → NQ$_1$Q$_1$Q$_2$(nA). One may expect that the phase-space model is well founded only for a range of masses near the production threshold, when the quarks move slowly in the c.m.s. and have an isotropic angular distribution. Approximately this situation holds for the production of proton-antiproton pairs, for which the yields of the particles and their momentum distributions near the production threshold are in agreement with calculations according to the phase-space model[34], while this model proves to be inadequate at higher primary proton energies.

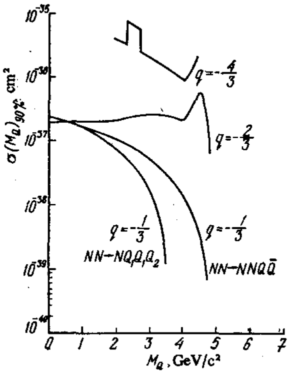

FIG. 6. Upper limits $\sigma(M_Q)|_{90\%}$ on the total cross sections for producing particles with fractional charge q = −1/3, −2/3 and −4/3 (see Sec. II.2) by 70 GeV protons in the reactions NN → NNQ$\bar{Q}$ and NN → NQ$_1$Q$_1$Q$_2$, determined according to the phase-space model (IHEP experiments [19]).

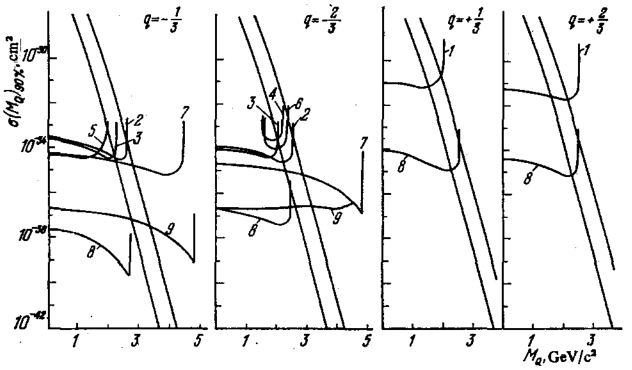

FIG. 7. Upper limits on the total cross sections for quark production obtained in accelerator experiments (according to the phase-space model for the reaction NN → NNQ$\bar{Q}$). 1–from [20], 2–[21], 3–[22], 4–[27], 5–[23], 6–[28], 7–first IHEP experiment [19a], 8–CERN experiment [24], 9–second IHEP experiment [19b]. The straight lines are two predictions for the total cross sections for quark production in the statistical model of Hagedorn [31]; the lower line in this model practically coincides with the predictions of the statistical theory of E. L. Feĭnberg et al. [32,33] (see Sec. IV).

The defects of the phase-space model have made it necessary to estimate upper bounds on the total cross sections for quark production with the aid of a simple phenomenological model that takes into account the characteristic features of the dynamics of the strong interactions[35]. This model makes use of the existing experimental information on the production of antiprotons and antideuterons. A formula has been derived which permits an adequate description of the experimental data on the momentum and angular distributions of antiprotons produced in nucleon-nucleon collisions for primary energies 19[36], 23[37] and 70[18,29] GeV. It has the following form (in the c.m.s.):

$$\frac{d^2\sigma(p^*, \vartheta^*)}{dp^*\, d\Omega^*} = A(s) \exp\left\{-\left[\frac{(p^*\cos\vartheta^*)^2}{B(s)+C} + \frac{(p^*\sin\vartheta^*)^2}{C}\right]\right\} p^{*2}\left[1-\left(\frac{p^*}{p^*_{\max}}\right)^2\right]^2; \tag{4}$$

here $p^*_{\max}$ is the maximum antiproton momentum, and $p^{*2}[1-(p^*/p^*_{\max})^2]^2 = R_4$ is the phase space for the reaction pp → pp$p\bar{p}$. The coefficient B(s) was chosen in the form $(P^*_{\max})^2 d$, where $P^*_{\max}$ is the maximum momentum of the system X (including the proton-antiproton pair) which is produced in the reaction pp → ppX (all quantities are in the c.m.s.). At energies near the antiproton production threshold, $(p^*)^2$ and $B(s) \ll C d^2\sigma/dp^*\, d\Omega^* = A(s)R_4$, by virtue of which the spectra of the particles are described by the phase-space model. The parameters d and C were determined from the data of[36], in which a detailed study was made of the spectra of antiprotons produced in proton-proton interactions at a primary momentum p = 19.2 GeV/c. They were found to have the values d = 0.21 and C = 0.27 (GeV/c)$^2$.

A comparison of calculations carried out according to Eq. (4) with the experimental data showed that the spectra of heavy strongly interacting antiparticles ($\bar{p}$, $\bar{d}$) is adequately described by the proposed formula.

This phenomenological model has been applied to the description of Q$\bar{Q}$ pair production processes. In other words, it was assumed that the differential cross sections for quark production have the form (in the c.m.s.)

$$\frac{d^2\sigma(p^*, \vartheta^*)}{dp^*\, d\Omega^*} = A(M_Q, S) \exp\left\{-\left[\frac{(p^*\cos\vartheta^*)^2}{\mathscr{P}^{*2}_{\max} d+C} + \frac{(p^*\sin\vartheta^*)^2}{C}\right]\right\} p^{*2}\left[1-\left(\frac{p^*}{p^*_{\max}}\right)^2\right]^2.$$

The same values of the parameters d and C are used here as in the description of the antiproton spectra[4)]. The function A(M$_Q$, S) naturally cannot be predicted within the framework of a phenomenological model. Below we shall present certain arguments regarding the form of the dependence A(S) for particles of mass M$_Q$.

In Fig. 8 we show the expected momentum spectra of quarks (in the l.s.) for the primary proton energy 70 GeV, calculated by means of the phenomenological model. They show that, for quarks with heavy masses M$_Q$ > 2.5–3 GeV and charge q = −1/3, the conditions of observation in the IHEP experiment were quite close to the optimum ones. In Fig. 9 we show the upper bounds $\sigma(M_Q)|_{90\%}$ on the total cross sections for quark production obtained by means of the phenomenological model for the experiments performed at the primary proton energy 70 GeV.

**e) Possible energy dependence of the cross section for quark production and allowance for the Fermi motion of the nucleons in the target nucleus**[35]. The estimates $\sigma(M_Q)|_{90\%}$ of bounds on the total cross sections for quark production which have been made in the phase-space model and in the phenomenological model and which are shown in Figs. 6, 7 and 9 correspond to the case of collisions of the primary protons with nucleons at rest. The motion of the nucleons inside the nucleus leads to a broadening of the range of collision energies and to an increase in the accessible masses of the quarks produced in the reactions (2) and (3). Estimates $\sigma(M_Q)|_{90\%}$ which allow for the motion of the nucleons inside the nucleus can be made on the basis of experimental data of Dorfan et al.[38] on the momentum spectrum of the nucleons in the copper nucleus. These estimates have a qualitative character, since the interpretation of the results of Dorfan et al. is ambiguous and since targets of various materials have been used in experiments on quark searches. In Fig. 10 we show the function $R(W, E_p)$, the probability of realizing the total energy $s^{1/2} = W$ in the c.m.s. at the primary energy $E_p$ of the bombarding protons, for the two values $E_p = 30$ and 70 GeV. Allowing for the Fermi motion of the n nucleons in the nucleus,[5)]

$$\sigma_{\text{eff}}(M_Q, E_p) = \int\limits_{W_{\text{thr}}}^{W_{\max}} R(W, E_p)\,\sigma(M_Q, W)\,dW;$$

here $\sigma(M_Q, W)$ is the total cross section for the production of quarks of mass $M_Q$ as a function of the energy in the c.m.s. or, equivalently, as a function of the primary energy. Since this dependence is unknown, we shall make several possible assumptions about the form of this function:

1) The simplest, although unfounded, assumption is that the cross section for quark production is constant, starting from the production threshold:

$$\sigma^{(1)}(M_Q, W) = \begin{cases} \sigma_a^{(1)}(M_Q) & \text{for } W > W_{\text{thr}} \\ 0 & \text{for } W < W_{\text{thr}} \end{cases} = 2(M_p + M_Q), \tag{5}$$

In this model

$$\sigma_{\text{eff}}(M_Q, E_p) = \sigma_{\text{eff}}^{(1)}(M_Q, E_p) = \int\limits_{W_{\text{thr}}}^{W_{\max}} R(W, E_p)\,\sigma^{(1)}(M_Q, W)\,dW = \sigma_a^{(1)}(M_Q)\int\limits_{W_{\text{thr}}}^{W_{\max}} R(W, E_p)\,dW.$$

2) A more substantiated form of $\sigma(M_Q, W)$ can be proposed on the basis of the assumed analogy between the production of quarks and of other heavy particles—antiprotons and antideuterons. In Fig. 11 we show the energy dependence of the total cross sections for $\bar{p}$ and $\bar{d}$ production, from which we see that the yields of these particles first rise rapidly with increasing energy and then vary rather slowly, perhaps even reaching a constant value. This behavior apparently means that many different channels for the production of heavy particles open up as the energy increases and, although the contribution of each individual channel falls off at high energy, the total cross section remains unchanged. The total cross section for producing pairs of heavy particles of mass $M_Q$ as a function of the energy in the c.m.s. W can be represented in the form

$$\sigma^{(2)}(M_Q, W) = \sigma_a^{(2)}(M_Q)\left\{1 - \exp\left[-b\left(\frac{W - 2M_p - 2M_Q}{M_Q}\right)^{5/2}\right]\right\}, \tag{6}$$

where near the threshold ($W - 2M_p - 2M_Q \ll M_Q$) we have

$$\sigma^{(2)}(M_Q, W) \approx b\sigma_a^{(2)}(M_Q)\left[(W - 2M_p - 2M_Q)/M_Q\right]^{5/2}. \tag{6'}$$

In this case

$$\sigma'_{\text{eff}}(M_Q, E_p) = \sigma_{\text{eff}}^{(2)}(M_Q, E_p) = \sigma_a^{(2)}(M_Q)\int\limits_{W_{\text{thr}}}^{W_{\max}} R(W, E_p)\left\{1 - \exp\left[-b\left(\frac{W - 2M_p - 2M_Q}{M_Q}\right)^{5/2}\right]\right\}dW \approx \sigma_a^{(2)}(M_Q)\,b\int\limits_{W_{\text{thr}}}^{W_{\max}} R(W, E_p)\times\left(\frac{W - 2M_p - 2M_Q}{M_Q}\right)^{5/2} dW$$

(since $R(W, E_p)$ is a very rapidly decreasing function and the integral depends on the integrand near $W_{\text{thr}}$). The coefficient b is determined from experiments on antiproton production and is assumed to be fixed and equal to b = 0.007. The choice of the value of b is not crucial for the rest of the analysis, since it merely determines the scale in which the "asymptotic" cross section $\sigma_a^{(2)}(M_Q)$ is measured. The effect of the Fermi motion becomes important at the very end of the range of

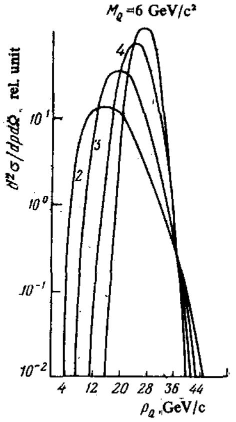

FIG. 8

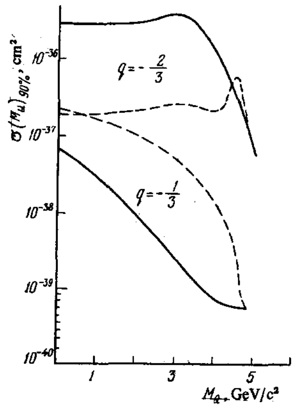

FIG. 9

FIG. 8. Expected momentum spectra of quark production in proton-nucleon interactions at E = 70 GeV for the phenomenological model. The production of particles with $M_Q$ = 6 GeV becomes possible as a result of the Fermi motion of the nucleons in the nucleus; for $M_Q \leqslant 4$ GeV the motion within the nucleus has a negligibly small effect.

