SOVIET PHYSICS USPEKHI VOLUME 8, NUMBER 5 MARCH-APRIL, 1966

539.12

QUARKS: ASTROPHYSICAL AND PHYSICOCHEMICAL ASPECTS

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Usp. Fiz. Nauk 87, 113-124 (September, 1965)

1. INTRODUCTION

THE preceding issue of Uspekhi contained a series of predictions about directions of development and about problems of elementary particle physics. In connection with this discussion it is worth mentioning another possible direction for investigation which has developed recently, along with studies using accelerators and cosmic rays.

We refer to attempts to find new rare types of stable particles in nature. Thus, in studying elementary particles one can use, in addition to the traditional methods (but of course not in place of them) physicochemical methods of enrichment and investigation. We shall discuss various aspects of this approach.

There has recently been discussion of the possible existence of new types of particles that are heavier than the proton and have fractional charge. The classification of the known strongly interacting particles (SU_3 or SU_6 symmetry) leads naturally to the assumption that there exist three particles (quarks) with charges $+(2/3)e$, $-(1/3)e$, $-(1/3)e$[1,2] (cf. the popular summary[48]).

There is still also the possibility that new types of particles with integral charge exist, both within the framework of the SU_3 symmetry,*[3,8] and also without any connection to the SU_3 symmetry.[9]

Among the quarks, these particles with fractional charge, there is one, the lightest, that should be stable not only in vacuum but, because of its fractional charge, also stable in contact with ordinary matter (nuclei, electrons). The particles with integral charge may be unstable, but there may be selection rules that cause these particles to be stable. These selection rules may be connected with the conservation of a new quantum number that is like the charge—the supercharge.† Under strict conservation of supercharge the creation and annihilation may also be selection rules because the particles have unusual combinations of the usual quantum numbers. In this case their numbers should not be conserved absolutely, but, as for the quarks, modulo some number. For example, baryons with integer spin can be created in pairs in nucleon collisions (conservation modulo 2). We note that the quarks are conserved modulo 3, i.e., in reactions only 3,6,9, etc., quarks can be created or destroyed; for example, 7 quarks cannot convert completely into ordinary matter—there still remains one free quark.

2. FORMATION OF QUARKS BY HIGH ENERGY PARTICLES

High energy experiments have so far not led to the discovery of new stable particles and have shown that the masses of such particles cannot be small. Experiments at accelerators[10-15] have detected no quarks up to masses of 3-5 GeV and above a cross section for creation of 10^{-34}–10^{-32} cm^2.

A cosmic-ray experiment[21] at a height of 2.5 km gives an upper limit for the flux of relativistic quarks with charge $(1/3)e$ of $I_{1/3} < 1.6 \times 10^{-8}$ cm^{-2} sec^{-1} sr^{-1} (a sea level experiment[22] gives the flux limit 20×10^{-8} cm^{-2} sec^{-1} sr^{-1}). If we assume that the slowing down of quarks in the atmosphere is approximately the same as for nucleons, and that the cross section for creating them is ~0.01 mb, the upper limits given show that $m_q > 7$ GeV. In this estimate we have used the integral spectrum of the primary cosmic radiation

$$N(E) = 0.9\,E^{-1.5}\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}\,\mathrm{sr}^{-1}, \qquad (1)$$

where E is in GeV.

Searches for longlived particles with integral charge at the accelerators at Brookhaven and CERN[16-20] have given a negative result up to a mass of 4 GeV, and have shown that if such particles are formed their numbers are approximately three orders smaller than the number of antiprotons.

Aside from a search for new stable particles in experiments on collisions at high energies, there is another procedure—a search for particles that were formed long ago and have assumed the temperature of their surroundings. If one assumes that quarks can be created by the primary cosmic ray nucleons with $E > 300$ GeV, then, for the parameters cited above, during 5×10^9 years there should have been 10^{11} cm^{-2} created in the atmosphere, and this is approximately 10^8 quarks per gram of absorbing layer of atmosphere. The quarks diffuse from the upper to the lower layers of the atmosphere, there

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*Schemes that combine the particle classification according to SU_3 or SU_6 with the assumption of the existence of fundamental particles with integral, instead of fractional, charges, are more complicated than the quark scheme, and contain more fundamental particles.

†By the supercharge we mean three times the average charge of an SU_3 supermultiplet. If SU_3 triplets with integral charge (like the p,n,Λ) exist, their supercharge is 1. For the quarks the supercharge is zero.

serve as nuclei for condensation of drops, fall with precipitation onto the earth's surface, and are mixed into the oceans. We then get approximately 10^5 quarks per gram of water. But if the precipitation is collected in outdoor reservoirs which are then allowed to evaporate, the concentration may be 1-2 orders of magnitude higher.