FIG. 9. Upper limits $\sigma(M_Q)|_{90\%}$ on the total cross sections for producing fractionally charged particles in the reaction $NN \to NNQ\bar{Q}$ with 70 GeV protons according to the phenomenological model (solid curves). For comparison, we also show the values of $\sigma(M_Q)|_{90\%}$ obtained in the phase-space model (dashed curves).

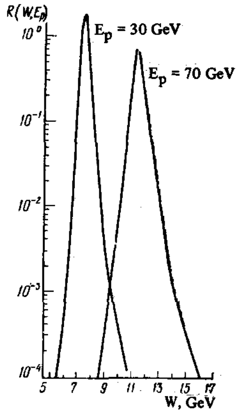

FIG. 10. Form of the function $R(W, E_p)$ for $E_p$ = 30 and 70 GeV.

masses of particles which can be produced in interactions of protons with nucleons at rest and in the region of "sub-threshold" production. Thus, for 70 GeV primary protons, the allowance for the Fermi motion does not show up for masses up to $M_Q$ = 4—4.5 GeV, and in this region[6)]

$$\sigma(M_Q)|_{90\%}=\sigma^{(1)}_{\text{eff}}(M_Q, E_p)|_{90\%}=\sigma^{(1)}_a(M_Q)|_{90\%}=\sigma^{(2)}_{\text{eff}}(M_Q, E_p)|_{90\%}.$$

The estimates $\sigma_{\text{eff}}(M_Q, E_p)$ of the upper bounds were made with the aid of the phenomenological model on the basis of the experimental data on the upper bounds on the differential cross sections for $E_p$ = 70 and 27 GeV. In this way, we determined upper bounds on the "asymptotic" cross sections $\sigma^{(1)}_a(M_Q)$ and $\sigma^{(2)}_a(M_Q)$. By means of this procedure, we can compare the results of various experimental quark searches, carried out at different primary energies (including those with cosmic rays; see Sec. III). This comparison is made in Figs. 12 and 13.

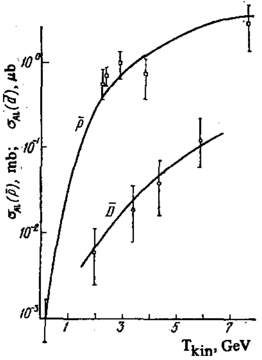

FIG. 11. Total cross sections for antiproton and antideuteron production as functions of the primary proton energy. The solid curves show the parametrization of this dependence according to Eq. (6) for $\sigma^{(2)}(M_Q, W)$ (W is the energy in the c.m.s.).

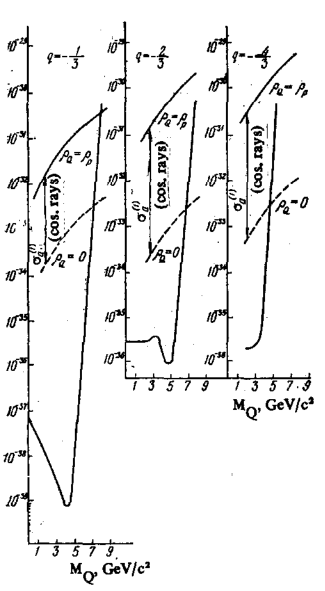

FIG. 12

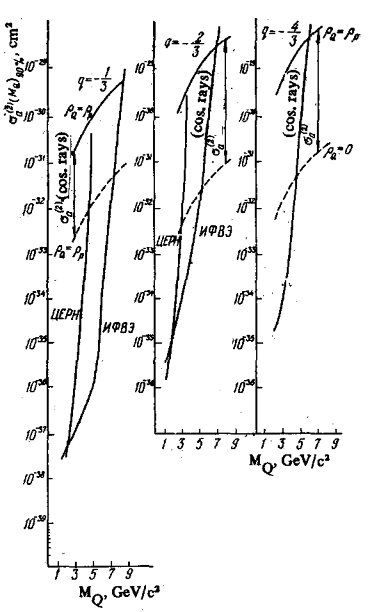

FIG. 13

FIG. 12. Upper limits $\sigma^{(1)}_a(M_Q)|_{90\%}$ on the "asymptotic" cross section for producing fractionally charged particles. The results of the experiment with the IHEP accelerator [19] are compared with the data obtained in cosmic rays, for various assumptions about the absorption coefficient of quarks in the atmosphere ($\rho_Q = \rho_p$ and $\rho_Q = 0$; see Sec. III.2).

FIG. 13. Upper limits $\sigma^{(2)}_a(M_Q)|_{90\%}$ on the "assymptotic" cross section for producing fractionally charged particles. The results obtained with the IHEP accelerator [19] are compared with the data of the experiment with the CERN accelerator [24] and experiments in cosmic rays, for various assumptions about the absorption coefficient of quarks in the atmosphere ($\rho_Q = \rho_p$ and $\rho_Q = 0$; see Sec. III.2).

## 2. The search for polyquarks

The experiments carried out with accelerators have shown that, if free quarks with a charge q = 1/3 or 2/3 exist, then either their masses must exceed ≈ 5 GeV or their production cross sections are unusually small. These results refer to long-lived particles with a lifetime greater than $10^{-6}$—$10^{-8}$ sec. It had been conjectured earlier[11] that there may exist stable systems of two or more quarks with charges 4/3, 5/3, 7/3, etc., whose masses, owing to the large binding energy, may be much less than the masses of free quarks. The free quarks with charges 1/3 and 2/3 may then be unstable and decay, emitting lighter particles such as those with charge q = 4/3 (diquarks or polyquarks). Thus, the negative results of quark searches do not exclude the possibility of observing polyquarks with the existing accelerators, provided that free quarks have a mass > 5 GeV or have a small lifetime.

In principle, of course, there can also exist polyquarks with charges q = 1/3 and q = 2/3 (e.g., $(nn)_{q=2/3}$, $(pnnn)_{q=-1/3}$, $(pn)_{q=1/3}$, etc.). Consequently, the absence of polyquarks with charges q = −1/3 and −2/3 and with masses up to 5 GeV evidently means that in this range of masses there should also be no polyquarks with q = 4/3, etc. However, we must not forget that the properties of quarks (as well as their very existence) are speculative; direct experimental searches for quarks with charge q = 4/3, etc. are therefore highly desirable. Such experiments have been performed with both accelerators and cosmic rays.

Polyquarks, which will be denoted by L, may be produced as a result of quark decays or directly in nucleon-nucleon collisions. Some of the simplest polyquark production reactions are:

$$N+N\to N+N+\mathscr{L}+\overline{\mathscr{L}},\quad N+N\to N+\mathscr{L}+Q$$

(e.g., L = $(pp)_{q=+4/3}$, Q = $n_{q=-1/3}$),

$$N+N\to N+\mathscr{L}+\overline{Q}$$

(e.g., L = $(ppnn)_{q=+2/3}$, $\overline{Q}=\overline{n}_{q=+1/3}$), etc.

A search for quarks with charge q = −4/3 was made with the IHEP 70 GeV accelerator[39]. The measurements were carried out with the beam of secondary negative particles extracted at an angle θ = 47 mrad and with momentum p = 13.3 GeV/c for particles with unit charge, corresponding to a diquark momentum $p_L = p|q|$ = 17.8 GeV/c. The scheme of the experimental set-up is shown in Fig. 14. Heavy particles with charge q = −4/3

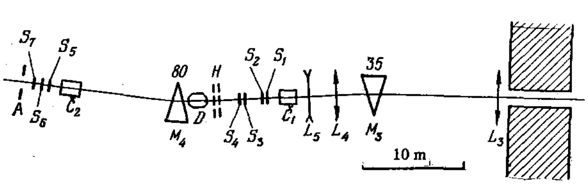

FIG. 14. Scheme of the experiment on the search for diquarks with charge q = −4/3 [39]. $M_3$, $M_4$—analyzing magnets (the numbers show the angle of deflection of the beam in mrad); $L_3$-$L_5$—quadrupole lenses; $S_1$-$S_7$—spectrometric scintillation counters; $C_1$, $C_2$—gas threshold Cerenkov counters, suppressing the background of pions, kaons and antiprotons to the level ~ 3 × $10^{-9}$; D—gas differential Cerenkov counter to suppress the background of antideuterons, sensitive to diquarks with masses 2.3-2.7 GeV; H—hodoscope of 6 scintillation counters to suppress the background of double particles; A—guard counter with aperture (the initial part of the magneto-optical channel is not shown).

were identified by repeated measurement of the electric charge of the particles according to their ionization energy loss in two groups of scintillation counters separated by an analyzing magnet, as well as measurement of their velocity by means of gas Cerenkov counters.

During the course of the experiment $3.9 \times 10^{10}$ particles passed through the apparatus, and not a single diquark with charge $q = -4/3$ and momentum $p_L = 17.8$ GeV/c was found in the mass ranges 1.9—2.3 GeV and 2.7—4.4 GeV. Two events which were registered in the mass range 2.3—2.7 GeV are interpreted as background from 13.3 GeV/c antideuterons. The corresponding estimates of the upper bounds on the differential cross sections for diquark production are given in Table VI. In Fig. 6 we show the upper bounds on the total cross section for the production of particles with $q = -4/3$ which are obtained in the phase-space model, and in Figs. 10 and 11 we show the estimates of bounds on the asymptotic cross sections obtained from the phenomenological model.

TABLE VI. Estimates of the upper bounds on the relative,

$$R = \frac{d^2\sigma_{\mathscr{L}}(p_{\mathscr{L}} = 17.8 \text{ GeV/c}, \vartheta = 47 \text{ mrad})/dp\, d\Omega}{d^2\sigma_{\pi}(p_{\pi} = 13.3 \text{ GeV/c}, \vartheta = 47 \text{ mrad})/dp\, d\Omega},$$

and the absolute, $d^2\sigma_{\mathscr{L}}/dp\, d\Omega$, differential cross sections for quark production by 70 GeV protons on nucleons at an angle 47 mrad in the l.s. (at the 90% confidence level).

| $p_{\mathscr{L}}$, GeV/c | Ranges of diquark masses, GeV/c² | $R\|_{90\%}$ | $d^2\sigma_{\mathscr{L}}/dp\,d\Omega\,\|_{90\%}$, cm²/sr·(GeV/c) |
|---|---|---|---|
| 17.8 | $1.9 \leqslant M_{\mathscr{L}} \leqslant 2.3$ | $6.2 \cdot 10^{-11}$ | $1.6 \cdot 10^{-36}$ |
| | $2.7 \leqslant M_{\mathscr{L}} \leqslant 4.4$ | | |
| | $2.3 \leqslant M_{\mathscr{L}} \leqslant 2.7$ | $1.4 \cdot 10^{-10}$ | $3.8 \cdot 10^{-36}$ |

## 3. The Search for Fundamental and Charmed Particles with Integral Charges

The production of fundamental or supercharged ("charmed") particles with integral charge can occur in various reactions, depending on the nature of these particles and on the presence of specific conserved quantum numbers for them. If supercharge is conserved (or if its conservation is weakly violated), these particles can be formed in the pair production reactions

$$N + N \to N + N + \alpha + \bar{\alpha}. \tag{7}$$

Fundamental particles may also be produced in nucleon dissociation reactions. In composite models in which the nucleon is a system of three fundamental components (see Sec. I), the dissociation reaction has the form

$$N + N \to N + a + b + c.$$

There also exist certain models involving two fundamental triplets $\alpha$ and $\beta$, in which the nucleon has the structure $(\bar{\alpha}\beta)$.[7] In that case the dissociation reaction proceeds according to the scheme

$$N + N \to N + \bar{\alpha} + \beta. \tag{8}$$

Searches for new stable or long-lived particles with masses differing from the known values have been made in numerous experiments with accelerators in which the masses of particles were determined by measuring their

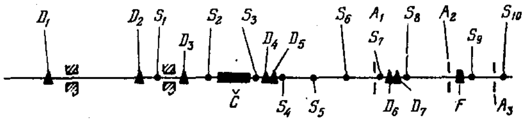

FIG. 15. Scheme of the experiment on the search for heavy particles [27]. $D_1$-$D_7$—bending magnets; the quadrupole lenses are not shown; $S_1$-$S_{10}$—scintillation counters for time measurements; to reduce the background, a comparison was made of the time of flight of the particles between the three pairs of counters, $S_1$-$S_5$, $S_3$-$S_8$ and $S_6$-$S_{10}$, each separated by 33 m; $A_1$-$A_3$—guard counters; C—threshold Cerenkov counter to suppress the background of light particles; F—differential Cerenkov counter with a range of sensitivity $0.81 < \beta < 0.96$.

TABLE VII. Searches for particles with integral charge using proton accelerators.

| Reference | Proton energy, GeV | Length of channel, m | θ, mrad | Target | p, GeV/c | $N_\pi$ | q | $M_\alpha$ max, GeV | Mass range in which the apparatus is sensitive, GeV | $\frac{d^2\sigma}{dp\,d\Omega}\Big\|_{90\%}$, cm²/sr·(GeV) | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 28 | 30 | 160 | 120 | W | 7 | $5 \times 10^8$ (allowing for the effect of the analyzer) | −1 to −2/3 | 2.8 | $2.5 \leqslant M_\alpha \leqslant 6$ ($q = -1$),<br>$1.5 \leqslant M_Q \leqslant 4$ ($q = -2/3$) | $\frac{n_\alpha}{n_\pi}\Big\|_{90\%} = 5 \cdot 10^{-9}$*$\cdot R$ | Using an analyzer and time-of-flight measurement. Result of the experiment:<br>$\frac{\sigma_\alpha}{\sigma_{\bar p}} < \begin{cases} 10^{-3}, & M_\alpha = 3 \text{ GeV} \\ 1/3, & M_\alpha = 4 \text{ GeV} \end{cases}$ owing to the Fermi motion of the nucleons in the nucleus |
| 27 | 30 | 100 | 76 | Be | 4.5—6 | $8 \cdot 10^9$ | −1 to −2/3 | 2.8 | | | Antideuterons were observed:<br>$\bar{d}/\pi^- \approx (5{,}5 \pm 1.5) \cdot 10^{-8}$ |
| | | | | | 9 | $2.4 \cdot 10^{10}$ | | | $2 \leqslant M_\alpha \leqslant 3$ | $5 \cdot 10^{-36}$ *) | |
| | | | | Fe | 10 | $1.6 \cdot 10^{10}$ | | | $3 \leqslant M_Q \leqslant 4$ ($q = -2/3$),<br>$3 \leqslant M_\alpha \leqslant 5$ ($q = -1$, reaction (7)),<br>$3 \leqslant M \leqslant 7$ ($q = -1$, reaction (8)) | $8 \cdot 10^{-37}$ *)$\cdot R$ | Owing to the Fermi motion of the nucleons in the nucleus, the mass range extends above $M_{\alpha\max}$. But the estimates of the bounds on the cross sections for this region rise sharply (by over 5 orders of magnitude for $M_\alpha = 5$ GeV; reaction (7)). |
| 41 | 70 | 140 | 0—12 | Al | 25—39 | | −1 | 4.8 | $M_{\bar p} < M_\alpha < M_{\bar d}$ | $n_\alpha/n_\pi\|_{90\%} = 5 \cdot 10^{-9}$,<br>$n_{\bar t}/n_\pi\|_{90\%} = 10^{-9}$ | |
| 30 | 70 | 125 | 27 | Al | 10 | $2.4 \cdot 10^{11}$ | −1<br>−2 | 3.8<br>4.7 | $2 \leqslant M_\alpha \leqslant 2.8$<br>$2 \leqslant M \leqslant 4.8$ | $1.2 \cdot 10^{-35}$<br>$1 \cdot 10^{-36}$ | 5 antihelium-3 nuclei were detected, for which $d^2\sigma/dp\,d\Omega = 2.2 \times 10^{-36}$ for other doubly charged particles the upper limit was $d^2\sigma/dp\,d\Omega\|_{90\%} = 10^{-36}$ (all in cm²/sr·(GeV/c) per nucleon). |
| 42 | 70 | 160 | 0 | Al | 25 | | −1 | 4.8 | $3 \leqslant M \leqslant 15$ | $1.5 \cdot 10^{-35} \cdot R$ | No estimates were made of bounds on the cross sections in the mass region depending on the Fermi motion. |

The notation is the same as in Table IV. $M_{\alpha\max}$ is the maximum mass of the particles formed in collisions with a stationary nucleon according to (7). Older results are not quoted. R is a factor depending on the Fermi motion of the nucleons in the target nucleus.

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*Results obtained from data presented in the corresponding work.

momenta and velocities. A classical example of such experiments was the discovery of the antiproton in 1955 by Segrè and his co-workers[40]. The results of a number of more recent experiments are summarized in Table VII. New unknown elementary particles were not found in any of these experiments, although they did lead to the discovery of the antideuteron[27] and antihelium-3[30] nuclei. In Fig. 15 we show the scheme of one of the experiments on the search for particles with heavy masses[27], which was carried out with the accelerator of the Brookhaven laboratory in the U.S.A. (energy 33 GeV). By repeated determination of the momenta and velocities of the particles, performed in this experiment by means of Cerenkov counters, as well as time-of-flight measurements, it was possible to raise the sensitivity of the set-up to $\sim 10^{-10}$ of the pion flux. Antideuterons were observed for the first time in this experiment. The experiment of the IHEP group in which antihelium-3 nuclei were detected[30] was characterized by a still greater sensitivity ($\sim 10^{-11}$) to doubly-charged particles.

Thus, fundamental long-lived particles with integral charges, "charmed" particles, etc. have so far not been observed. It would be of great interest to extend the scope of the searches so that the experiments become sensitive to short-lived particles. In fact, if, for example, supercharge is conserved only in the strong or in the strong and medium-strong interactions, then the lifetimes of supercharged particles with integral values of the electric and baryon charges would be quite small ($\sim 10^{-20}$–$10^{-22}$ sec). Since these particles should be produced in pairs with the greatest probability, the mass-defect method of searching for short-lived particles is inapplicable, and it may be very complicated or entirely impossible to employ the effective-mass method if the number of decay products is large, and particularly if there are neutral $\pi^0$ mesons among them. Consequently, we see no effective means of carrying out such search experiments at the present time. Nevertheless, individual attempts have been made to search for relatively short-lived "charmed" particles. Thus, in[43] a study was made of the possible annihilation of antiprotons stopped in a liquid-hydrogen bubble chamber in the channel $\bar{p} + p \to \bar{c} + c$, where c are "charmed" particles with masses $<940$ MeV. For particles c having masses $>650$ MeV, the weak decay channels $c \to \pi\pi$ and $c \to K\pi$ with lifetimes $<10^{-12}$ sec are possible. Owing to these decays, the reaction $\bar{p} + p \to \bar{c} + c$ can be observed in the chamber as a process taking place according to the scheme $\bar{p} + p \to K^0 + \pi^+ + \pi^- + \pi^0$ (with obvious violation of strangeness, which, however, depends on the weak decays). Such cases were not found among 200,000 annihilation events, and the following limit was established for them:

$$N(\bar{p}p \to K_1^0\pi^+\pi^-\pi^0)/N(\bar{p}p \to K^0\bar{K}^0\pi^+\pi^-) < 1/700.$$

However, as the ratio of the partial probabilities of the decays $c \to \pi\pi$ and $c \to K\pi$ is unknown, it is not possible to obtain from this a bound on the ratio $N(\bar{p}p \to \bar{c}c)/N(\bar{p}p \to \bar{K}K)$. In any case, it is desirable to repeat the experiments of this type for antiprotons with a large momentum, in order to extend the mass range for the search for such "charmed" particles.

## III. QUARK SEARCHES IN COSMIC RAYS AND BY PHYSICO-CHEMICAL METHODS

**1. Results of experimental searches in cosmic rays.** There occur in cosmic rays particles of very high energies, which, when interacting in the atmosphere, can produce quarks or fundamental particles with masses greater than what is possible with the existing accelerators. However, the fluxes of high-energy cosmic particles are small. It is therefore not possible to attain such small values of the production cross sections for particles in experiments with cosmic rays as when working with accelerators. Experiments with cosmic rays have a number of specific peculiarities when compared with experiments with accelerators. First of all, in cosmic-ray studies there is generally no selection of the particles according to their momenta, and no problems connected with the optimum choice of the momenta of the secondary particles arise. However, in this case there arises the complicated problem connected with the possibility that a quark enters the experimental apparatus in conjunction with other secondary charged particles formed in the same interaction event. In a number of cases in which no special measures are taken to allow the search for fractionally charged particles in the presence of such showers, these secondary particles make the apparatus insensitive to the detection of quarks.

Work on the search for quarks and fundamental particles in cosmic rays has followed three main courses:

a) The search for single fractionally charged particles. Searches for single (without shower accompaniment) fractionally charged particles in cosmic rays have been made in numerous experiments, which are rather similar in their technique. In all these experiments, repeated measurements of the ionization of the particles were made in scintillation or proportional counters in order to distinguish quarks. In addition, most of the set-ups contained track detectors (spark, wire and streamer chambers, and Conversi flash tubes) which made it possible to suppress the background from showers and select events associated with the passage of single particles through the apparatus. In Fig. 16 we show the scheme of one of the experiments[44] on the search for single quarks in cosmic rays. The results of the main studies of this type which have been carried out in recent years are summarized in Table VIII$^{8)}$. Quarks

TABLE VIII. Results of experiments on the search for relativistic quarks in cosmic rays

| Reference | Matter in the apparatus, g/cm² | Number of counters | Track detectors | $S\Omega$, $m^2$sr $ep$ | Height above sea level | Time of measurement, h | Charge q | Number of events detected | Upper bound on the quark flux $I(0^\circ)_{90\%}$, $10^{-10}$ cm$^{-2}$sr$^{-1}$sec$^{-1}$ | $I(0^\circ)_{90\%}$, allowing for the matter in the apparatus**) |
|---|---|---|---|---|---|---|---|---|---|---|
| 45 | 41 | 8 layers Soc | H (48) | 1.0 | 0 m, 1030 g/cm² | 1000 | 4/3 | 2 | 1.5 *) | 2.3 *) |
| 46 | ≈ 40 | 6 Soc | CFT | 0.47 | 0 m, 1030 g/cm² | | 1/3<br>2/3 | — | 1.15<br>0.8 | 1.4 *)<br>1.0 *) |
| 47 | ≈ 50 | 3 ScC<br>2 Pc | H of PC (16) | 0.52 | 0 m, 1030 g/cm² | 2224 | 1/3<br>2/3 | 0 | 0.5 *)<br>3.0 *) | 0.6 *)<br>3.9 *) |
| 48 | 115 | 6 ScC | WGSC | 0.95 | 750 m, 940 g/cm² | 1160 | 1/3<br>2/3 | 0<br>1 | 1.0<br>1.6 | 1.7 *)<br>3.0 *) |
| 44 | ⩾ 60 | 6 СцС | WSC | 0.38 | 0 m, 1030 g/cm²<br>2770 m, 740 g/cm² | 2048<br>5540 | 1/3<br>1/3 | 1<br>0 | 2.1 *)<br>0.57 | 2.7 *)<br>0.8 *) |
| 49 | | | | | 0 m | | 4/3—7/3 | | 8.2 | |
| 96***) | 120 | 8 ScC | WGSC | 0.63 | 2750 m, 750 g/cm² | 1500 | 1/3<br>2/3<br>4/3 | | 0.83<br>0.96<br>4.1 | 1.4<br>1.6<br>12 *), |

Notation: WSC—wire spark chamber, WGSC—wide-gap spark chamber, CFT—Conversi flash tube, ScC—scintillation counters, PC—proportional counters, H(48)—hodoscope (48 elements).