Because of the absence of mixing, the concentration of quarks formed by cosmic rays may be of the order of 10^9 per gram in meteorites. But the size of the meteorite must be very large (~ 30 cm) to retain the quarks at the time they are created.

Under special circumstances the concentration of cosmic rays may be much higher than average. On the sun, at the time of chromospheric flares, many cosmic rays are produced, albeit of relatively low energy. Much more powerful sources are the variable stars like Taurus τ which are in the process of gravitational collapse: in these stars there is strong convection which results in varying magnetic fields and acceleration of particles. Thus the stars are the source of the "real cosmic rays." This is indicated by the anomalously large content of Li and certain other elements that are fragments of heavier nuclei. There are stars with an anomalously high content of He^3 which, according to [33], is formed from He^4 by cosmic rays. The increased deuterium and Li content of the earth is also related to the period of formation of the solar system, when the sun was a star like Taurus τ and irradiated the planetary matter. This energy spectrum is not known, but if it were sufficiently hard, quarks would have been formed along with the Li.

The most powerful sources of cosmic rays, superstars or quasars,[24] also must produce quarks. Finally quarks may be produced in small-scale explosions occurring in galactic cores. But the relatively short duration of the explosion process and the small mass of gas leads one to think that the main contribution in the galaxy comes from ordinary cosmic rays.

3. CREATION AND BURNUP OF QUARKS IN THE INITIAL PERIOD OF EXPANSION OF THE METAGALAXY

If the hypothetically stable particles (not quarks) possess some particular strictly conserved quantum number, like the baryonic charge, their minimum concentration is a universal constant like the total baryonic charge of our portion of the universe, and can in principle be arbitrary. If, however, these particles are conserved modulo some base, their concentration will depend on their history, i.e., on the earlier physical condition of the material and on the processes that lead to the annihilation of the particles. For example, let us consider annihilation of quarks.

Since quarks are heavier than nucleons we can have the process

$$q_1 + q_1 \rightarrow q_3 + q_{-1} \qquad (2)$$

followed by $q_1 + q_{-1} \rightarrow n\, q_0$. Here the subscript indicates the number of quarks contained in the particle, the minus sign denoting the antiparticle. Thus q_1 denotes single quarks, q_2 pairs of quarks coupled by the strong interaction, q_3 ordinary baryons made up of three quarks, and q_0 mesons. Because of reaction (2), annihilation of the quarks can occur in a series of pair collisions instead of via the much rarer triple collisions.

The process (2) does not consider the possibility of the existence of a q_2. But including q_2 does not alter the conclusion about the role of pair collisions. If $m_2 > m_1 + m_3$, the reaction $q_2 \rightarrow q_3 + q_{-1}$ goes; but if $m_2 < m_1 - m_3$, the free quarks are unstable: $q_1 \rightarrow q_3 + q_{-2}$. In this case the particles with fractional charge that can exist in nature are the diquarks. If, finally, m_2 lies in an interval that guarantees the simultaneous stability of q_2 and q_1, both types of particles are annihilated in all variants with double collisions. One can treat $q_4, q_5, \ldots$, similarly with the same conclusions.

From the point of view of possible creation and burnup of quarks, the most important period is the initial expansion of the metagalaxy, if this expansion proceeded from a singular state. We must start from some definite cosmological hypothesis. Here we shall assume that the Friedmann model of a homogeneous isotropic universe (cf., for example, the survey[25]) is applicable with sufficient accuracy up to $t \lesssim 10^{-7}$ sec. Deviations from homogeneity and isotropy, which may be significant at an early stage,[26,27] can of course significantly change the results. The choice between open and closed models is entirely unimportant at the early stage. On the other hand the Friedmann theory leaves free the values of the thermodynamic parameters, the specific entropy and specific leptonic charge of unit rest mass of the matter.

Let us assume following Gamow [28] that in the singular state at infinite density the specific entropy was large ("hot model").* Then in the early stages of the expansion the densities of quanta and of all types of particle-anti-particle pairs greatly exceeded the excess density of baryons, corresponding to a charge asymmetry in our vicinity, which we extrapolate to the whole universe. For $t \rightarrow 0$, $\rho \rightarrow \infty$, $T \rightarrow \infty$. Fixing the quark mass m, one can easily find the relative equilibrium concentration of quarks for $T \ll m$:† this concentration is $n \sim e^{-m/T}$.