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* Obtained from data given in the corresponding work.

** Assuming interaction cross sections $\sigma(Q + C) = \sigma(\pi + C)/2 = 100$ mb for quarks, $\sigma(\mathcal{L} + C) = \sigma(\pi + C) = 200$ mb for diquarks.

***Added in proof.

were not observed in any of these studies, and upper bounds were established on the possible fluxes of these particles in cosmic rays.

b) The search for single particles with integral charge. In Table IX we show the results of searches for single heavy particles based on measurements of their mass according to their momentum and velocity, range and ionization, etc. In Fig. 17 we show the scheme of one of the experiments and give the corresponding experimental details. New heavy particles have also not been observed in any of these experiments. However, it should be noted that these experiments are sensitive only to rather slow particles and that it is difficult to interpret their results quantitatively.

c) The search for quarks and heavy particles in extensive atmospheric showers. In recent years great attention has been given to the search for quark production in processes of ultra-high energies ($10^{13}-10^{15}$ eV) accompanied by extensive atmospheric showers. These experiments can be divided into two categories. In the first group, searches have been made for particles with a small ionization among the fluxes of cosmic particles, using track detectors (Wilson chambers, streamer chambers, etc.)[55-61]. In experiments of the second type[62-64], attempts have been made to observe heavy, relatively slow particles that are retarded in relation to the front of the shower.

In the experiments of the Sydney group (McCusker et al.[55]), a study was made of extensive atmospheric showers corresponding to primary energies $10^{15}$ eV. The set-up included 4 small Wilson chambers triggered by a system of Geiger counters. The density of particles in the showers was determined by means of scintillation counters. In an analysis of ≈5000 extensive atmospheric showers, from among ≈55,000 tracks in the chambers 5 tracks were found which had a mean ionization 0.58, 0.45, 0.46, 0.58 and 0.48 (in units of specific ionization). Two of these events corresponded to shower energies $\sim 1.5 \times 10^{15}$ eV, and the shower axes fell within the field of the chambers. The authors conclude that they detected 5 quarks with charge q = 2/3, whose flux is equal to $5.5 \times 10^{-10}$ $\text{cm}^{-2}\text{sr}^{-1}\text{sec}^{-1}$. This means that, on the average, about 10 quarks are produced in showers with an energy $10^{15}$ eV.

The experiments of McCusker's group have been subjected to serious criticism in a number of other papers[65-69]. This criticism reduces mainly to the following two points: 1) allowance for the relativistic growth of the ionization in the argon of the Wilson chamber (by a factor ~1.5 in comparison with the minimum ionization when $\gamma \sim 3$) shows the the results of the Sydney group can evidently be explained by fluctuations in the number of droplets for tracks of slow muons or electrons which have an energy near the minimum of the curve of ionization losses; 2) the tracks on the photographs obtained by McCusker's group—the "quark candidates"—go at an angle $\gtrsim 20$ mrad with respect to the axis of the shower; such particles diverge from the main stream of the shower and, consequently, should be detected in experiments in which the equipment is sensitive to single quarks. However, in these experiments (see Table VIII) quarks have not been found, and an upper bound on their fluxes has been obtained which is an order of magnitude lower than in the experiments of the Sydney group.

TABLE IX. Searches for slow single quarks and fundamental particles in cosmic rays

| Reference | Method | Upper limit on the flux of particles, $\text{cm}^{-2}\text{sr}^{-1}\text{sec}^{-1}$ |
|---|---|---|
| 51 | Measurement of the range and velocity (by time of flight); particles with unit charge and $0.5 < \beta < 0.9$. | $I(87^\circ) \leqslant 5 \cdot 10^{-8}$ (90% confidence level); no correction for absorption. |
| 52 | Measurement of the momentum in a magnetic field and the velocity (by time of flight); particles with unit charge and $\beta < 0.75$. | $I(75^\circ) \leqslant 2.4 \cdot 10^{-8}$ (90% confidence level); production cross section $< 10^{-29}$ cm$^2$. |
| 53 | Measurement of the range and velocity (according to the ionization and by Cerenkov counters); particles with arbitary charge (i.e., q = 1/3, 2/3, 1, 4/3, etc.) and $\beta < 0.9$. | $I(0^\circ) \leqslant 4.9 \cdot 10^{-10}$ (90% confidence level); allowance for absorption raises the limit by a factor 17. |
| 54 | Measurement of the range and velocity (by a Cerenkov counter); particles with unit charge and momenta: $M = 5m_p$, 860-1080 MeV/c; $M = 10m_p$, 1250-2250 MeV/c. | $I(0^\circ) \leqslant 3.4 \cdot 10^{-8}$; no correction for absorption. |

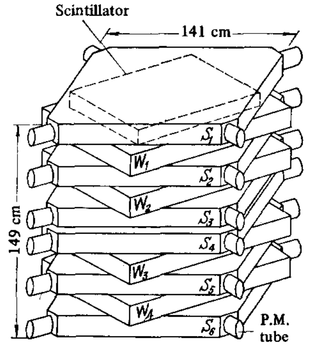


FIG. 16. Experimental arrangement to search for single relativistic quarks with charges q = 1/3 and 2/3 in cosmic rays [44]. $S_1$-$S_6$—scintillation counters for repeated measurement of the ionization and identification of fractionally charged particles; $W_1$-$W_4$—wire spark chambers to distinguish single particles and suppress the background of soft showers.

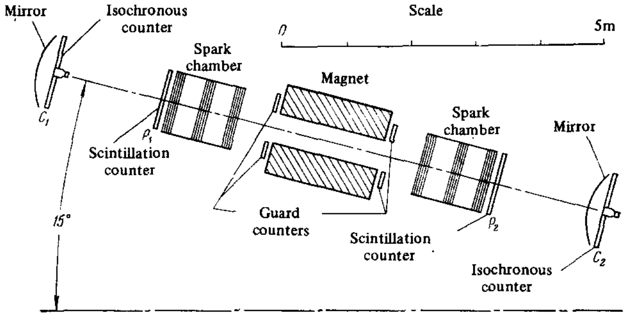


FIG. 17. Experimental arrangement [52] to search for single particles with heavy masses by determining their momenta and velocities. The arrangement consists of a large magnet, spark chambers and two systems of scintillation counters $C_1$, $C_2$ and $P_1$, $P_2$ for measuring the time of flight. The counters $C_1$ and $C_2$ are special coungers with isochronous collection of light to improve the time resolution, which was $\tau = 1.6$ nsec.

It was reported in[56] that, in the analysis of a series of 10,000 photographs in a 100 cm heavy-liquid bubble chamber exposed to an accelerator, a track of a cosmic particle accompanied by a shower was found with a reduced ionization. The authors interpret this event as a photograph of the passage through the chamber of a quark with charge q = 2/3 and mass $M_Q \leq 6.5$ GeV or q = 1/3 and $M_Q = 8.0 \pm 3.0$ GeV. However, this conclusion is not convincing. Their work has been strongly criticized by physicists with great experience of the operation of the same bubble chamber, who showed[70] that the reduced ionization on the "quark" photograph can easily be attributed to a background cosmic-ray particle which arrived too early (in relation to the time of expansion), when the chamber was not yet on its plateau of sensitivity. Moreover, the event in question corresponds to the small part of the exposure during which the chamber had not yet entered its correct operational mode. It was also noted that the bubble-chamber experiment has a sensitivity lower than that of the experiments of McCusker's group by a factor $10^4$, since its total effective time is ~ 75 sec.

After the appearance of[55,56], several further experiments were performed[57–61] in which quarks were sought in cosmic-ray showers and not detected. The results of these studies are shown in Table X.

One of these studies carried out by the group of Faissner[57] made use of a complex system of a large number of proportional counters and scintillation counters operating on-line with a computer. The scheme of this experiment is shown in Fig. 18. The set-up made it possible to distinguish fractionally charged particles accompanied by showers with a small multiplicity of particles, according to the ionization in the counters. In another study by the same group[58], a quark search was carried out with the aid of a large streamer chamber (100 × 32 × 26 cm) triggered by showers that were detected by a system of scintillation counters. By measuring the ionization of the tracks in a streamer chamber, it was possible to make a search for quarks with charges $q = 2/3$ and $1/3$ in the presence of showers of particles with a density up to 500 particles/m$^2$.

Hazen[59] carried out a search for quarks with charges $q = 2/3$ and $1/3$ by the same method as in the experiments of McCusker—with the aid of a Wilson chamber triggered by cosmic-ray showers of energy $\sim 10^{15}$–$10^{16}$ eV. Special measures were taken to ensure that the measurements of the ionization and the determination of the time of passage of a particle through the chamber (which is important to suppress the background) could be made under the most favorable conditions. The negative result of Hazen's experiments is in direct contradiction with the work of McCusker and his coworkers.

The Berkeley-Livermore group[60] also carried out a quark search in cosmic-ray showers by measuring the ionization with a Wilson chamber. No quarks were detected in the analysis of the ionization of about 100,000 shower tracks, although the expected number of such events on the basis of the data of the McCusker experiments is about 10–20.

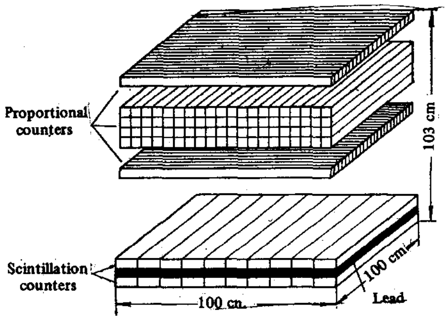


FIG. 18. Experimental arrangement [57] to search for quarks in low-density showers of particles. In the first variant of the work, the arrangement contained 6 layers of proportional counters (120 counters) and was sensitive to the detection of particles with charge $q = 1/3$. Later [58] 12 layers were set up instead of 6 (with 6 layers in each direction), making it possible to search also for quarks with charge $q = 2/3$. The arrangement was triggered by coincidences of two counters of the lower scintillation hodoscope, one above the other. The trigger rate was 126 sec$^{-1}$. The registration of events and their subsequent analysis was carried out by means of a computer "on-line" with the apparatus. The number of triggers during the period of operation was $\sim 1.9 \times 10^8$.

Another series of experiments on the search for quarks and heavy, relatively slow fundamental particles generated in extensive atmospheric showers is based on the search for events which are retarded in time with respect to the front of the shower due to relativistic particles. In fact, we may assume that, owing to the rapid fall-off of the spectrum of primary protons of cosmic radiation, quarks of mass $M_Q$ should be produced mainly near their production threshold. The energy of a quark in the l.s. is $E_Q \approx M_Q\gamma_c \approx M_Q^2/M_p$ (for $M_Q \gg M_p$). We see from this that $1 - \beta_Q \approx M_p^2/2M_Q^2$ and that a heavy particle of mass $M_Q$ lags behind the light ultra-relativistic particles by a time $\Delta t \approx 2ZM_Q^2/M_p^2$, where Z is the altitude at which the shower is produced. For particles of mass $M_Q = 10$ GeV produced at an altitude of about 7 km, we have $\Delta t \approx 80$ nsec. To determine the mass of such a particle, it is also necessary to measure its energy. In a number of cases, it is sufficient to convince oneself that the energy of the detected retarded particle is above a definite threshold in order to eliminate the background of known slow particles.

In certain experiments on the search for retarded particles, the additional assumption was made that particles with a large mass can transfer only a small fraction of their energy in a single collision event, so that they are weakly absorbed in matter. The detectors in these experiments were placed under a heavy layer of matter, thereby specifying an energy threshold and also improving the experimental background conditions. The results of experiments on the search for retarded particles are given in Table XI.

An indication of the possible existence of heavy fundamental particles was obtained in only one of these experiments[64]. However, the authors themselves note that their data do not constitute a proof of the observa-

TABLE X. Quark searches in cosmic rays

| Reference | Method | Results |
|---|---|---|
| 55 | 4 Wilson chambers controlled by extensive atmospheric showers of $\sim 10^{15}$ eV; the apparatus could detect quarks with charge $q = 2/3$. | Detected 5 events which are interpreted as quarks with charge $q = 2/3$; quark flux equals $5.5 \cdot 10^{-10}$ cm$^{-2}$sr$^{-1}$sec$^{-1}$. |
| 56 | 100-cm bubble chamber used to search for cosmic-ray quarks; total sensitive time of the experiment 75 sec. | A track was found which is interpreted as a quark with charge $q = 2/3$ or $1/3$; this corresponds to a quark flux $10^{-6}$ cm$^{-2}$sr$^{-1}$sec$^{-1}$. |
| 57 | The apparatus could detect quarks with charge $q = 1/3$ in showers with a low density of particles; average shower energy $10^{13}$ eV. | No quarks found; upper limits on the fluxes (at the 90% confidence level):<br>I (one quark) $\leq 1.9 \cdot 10^{-10}$,<br>I (quark + 1 particle) $\leq 6.5 \cdot 10^{-10}$,<br>I (quark + 2 particles) $\leq 2.2 \cdot 10^{-9}$<br>cm$^{-2}$sr$^{-1}$sec$^{-1}$ |
| 58 | a) The apparatus could detect quarks with charge $q = 1/3$ and $q = 2/3$ in low-density showers. | The upper limit on the flux of quarks with charge $q = 1/3$ and $2/3$ in showers of energy $10^{14}$-$10^{16}$ eV equals $1.0 \cdot 10^{-10}$ cm$^{-2}$sr$^{-1}$sec$^{-1}$ (90% confidence level). |
|  | b) Apparatus with a large streamer chamber (100 × 32 × 26 cm$^3$), triggered by showers, detects quarks with $q = 1/3$ and $2/3$ in high-density showers (up to 500 particles/m$^2$). | *Preliminary results: ~ 2000 showers analyzed in* the streamer chamber; no quarks detected. |
| 59 | Wilson chamber triggered by showers of energy $2 \cdot 10^{15}$-$10^{16}$ eV. The apparatus could detect quarks with charge $q = 1/3$ and $2/3$. | 3200 showers analyzed. No quarks detected; upper limit on the flux of quarks $I \leq 10^{-10}$ cm$^{-2}$sec$^{-1}$sr$^{-1}$ (90% confidence level). |
| 60 | Apparatus with Wilson chambers triggered by showers of energy $\sim 10^{15}$ eV; it could detect quarks with charge $q = 1/3$ and $2/3$. | No quarks detected in 100,000 analyzed showers of particles; upper limit on the quark flux in showers:<br>$I(q = 1/3) \leq 3 \cdot 10^{-10}$ and $I(q = 2/3) \leq 3 \cdot 10^{-11}$ cm$^{-2}$sr$^{-1}$sec$^{-1}$ (90% confidence level). |
| 61 | Apparatus with a track detector of neon Conversi flash tubes could detect quarks with $q = 1/3$ in showers of energy $\sim 3 \cdot 10^{14}$ eV. | Preliminary result: no quarks detected in the analysis of 451 tracks in cosmic rays; owing to the selection criteria of the tracks, this result has a larger sensitivity than the data of McCusker [55]. |

TABLE XI. Searches for retarded particles in extensive atmospheric showers

| Reference | Apparatus | Result |
|---|---|---|
| 62 | The apparatus could detect penetrating particles with masses $M > 5$ GeV, $\tau > 10^{-6}$ sec and $\gamma \leqslant 40$, having unit charge or interacting in the detector. | No heavy particles detected; upper limit on the flux of these particles $(1\text{-}3) \cdot 10^{-10}$ cm$^{-2}$sr$^{-1}$sec$^{-1}$ (production cross section $\leqslant$ 1-100 μb). |
| 63 | The apparatus could detect particles masses $5 \leqslant M \leqslant 15$ GeV, $\tau > 10^{-6}$ sec, the energy of such particles being determined by a nuclear calorimeter; altitude 3200 m. | No heavy particles detected; upper limit on the flux of these particles $5 \cdot 10^{-10}$ cm$^{-2}$sr$^{-1}$sec$^{-1}$ (production cross section $\leqslant$ 0.1-20 μb for $M = 5$ GeV and $\leqslant$ 20-300 μb for $M = 15$ GeV). |
| 64 | Apparatus to detect heavy particles placed underground at a depth 70 m water equivalent. | Several tens of retarded events were recorded; flux of these particles $10^{-7}$ cm$^{-2}$sr$^{-1}$sec$^{-1}$. |

tion of such particles. It appears to be difficult to explain the discrepancy between their results and the measurements of other groups[62,63] without making unfounded assumptions.

Summing up the numerous experiments on the search for quarks and fundamental particles in cosmic rays, we can conclude that there has so far been no reliable experimental demonstration of the existence of such particles. Thus, quarks have not been detected in experiments with cosmic rays.

**2. Estimates of the cross sections for quark production by the primary nucleons of cosmic radiation.** We shall consider a simple model which makes it possible to relate the experimentally obtained upper bounds on the fluxes of quarks in cosmic rays to upper bounds on the production cross sections for these particles.

The differential spectrum of primary cosmic rays has the form

$$n(E) = 1.35E^{-2.5}\ \text{cm}^{-2}\ \text{sec}^{-1}\ \text{sr}^{-1}\ \text{GeV}^{-1}$$

(where E is the proton energy in the l.s. in GeV). The spectrum n(E) can be written in the c.m.s.:

$$n(E)\,dE = n(W)\,dW = 1.35 \times \left(\frac{W^2}{2M_p} - M_p\right)^{-2.5} \frac{W\,dW}{M_p} \approx 7.6\,M_p^{1.5} W^{-4}\,dW,$$

i.e.,

$$n(W) = 6.9W^{-4}\ \text{cm}^{-2}\ \text{sec}^{-1}\ \text{sr}^{-1}\ \text{GeV}^{-1}.$$

Let us determine the quark flux at the angle $\theta$ (using the scheme of Fig. 19). To good accuracy, we may assume that the quarks are produced in the l.s. along the direction of motion of the primary nucleon:

$$I(\vartheta) = \frac{N_0}{A}\int_0^D \frac{dx}{\cos\vartheta}\left[12\int_{W_{\text{thr}}}^{\infty} \sigma(M_Q, W)\,n(W)\,dW\right] \exp\left(-\frac{x\rho_p}{\cos\vartheta}\right) \exp\left[-\frac{(D-x)\rho_Q}{\cos\vartheta}\right]; \tag{9}$$

here D is the thickness of the layer of atmosphere above the apparatus; the factor 6 appears as a result of the transition from a nucleon to a nucleus ($\sigma_{\text{nucleus}} \approx A^{2/3}\sigma_{\text{nucleon}}$; for air, $A^{2/3} \approx 6$), and the factor 2 appears because a quark-antiquark pair is produced in one event; $\rho_p$ is the absorption coefficient for quarks; $N_0$ is Avogadro's number; $A = 14.4$ is the average atomic weight of air; $\exp(-\rho_p x/\cos\theta)$ is the probability that a primary proton reaches the depth x; $\exp[-(D - x)\rho_Q/\cos\theta]$ is the probability that a quark produced at the depth x reaches the depth D. The vertical flux of quarks is determined by the expression

$$I(0^\circ) = (12N_0/A)\left\{\int_0^D \exp[-x(\rho_p - \rho_Q)]\,dx\right\} \exp(-\rho_Q D) \int_{W_{\text{thr}}}^{\infty} \sigma(M_Q, W)\,n(W)\,dW, \tag{10}$$

$$\int_{W_{\text{thr}}}^{\infty} \sigma(M_Q, W)\,n(W)\,dW = \sigma_a(M_Q)\,B. \tag{11}$$

Thus, the relation between the flux and the asymptotic value of the cross section is of the form

$$\sigma_a(M_Q) = (A/12N_0)\,R^{-1}B^{-1}\,I(0^\circ) = 2.04 \cdot 10^{24} R^{-1}B^{-1} I(0^\circ). \tag{12}$$

Then for $\sigma^{(1)}(M_Q, W)$ and $\sigma^{(2)}(M_Q, W)$ (see (5) and (6)),

$$B^{(1)} = \int_{W_{\text{thr}}}^{\infty} n(W)\,dW = 6.9\int_{2(M_Q+M_p)}^{\infty} W^{-4}\,dW \approx 0.29\,(M_Q + M_p)^{-3},$$

$$B^{(2)} = \int_{2(M_Q+M_p)}^{\infty} \left\{1 - \exp\left[-b\left(\frac{W - 2M_Q - 2M_p}{M_Q}\right)^{5/2}\right]\right\} (6,\ 9W^{-4})\,dW$$

and

$$R = \exp(-\rho_Q D)\int_0^D \exp[-x(\rho_p - \rho_Q)]\,dx = \frac{\exp(-\rho_Q D)}{\rho_p - \rho_Q}\,\{1 - \exp[-(\rho_p - \rho_Q)\,D]\}.$$

We shall consider below two extreme cases:

a) $\rho_Q^{-1} = \rho_p^{-1} = 120\ \text{g/cm}^2\quad R_{(a)} = D\exp(-\rho_p D);$

b) $\rho_Q = 0,\ R_{(b)} = \rho_p^{-1}\,[1 - \exp(-\rho_p D)] \approx \rho_p^{-1}.$

The absorption coefficient $\rho_Q$ takes into account not only the absorption of fast quarks, but also the inefficiency of the apparatus in detecting fractionally charged particles accompanied by showers. It should be noted that the possible production of quarks by secondary particles is not taken into account in this model.