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*This hypothesis has also been supported recently by Hoyle and Tuler.[44]

†We work in units with $h = c = k = 1$. In these units, mass, energy and temperature have the same dimensions, and can be in degrees, MeV, proton masses. etc.

There are no conditions at the present time under which a significant number of quarks would be in equilibrium. We must therefore determine the moment when, in the course of the expansion, the actual quark concentration ceased following the equilibrium behavior (the moment of "quenching" of the equilibrium). The analogous problem was solved earlier for the freezing in of antinucleons.[29]

From the equations of general relativity for the Friedmann solution and from thermodynamics

$$\varrho = ahT^4 = \frac{3}{32\pi G t^2}, \qquad s = \frac{4ahT^3}{3\varrho_b}; \tag{3}$$

here $a = 4\sigma/c = \pi^2/15$, where σ is the Stefan-Boltzmann constant, ρ_b the density of rest mass of excess baryons, s the specific entropy per unit of this mass, h a dimensionless number that takes account of the presence of other particles, that are in equilibrium with the radiation at the given temperature ($h = 1$ for single quanta, $h = 2.75$ for quanta and e^+, e^- pairs when $T > m_e c^2$).

With muons and neutrinos included, $h \sim 9$. Formula (3) applies to the initial stages, when $\rho_b \ll \rho$. We denote by n the concentration of quarks relative to the concentration of excess baryons $N = \rho_b/M$, where M is the baryon mass. The equilibrium concentration when $T \ll m$ is

$$n_{eq} \approx \left(\frac{2}{N}\right)^{2/3} \frac{mT}{2\pi} e^{-\frac{m - M/3}{T}}. \tag{4}$$

This equation reminds one of the Saha equation, but for a system of three particles. The kinetic equation has the form

$$\frac{dn}{dt} \approx v\sigma_2 N (n_{eq}^2 - n^2), \tag{5}$$

where v is the mean velocity, σ_2 the cross section for collision of two quarks, antiquarks or diquarks, leading to a reduction of the number of such particles by unity. The factor N appears because the quark concentration expressed in cm^{-3} is $C_q = nN$. It is clear that C_q changes both because of reactions and because of the general expansion, whereas n changes only because of reaction. The time for establishing equilibrium is $\tau \approx (v\sigma_2 N n_{eq})^{-1}$.

In order to determine the moment of "quenching", we must compare the time τ with the characteristic time for change of n_{eq} because of the expansion, described by formula (3). This characteristic time t_1 is gotten from the condition

$$t_1^{-1} = \frac{d \ln n_{eq}}{dt} \approx \frac{m}{T}\frac{1}{2t} = \frac{1}{2\theta t}, \tag{6}$$

where we use (4) and $T \sim t^{-1/2}$ from (3). The quantity $\theta = T/m$. (We neglect the change in the factor multiplying the exponential in (4).)

The whole period of expansion can be divided into two stages. In the first $t < t_1$ and $n \approx n_{eq}$. In the second stage $t > t_1$, $n > n_{eq}$ and one can neglect the creation of new quarks. At the time t_0 separating the two stages, one can approximately set $n \approx 2 n_{eq}(t)$. Integration of the equation

$$\frac{dn}{dt} = -v\sigma_2 N n^2 \tag{7}$$

from t_0 gives for the relative concentration after "quenching" the expression

$$\frac{1}{n(\infty)} = \int_{t_0}^{\infty} v\sigma_2 N \, dt \approx 2\sigma_2 v N_0 t_0. \tag{8}$$

The last result is obtained if we use the relation $N = N_0 (t_0/t)^{3/2}$ (cf. (3)) and $\sigma_2 v = \text{const}$. Using t_0 from (3), we rewrite (8) in the form

$$n(\infty) = \sqrt{\frac{32\pi a}{3}} \frac{\sqrt{G}}{\sigma_2 v T_0 h_0^{1/2}} \frac{h_0 T_0^3}{N_0} = \sqrt{\frac{32\pi a}{3}} \frac{\sqrt{G}}{\sigma_2 v T_0} \left(\frac{h^2}{h_0}\right)^{1/2} \frac{T^3}{N}, \tag{9}$$

where T is the temperature of the radiation remaining at the present time (the expansion is assumed to be isentropic) while N is the average nucleon density at the present time. The value $h \approx 3$ refers to the time when only quanta and the two kinds of neutrino pairs were left, ν_e, $\overline{\nu}_e$, ν_μ, $\overline{\nu}_\mu$; $h_0 \approx 9$.