From the analysis of all the searches for quarks in cosmic rays, we can conclude that the upper bounds on the fluxes of quarks (at the 90% confidence level) are

$$|q| = 1/3:\ I(0^\circ)|_{90\%} = 0.8 \cdot 10^{-10}\ \text{cm}^{-2}\text{sr}^{-1}\text{sec}^{-1}\quad (D = 740\ \text{g/cm}^2),$$
$$|q| = 2/3:\ I(0^\circ)|_{90\%} = 3.0 \cdot 10^{-10}\ \text{cm}^{-2}\text{sr}^{-1}\text{sec}^{-1}\quad (D = 940\ \text{g/cm}^2),$$
$$|q| = 4/3:\ I(0^\circ)|_{90\%} = 2.3 \cdot 10^{-10}\ \text{cm}^{-2}\text{sr}^{-1}\text{sec}^{-1}\quad (D = 1000\ \text{g/cm}^2).$$

These values have been obtained in experiments in which searches for single quarks were made (see Table VIII). The results of individual experiments cannot be summarized, since practically all the studies have arrived at upper bounds on the fluxes of quarks which are dependent on the level of background. Experiments to detect quarks in extensive showers result in higher values of the upper bounds on the cross sections, since the selection of showers with large energies already leads to rather low values of the fluxes.

The upper bounds on the asymptotic cross sections $\sigma_a^{(1)}(M_Q)$ and $\sigma_a^{(2)}(M_Q)$ obtained from (9)–(12) are shown in Figs. 12 and 13. We see from these figures that the bounds on the total cross sections for quark production obtained from accelerator experiments are definitive up to masses $M_Q = 6$–$8$ GeV.

**3. Quark searches by physico-chemical methods. Quarks and cosmology.** If there existed stable particles different from the currently known stable elementary particles (e.g., the lightest of the fractionally charged particles), they would have to be continually produced by cosmic rays in the atmosphere, retarded to thermal

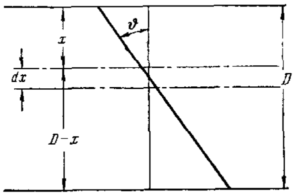


FIG. 19. Scheme for the calculation of quark production in cosmic rays.

velocities, and accumulated in the matter which surrounds us during the entire period of existence of the Earth ($\sim 3 \times 10^{16}$ sec).

Let the entire flux of these particles produced in the atmosphere and incident on 1 $cm^2$ of the Earth's surface, $2\pi I(0°)$, be stopped in several tens of nuclear units of matter ($(2-4) \times 10^3$ g/$cm^2$). Then for the quark flux $I(0°) = 10^{-10}$ particles $\cdot cm^{-2}sr^{-1}sec^{-1}$, the equilibrium concentration of these particles should be $\sim 10^{-20}$ quarks/nucleon. In fact, owing to mixing and a number of other factors, the expected concentration in most substances must be appreciably lower[71,72]: $10^{-29}-10^{-21}$ in sea water, $10^{-25}-10^{-22}$ in dust in the air, $10^{-25}-10^{-21}$ in solid rocks, and $10^{-20}$ quarks/nucleon in meteorites[9]. The results of some experiments in which searches were made for small admixtures of quarks in the surrounding matter are given in Table XII. Quarks have not been detected in these experiments, and upper limits have been set on their possible concentration in matter.

It should be noted that the results obtained in[72,73], as well as the data for water[74], are based on methods of enriching matter with quarks and are valid only under certain assumptions. Therefore, as we see from Table XII, quark searches in the surrounding matter do not impose new well-defined bounds on the magnitude of the quark production cross section in comparison with the direct data obtained with cosmic rays.

Physico-chemical methods of searching for stopped quarks can also be applied in experiments with accelerators. If for a period of a year the extracted beam of an accelerator irradiates a large tank of water in which all strongly interacting particles produced, including quarks, could be stopped (a typical volume of the tank is $10^3$ l, i.e., $10^{30}$ nucleons, and the number of interacting protons is $2 \times 10^{18}$) and if the sensitivity of the search for quarks in water can actually be raised to $5 \times 10^{-27}$[73a] as a result of the processes of enrichment, then in such an experiment one can attain an upper limit of about $10^{-40}$ $cm^2$ for the quark production cross section in nucleon-nucleon interactions.

The cosmological model of the hot universe leads to the conclusion that if quarks do exist they had a very high concentration in the pre-stellar hot stage of evolution (at a temperature $T \sim M_Q c^2/k$). During the process of expansion and cooling of the universe, quarks should have been "burnt out" as a result of the reactions $Q + Q \rightarrow N + \bar{Q}$; $Q + \bar{Q} \rightarrow \pi, \rho, K$; $\bar{Q} + \bar{Q} \rightarrow \bar{N} + Q$[82]. Estimates show that the concentration of residual "relic" quarks in matter may be rather high: $10^{-10}-10^{-13}$ quarks/nucleon[82]. If these estimates are correct, they contradict the results of the studies shown in Table XII and refute the hypothesis that quarks exist. However, at the present time cosmological processes are still rather poorly studied. It is possible that during its history our Earth passed through a stage in which its matter was hot and the quarks "burnt out"[71a]. Therefore cosmological data cannot definitively refute the quark model.

Further searches for relic quarks in both the surrounding matter and the composition of the primary cosmic radiation will be of great interest.

TABLE XII. Searches for retarded particles in extensive atmospheric showers

| Reference | Method | Substance | Upper limit on the concentration of quarks (per 1 nucleon) |
|---|---|---|---|
| 73a | Enrichment of matter with quarks by various methods (evaporation of water, collection of quark-atoms by an electric field, etc.); mass spectrography; the experiment is characterized by high sensitivity, but its results are not sufficiently reliable and are difficult to interpret. | Meteorites<br>Air<br>Dust<br>Water | $< 10^{-17}$<br>$< 10^{-30}-10^{-33}$<br>$< 3 \cdot 10^{-27}$<br>$< 3 \cdot 10^{-24}-5 \cdot 10^{-27}$ |
| 75 | Modified Millikan experiment: quark search in test bodies with magnetic suspension and measurement of their charge. | Graphite | $< 10^{-18}$ |
| 74 | Modified Millikan experiment: quark *search in test bodies with magnetic suspension* and measurement of their charge: | | |
| | a) diamagnetic test body–graphite; a solution of stony meteorite and salt from evaporation of water is added to graphite; the result for water is based on enrichment by evaporation and hence not sufficiently reliable; | Graphite<br>Water | $< 10^{-18}$<br>$< 10^{-23}$ |
| | b) ferromagnetic test body. | Iron | $< 10^{-20}$ |
| 76 | Modified Millikan experiment: quark search in test bodies with magnetic suspension and measurement of their charge. | Iron | $4 \cdot 10^{-19}$ |
| See 7 (L. Marshall-Libby et al.) | Negatively charged quarks (and other stable particles) can induce fission of heavy nuclei (such as U) and lead to very great radioactivity; the absence of such a pathological activity implies an upper estimate of the concentration of these particles. | U | $< 2 \cdot 10^{-30}$; the reliability of the estimate is subject to serious doubt [77]. |
| 78 | Spectroscopic search for quark atoms. | Spectral analysis of the sun. | $3 \cdot 10^{-12}$ |
| 79 | Search for stable elementary particles with integral charge by mass spectrometric methods (with and without enrichment). | Air, hydrogen, deuterium. | $< 1 \cdot 10^{-8}-1.5 \times 10^{-12}$ ($M_p < M_x < M_d$), $< 1.5 \times 10^{-12}$ ($M_x > M_d$) |
| 80 | Search for stable elementary particles with integral charge by mass spectrometric methods (with and without enrichment). | Water, heavy water. | $< 5 \cdot 10^{-19}$ ($6M_p < M_x < 16M_p$) |
| 73b | a) Search for quarks with charge $q = +2/3$ *by spectroscopic methods*; samples were first enriched by evaporation and collection of ions by an electric field.<br>b) Modified Millikan oil-drop experiment to search for quarks with charge $q = +1/3, \pm 2/3$; enrichment of oil with quark-atoms (by 4-5 orders of magnitude) by an electric field. | Sea water, lake water | $< 10^{-18}$ |
| 72 | Electro-chemical enrichment of matter with quarks (by 5-7 orders of magnitude), followed by evaporation and acceleration of quark-atoms in a strong electric field V and measurement of their kinetic energy $T = qV$ and hence charge q by means of semiconductor detectors; the experimeng was sensitive to quarks of mass up to 5–10 GeV. | Sea water, Rocks | $10^{-24}$<br>$10^{-20}$ |
| 81 | Spectrometer for simultaneous measurement of the mass and charge of ions accelerated in a field $10^6$ V; a quark search was made for particle masses in the range from M/3 to $60M_p$. | Oxygen, nitrogen, air, helius, hydrogen (from sea water)., $CO^2$ (from limestone) | $10^{-14}-10^{-16}$ |

The results of all the experiments which employ methods of enriching matter with quark-atoms are based on assumptions about their properties and are therefore not so reliable as the direct Millikan-type experiments. The estimates based on the catalysis of uranium fission are also unreliable.

## IV. THEORETICAL MODELS FOR QUARK PRODUCTION

At the present time, it does not seem possible to make reliable theoretical estimates of the cross sections for producing quarks, fundamental triplets and other heavy particles. The results of various models differ from one another by many orders of magnitude and have an illustrative character. Nevertheless, the models prove useful when comparing the results of different works; they can also stimulate higher-precision experiments on the search for new particles.

**1. Statistical theory of quark production.** E. L. Feĭnberg and his co-workers[32,33,83,84] first employed a statistical theory to analyze processes in which quarks and other heavy particles are produced. Similar results were later obtained by Hagedorn[31]. The data on antinucleon and antideuteron production which existed at that time played a major role in formulating the statistical approach to the problem of quark production. Studies of the yields of different types of particles carried out with the IHEP accelerator using 70 GeV protons, particularly the data on antideuteron and antihelium-3 production, have significantly extended this information. The experimental results on the yields of these particles are in reasonable agreement with the statistical theory[83,84].

In the statistical model, the total cross section in $cm^2$ for the production of quarks with charge $q = -1/3$ or $-2/3$ has the form

$$\sigma\,(NN \to NNQ\bar{Q}\ldots)\,|_{q=-1/3,\,-2/3} = 5\cdot 10^{-24}\,(M_Q/m_\pi)^3 \exp\,(-2M_Q/T_c); \quad (13)$$

here $T_c \approx 0.95 m_\pi$ is the critical temperature of the statistical system. The very rapid fall-off of the cross section for producing heavy particles as their mass increases is explained physically by the fact that the production of $N = 13M_Q/M_p$ pions is statistically much more probable than the production of a quark-antiquark pair of mass $2M_Q$. It should be borne in mind that, owing to the crudeness of a number of assumptions made in the statistical model, the estimates of the cross sections are intended to be valid only with an order-of-magnitude accuracy. Nevertheless, if the statistical model of quark production is correct, then, as we see from Fig. 20, the mass of the quarks (if they do exist) must be $M_Q \gtrsim 2.5$–$3$ GeV. Similar results are obtained in the statistical model for the nucleon "dissociation" reaction $NN \to NQ_1Q_1Q_2$ (in this case, $M_Q \gtrsim 2$ GeV). Thus, from the point of view of the statistical model, the search for quarks more massive than 3–4 GeV seems practically hopeless, owing to the extremely small values of the cross sections for producing very heavy particles.

Calculations of the probabilities for producing heavy particles have been made in the statistical theory under the assumption that there is established an equilibrium state that is maintained during the process of expansion of the system. In reality, the picture can be substantially different from such an idealized scheme; moreover, one can quote many examples in which the effect of direct peripheral processes is decisive and in which the phenomenon cannot be described by a statistical mechanism.

Consider, for example, the production of narrow boson resonances in the reaction $\pi^- p \to pX^-$ in the experiments with the CERN boson spectrometer[85]. In these experiments, observations were made of the production of a number of heavy particles with masses up to 3.5 GeV and production cross sections 20–40 $\mu$b, which were practically independent of their masses. All these resonances were narrow ($\Gamma < 10$–$30$ MeV). The processes of producing the resonances and their decay must therefore be considered independently. One can evidently apply in this case a statistical model with the same basis as in quark production. Estimates made by means of the statistical model predict an exponential fall-off of the cross sections as the resonance masses increase. For $X^-$ particles of mass 3.5 GeV, the discrepancy between experiment and the statistical theory is $\sim 10^6$. Thus, if narrow boson resonances actually exist, the data on their production cross sections conflict sharply with the statistical estimates.

The data on the production of antinuclei, which are in agreement with the corresponding theoretical estimates[83,84], are usually cited as an argument for the validity of the statistical theory of the production of heavy particles. We see from Fig. 21 that, as the mass of the antinuclei increases, their yields actually fall off exponentially, decreasing by 4 orders of magnitude when the mass of the antinucleus increases by one nucleon mass. However, this behavior of the cross section for producing antinuclei may be due to their composite nature, and can be described with reasonable accuracy by a simple model according to which several nucleon-antinucleon pairs are produced and subsequently "adhere" into an antinucleus[27,30]. Therefore it appears to us that the data on the yields of antinuclei do not constitute a convincing confirmation of the statistical mechanism of their production.

Thus, we must be especially cautious in regard to the quantitative predictions of the statistical theory for processes with very small cross sections. In this connection, one cannot allow for the role of the direct processes of producing heavy particles, or possible mechanisms by which these particles are "lost" during the early stages of expansion of the statistical system, when the temperature characterizing this system may be rather high ($T \gg T_c$). It should be noted that the possible role of these phenomena was already considered in the first works on the statistical theory of the production of heavy particles. In particular, it was shown[33] that, if at distances $\sim 1/m_\pi - 1/M_p$ quarks interact with pions more weakly than pions with each other ($\sigma_{Q\pi} < 0.1$–$0.01\,\sigma_{\pi\pi}$), then the probability that quarks are lost from the system is quite large and their production cross section will not fall off exponentially with increasing mass.

In[86] a study was made of a specific temperature model for the production of particles at very high energies ($10^{12}$–$10^{15}$ eV) in which the temperature of the system grows with the energy (and does not remain constant and close to $T_c$). In this case, the cross sections for heavy particle production at sufficiently high energy will be close to the geometric cross section (~30 mb). In

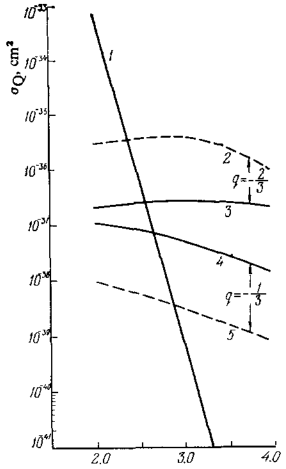


FIG. 20

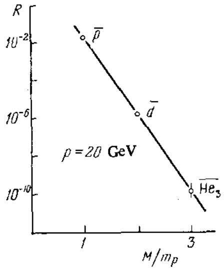


FIG. 21

FIG. 20. Total cross section for quark production in the statistical theory (the solid curve 1 is for $\sigma(NN \to NNQ\bar{Q}\ldots)_{q} = -1/3$-$2/3$ according to (13)). The solid and dashed curves show the experimental upper limits $\sigma_Q|_{90\%,q=-1/3}$ and $\sigma_Q|_{90\%,q=-2/3}$ in the phase-space model (curves 3 and 4) and in the phenomenological model (2 and 5). All the results refer to the proton energy $E_p = 70$ GeV.

FIG. 21. Ratio of the differential cross sections for production of antiparticles and $\pi^-$ mesons at $p = 20$ GeV/c, $\theta = 27$ mrad [30]. M is the particle mass, and $m_p$ the proton mass. We see from the figure that, when the mass of the antinucleus increases by one nucleon mass, the production cross section falls by 4 orders of magnitude, in reasonable agreement with the statistical theory [83,84]. Extrapolating this dependence to the large-mass region, we find the expected value $R(\overline{He^4}) \sim 10^{-14}$. Experiment gives $R(\overline{He^4}) < 6 \times 10^{-11}$ (at the 90% confidence level).

this model there must be a very high probability for producing proton-antiproton pairs (there will be more of them than pion pairs).

**2. Direct processes of producing heavy particles.** In[87] a model was considered for the peripheral production of quarks in accordance with the diagrams of Fig. 22, with allowance for absorption. The authors of this paper noted that their results can be better substantiated at sufficiently high energy, i.e., not very near the threshold for producing the particles. The results of the calculations are shown in Fig. 22, from which we can conclude that for the primary proton energy 70 GeV the cross sections for quark production lie in the range $10^{-30}$–$10^{-32}$ cm$^2$. However, this model does not allow for the effect of the structure function of the vertex at which the heavy quarks are formed. If this structure function falls off sharply as the mass increases, the cross sections will have a corresponding rapid decrease.

The case of peripheral production with quark exchange (Fig. 23) has also been considered[33]. In this case, a quark and antiquark appear in various excited systems and cannot annihilate, i.e., the mechanism of statistical "extinction" of heavy masses does not operate. The corresponding estimates of the cross section have the form

$$\sigma(pp \to pp Q\bar{Q}\ldots) \approx \sigma(pp \to pp\bar{p}p\ldots)(M_p/M_Q)^{12} \approx 10^{-27}(M_p/M_Q)^{-12}\,\mathrm{cm}^2$$

For $M_Q = (2-5)M_p$, the quark production cross sections lie in the range $10^{-31}$–$10^{-36}$ cm$^2$.

One of the possible mechanisms of direct production of heavy particles is diffraction production of a quark-antiquark pair, or diffraction dissociation of a nucleon into three quarks (Fig. 24). The minimum value of the momentum transfer $\Delta^2$ is determined by the mass M* of the system produced ($M^* = 2M_Q + M_p$ or $M^* = 3M_Q$) and the primary momentum p: $\Delta^2_{\min} = (M^{*2} - M_p^2)^2/4p^2$. The diffraction production cross section can be estimated very crudely as

$$\sigma_{\text{diff}} \approx \sigma_0 \exp(-b\Delta^2_{\min})\, R(M^*);$$

here the factor $(-b\,\Delta^2_{\min})$, where $b \approx 10$ (GeV/c)$^{-2}$, determines the dependence of the diffraction production cross section on the primary energy: the cross section rises up to energies 5–6 times higher than the production threshold of the M* system (in the l.s.) and then remains practically constant; $\sigma_0 \approx \sigma(pp \to pp\bar{p}\ldots) \approx 10^{-27}$ cm$^2$ (at $E_p$ = 70 GeV); and R(M*) is some structure function of the vertex at which quarks are formed. Depending on the various assumptions about this structure function, $\sigma_{\text{diff}}$ can have the value $10^{-30}$–$10^{-37}$ cm$^2$.

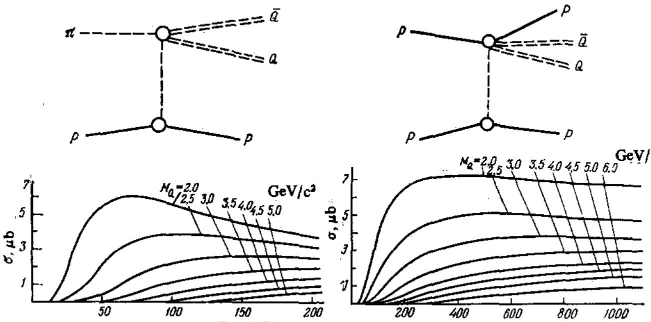


FIG. 22. Diagrams for the peripheral production of quarks due to single-pion exchange and the results of a calculation of the total cross sections for quark production in the peripheral model [87]: a–$\pi + N \to N + Q + \bar{Q}$, b–$N + N \to N + N + Q + \bar{Q}$.

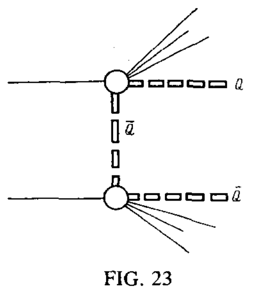


FIG. 23

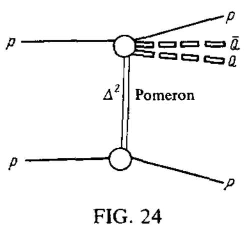


FIG. 24

FIG. 23. Diagram for the peripheral production of quarks with quark exchange [33].

FIG. 24. Diagram for the process of diffraction production of quarks.

It should be noted that, in analogy with the weak dependence of the structure functions of the nucleon on the momentum transfer in the region of deep inelastic ep scattering, when all the inelastic channels are summed, it is not excluded that the value of R(M*) will also not fall off sharply with increasing M* and that the cross sections for diffraction production of quarks may be much larger than in the statistical theory.

**3. Quark production in electromagnetic processes. "Leptonic quarks."** a) Experiments with electron accelerators. If quarks exist, they can also be produced in electromagnetic processes. In this connection, if the quarks are point-like, e.g., "leptonic quarks"[12] not possessing the strong interaction, the cross section for producing pairs of these particles can be calculated by means of quantum electrodynamics (the Bethe-Heitler formula). For "ordinary" strongly interacting quarks, the calculations are complicated by the effect of their intrinsic form factor. However, as we have already noted in Sec. I, the data on the electromagnetic structure of hadrons favor a small value of the quark "radius": $r_Q \ll r_{\text{had}}$. In this case, the role of the intrinsic form factors of the quarks becomes less important.

Three experiments on the search for quarks have been performed with electron accelerators with energies 6 and 12 GeV. In two of these studies[88,89], searches were made for quarks which have no strong interactions and which pass through a large thickness of matter. In the third experiment[90], measurements were made in a "no-background" beam tuned to the momentum 12.5 GeV/c, at an accelerator electron beam energy 12 GeV. Searches were carried out in this case for both "leptonic" and strongly interacting quarks. Quarks were not detected in any of the above-mentioned experiments. The results of the experiments are shown in Figs. 25 and 26 in the form of the upper limits on the masses of fractionally charged particles that were established in these studies. The estimates of the upper limits were made on the basis of the Bethe-Heitler formula for the production of pairs of particles without allowing for the form factor of the quarks.

b) Electromagnetic virtual processes in nucleon-nucleon collisions[35,91–93]. The electromagnetic production of quarks can also occur in processes with virtual γ quanta in nucleon-nucleon collisions. Owing to this mechanism, estimates of the cross sections for producing "leptonic quarks" can be obtained with sufficient reliability from the results of the experiments of Lederman's group[94], in which a study was made of the production of muon pairs with a large effective mass in nucleon-nucleon collisions at a primary energy $E_p \approx 30$ GeV, since both of these processes are described by one and the same diagram (Fig. 27).

The general expression for the differential mass spectrum of leptonic pairs has the form (for particles with unit charge)

$$\frac{d\sigma}{d\omega}=\frac{\alpha^2}{\omega^3}\left(1-\frac{4M_\lambda^2}{\omega^2}\right)^{1/2}\left(1+\frac{2M_\lambda^2}{\omega^2}\right)R(\omega, S);$$

here $\omega$ is the effective mass of the leptonic pair, $M_\lambda$ is the lepton mass, $\alpha = 1/137$, and $R(\omega, S)$ is a function depending on the structure of the nucleon. In particular, for the production of muon pairs with a large effective mass $4M_\lambda^2 \ll \omega^2$,

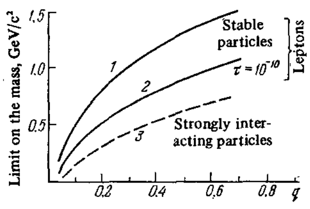
$$(d\sigma/d\omega)_{\mu+\mu-} \approx (\alpha^2/\omega^3)\, R(\omega, S).$$

If the mass spectrum of dimuon pairs at a given primary proton energy $E_p$ is known, one can readily obtain from this the expected value of the total cross section for producing pairs of heavy "leptonic quarks"$^{10)}$ with mass $M_Q$ and charge q:

$$\sigma(M_Q)_{E_p}=q^2\int\limits_{\omega_{\min}=2M_Q}^{\omega_{\max}=S^{1/2}-2M_p}\left(\frac{d\sigma}{d\omega}\right)_{\mu+\mu-,\,E_p}\left(1-\frac{4M_Q^2}{\omega^2}\right)^{1/2}\left(1+2\frac{M_Q^2}{\omega^2}\right)d\omega. \qquad (14)$$

Since experimental data on the spectra of muon pairs exist only for $E_p = 20-30$ GeV, estimates of $\sigma(M_Q)$ at other primary proton energies were made by using an extrapolation of the spectrum $(d\sigma/d\omega)_{\mu^+\mu^-}$-$E_p = 28.5$ GeV. In accordance with the parton model of Drell and Yan[95], it was assumed here that the function $R(\omega, S)$ must satisfy scale invariance in the region of deep inelasticity, i.e., that $R(\omega, S) = R(\tau)$, where $\tau = \omega^2/S$. The effective mass spectra of the dimuon pairs produced in proton-nucleon collisions at $E_p = 28.5$ GeV (the experimental data of[94]) and at $E_p = 70$ GeV (the results of the extrapolation procedure described above) are shown in Fig. 28.

In Fig. 29 we show the results of calculations of the total cross sections for producing "leptonic quarks" with charges q = 1/3, 2/3 and 4/3 in proton-nucleon interactions at $E_p = 70$ GeV. In the same figure we indicate the upper experimental limits on the total cross sections for quark production at this same energy, as obtained in the phase-space model and in the parton model (see[93]). Thus, "leptonic quarks" with charge $q = -1/3$ could have been detected in the experiments of the IHEP group[19,39] if their mass were less than 4.2 GeV, while "leptonic quarks" with charges $q = -2/3$ and $-4/3$ could have been detected up to a mass 3.7 GeV. If "ordinary" strongly interacting quarks are actually point-like ($r_Q \ll r_{had}$), the estimates of the electromagnetic production of quarks



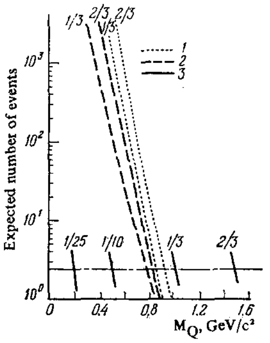


FIG. 25 FIG. 26

FIG. 25. Results of the SLAC experiment [90] on the search for fractionally charged particles for electromagnetic pair production by a 12 GeV electron beam. We show the limits on the mass of the particle as functions of its charge, for stable leptonic quarks (1), leptonic quarks with a lifetime $10^{-10}$ sec (2), and stable strongly interacting quarks that are appreciably absorbed in the target and matter of the apparatus (3).

FIG. 26. Comparison of the results of three experiments on the search for "leptonic" quarks with electron accelerators–[88] (1) ($E_e = 6$ GeV), [89] (2) ($E_e = 6$ GeV), and [90] (3) ($E_e = 12$ GeV). The intersection of the horizontal line with the limiting curves for each experiment determines the limit on the quark mass that is established at the 90% confidence level (for various values of the charges of the particles: q = 2/3, 1/3, 1/10 and 1/25; the last two values characterize the sensitivity of the experiments to hypothetical particles with very small charge).

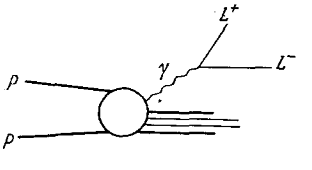


FIG. 27. Diagram for electromagnetic production of lepton pairs in nucleon-nucleon collisions.

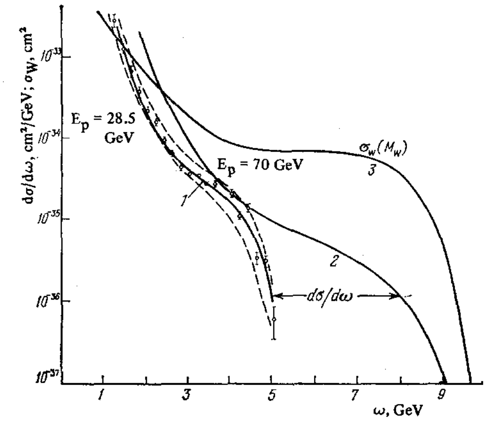


FIG 28. Differential cross sections for dimuon pair production in proton-nucleon collisions for a proton energy $E_p = 28.5$ GeV–results of the experiments [94] (1) and $E_p = 70$ GeV–calculation (2). We also show an estimate of the total cross section for production of the intermediate boson W (for $E_p = 70$ GeV), based on the relation $\sigma_W \approx 0.05M_W^3[d\sigma/d_\omega(\omega = M_W)]_{\mu^+\mu^-}$ (3).

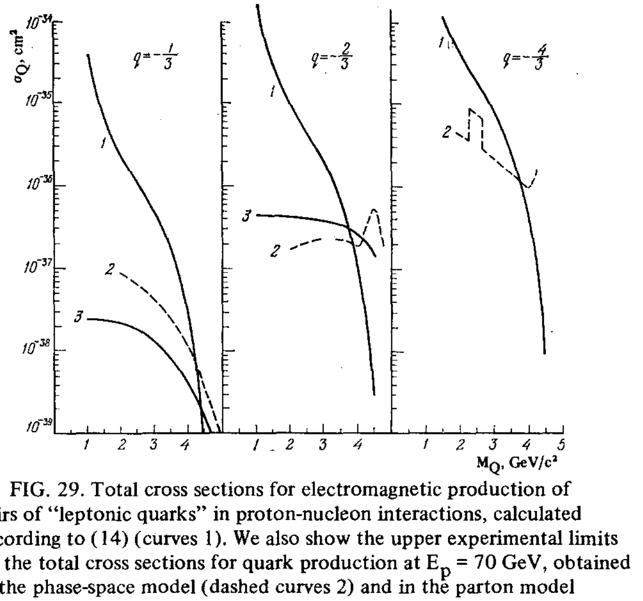


FIG. 29. Total cross sections for electromagnetic production of pairs of "leptonic quarks" in proton-nucleon interactions, calculated according to (14) (curves 1). We also show the upper experimental limits on the total cross sections for quark production at $E_p = 70$ GeV, obtained in the phase-space model (dashed curves 2) and in the parton model [93,95] (solid curves 3).

which we quote also refer to the "ordinary" quarks to a great extent. In this connection, it seems quite probable that, owing to the strong interaction processes, the estimates of the expected cross sections for producing "ordinary" quarks will be increased by at least 4—5 orders of magnitude (i.e., by a factor $\sim (q^2\alpha^2)^{-1}$).

## V. CONCLUSIONS

It is perfectly obvious that all the theoretical estimates of the production cross sections for strongly interacting quarks which we have quoted in this review are quite arbitrary. Nevertheless, they show that these cross sections may be rather high in comparison with the results of the statistical model. Then it follows from the experiments carried out with accelerators that the masses of the quarks, if they exist in the free state, must be greater than 5 GeV. The interpretation of experiments with cosmic rays is much more ambiguous. It is possible that their sensitivity is insufficient to detect quarks with high masses.

Thus, nine years after the quark hypothesis was put forward, the question as to whether quarks exist in the free state is still open. Several tens of experimental studies aimed at the search for these fundamental constituents of matter have so far led only to negative results. Still in front of us are experiments with the new generation of accelerators, especially with the intersecting proton-proton rings at CERN (at an energy 30 + 30 GeV in the c.m.s.) and with the accelerator at Batavia (at $E_p$ = 300—400 GeV). It is possible that the extension of the range of masses of the particles for which sensitive quark searches can be carried out will play a decisive role in solving this problem. There may also be excellent prospects for physico-chemical searches for quarks in various substances.

However, it is quite possible that quarks are quasiparticles of some kind, which in general cannot exist in a free form. And last (but not least!), the successes of the quark-model description of hadrons may be merely outward manifestations of some hitherto unknown internal regularities in the structure of matter.

Note added in proof. In [97] an analysis was made of the probabilities of detecting single quarks in experiments of the type of Table VIII. The analysis showed that, owing to the accompanying showers, this probability (P) for heavy quarks may be quite small ($M_Q$ = 5 GeV, P ~ 1.0-0.6; $M_Q$ = 10 GeV, P ~ 0.09-0.25; $M_Q$ = 20 GeV, P ~ 0.9-0.01).

---

1) There may exist spin-orbit and spin-spin interactions, which break $SU_6$ symmetry, as well as forces which break $SU_3$ symmetry.

2) The particles P, N and Λ hyperon—the fundamental fields in the original form of the Sakata model; it is significant that these particles are all characterized by integral electric and baryon charges, the P and N having isospins T = ½ (they are carriers of isospin) and the Λ having isospin T = 0 and strangeness S = −1 (it is a carrier of strangeness).

3) The Sakata model corresponds to the following structure of the baryon supermultiplets: $\{3\}\times\{\bar{3}\}\times\{3\}=\{3\}+\{3\}+\{6\}+\{15\}$, i.e., triplets, sextuplets and 15-plets, which are not realized in nature.

4) These parameters also describe the antideuteron spectra.

5) $A^{2/3}\sigma_{\text{eff}}(M_Q, E_p)$ is the production cross section for quarks of mass $M_Q$ by primary protons of energy $E_p$ on a nucleus with atomic weight A. Here $M_Q$ may exceed $[(2E_pM_p + 2M_p^2)^{1/2} - 2M_p]/2$, the limiting value of the mass of the quark which can be produced in collisions of protons of energy $E_p$ with a nucleon at rest; $A^{2/3}$ is the effective number of nucleons in the nucleus.

6) Let us recall the notation: $\sigma(M_Q)|_{90\%}$ is the upper bound on the total cross section for the productionof quarks of mass $M_Q$ in interactions of primary protons of energy $E_p$ with nucleons at rest; $\sigma_{\text{eff}}^{(1)}(M_Q, E_p)|_{90\%}$ and $\sigma_{\text{eff}}^{(2)}(M_Q, E_p)|_{90\%}$ are the same, but allowance for the Fermi motion of the nucleons in the target nucleus under two assumptions about the form of the cross section for the production of quarks of mass $M_Q$ as a function of the energy $E_p$, Eqs. (5) and (6). $\sigma_a^{(1)}(M_Q)|_{90\%}$ and $\sigma^{(2)}(M_Q)|_{90\%}$ are the upper bounds on the "asymptotic" total cross sections for quark production corresponding to (5) and (6) (all estimates of the bounds correspond to the 90% confidence level).

7) E.g., a baryon triplet β and a boson triplet α, or a triplet with double baryon charge β and a baryon triplet α [15].

8) The results of older work are contained in the review [50].

9) It has been noted that, owing to the Earth's electric field, the length of time for which quarks are stored in water and air may be reduced to the order of magnitude of a year. If this is so, the expected concentration of quarks in these substances is further reduced by a factor ~ $10^9$ (see, e.g., [72]).

10) Of course, analogous arguments are also valid for the cross sections for producing heavy leptons [91,93].

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