In units of the nucleon mass M we may take $\sigma_2 v \approx M^{-2}$, $T_0 \approx M$ (cf. below), $G = 0.6 \times 10^{-38}\, M^{-2}$. It then follows that

$$n(\infty) \approx 6 \cdot 10^{-19} \left(\frac{T^3}{M}\right). \tag{10}$$

Basically the low concentration of quarks is a consequence of the smallness of the gravitational forces. To give a dimensionless characteristic of the gravitational interaction, we must write $GM^2/\hbar c$ (M is the nucleon mass), by analogy with $e^2/\hbar c$, the fine structure constant. It is qualitatively easy to understand why the weakness of the gravitational interaction results in a low concentration: the rate of expansion in the initial stages must be chosen so that the kinetic energy of expansion overcame the gravitational attraction and enabled the material to go over from the value $\rho = \infty$ to the present value $\overline{\rho} = 10^{-30}$. The weakness of gravitation means a slow expansion and produces the conditions for the death of quarks.

On the other hand, the higher the temperature and entropy, the more different particles (quanta, e^+, e^- pairs, etc) appear per nucleon; in a more dilute system the quarks collide and die more infrequently, and the concentration of quarks per nucleon is higher.

The value of T^3/N taken per nucleon is now known with a very large uncertainty. If $T \approx 1°$, while $N \approx 2 \times 10^{-7}\ \mathrm{cm}^{-3}$, which corresponds to the lower limit of the density including some galaxies (cf.[30] with reduction to the Hubble constant $H = 100$ km/sec-Mps), then $T^3/N \approx 10^9$. This corresponds to a hot model of the universe. Direct measurements of the metagalactic background radio emission lead to the conclusion that $T < 3°$K.* But the

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*The latest information, obtained by measuring radio noise at 7 cm, favors the value $T \sim 4$ °K.[47]

value $T^3/N \approx 1$ does not contradict the observations. Such a small entropy corresponds to a model with initially cold matter consisting of free quarks and nucleons.* Thus, depending on the value of T^3/N, one can have a quark concentration after the primary expansion of 10^{-9}—10^{-18}. It should be emphasized that these numbers are rough estimates. In particular they may change drastically if we include inhomogeneity and anisotropy.

Let us now fix the values of T_0 and t_0, which are determined from the equation

$$(v\sigma_2 N n_{eq})^{-1} = 2\theta t \tag{11}$$

or

$$\theta e^{-\frac{1}{\theta}} \approx \sqrt{\frac{32\pi a}{3}\frac{G^{1/2}s^{1/3}}{v\sigma_2 m}}\left(\frac{h}{h_0}\right)^{1/3} \approx 5\cdot 10^{-16}, \tag{12}$$

if $s \approx 10^9$. From this it follows that $\theta \approx 1/30$. If the quark mass is $m \approx 10$ GeV, the freezing temperature $T_0 \sim 300$ MeV, and the time of the freeze $t_0 \approx G^{-1/2}T_0^{-2} \approx 10^{-5}$ sec. From (8) and (10) it follows that the value of T and consequently also of $n(\infty)$ are weakly dependent on the quark mass m. The point is that although the equilibrium concentration n_{eq} depends exponentially on m and T, the reaction rate itself depends on n_{eq}. Thus the time t_0 turns out always to correspond to a definite n, which depends on m only algebraically.

The whole process of freezing is completed at a temperature above 100 MeV, so that Coulomb barriers and Coulomb attraction of the quarks to nucleons play no part in the estimate of $v\sigma_2$, characterizing the cross section for the reaction between two quarks. Under these conditions nuclei do not exist.

4. CONSERVATION OF QUARKS DURING THE EVOLUTION OF THE GALAXY

Earlier we estimated the burnup of quarks during the first microseconds of the Friedmann expansion Now let us consider how the quark content must change during the process of further evolution of matter. This problem is of such great interest because an improvement of the upper limit for the quark content could give some limitations on the choice of cosmological models.

According to the present cosmological pictures, the primary gas developed condensations which, gradually coalescing, gave the first galaxies. The gas in the galaxies changed into stars, of which the more massive ones went through their evolution rapidly, ejected part of the gas, enriched in heavy elements, into interstellar space. In our Galaxy more than 98% of the gas has already been converted into stars. In the stars the process of burnup of the quarks in pair collisions has continued. But now the Coulomb interaction between quarks and nuclei and between the quarks themselves begins to be important.

For a Maxwell distribution the number of reactions per cm^3 per sec is (cf., for example,[32])

$$C_1C_2F_{12} = C_{12}C_1C_2\left(\frac{Z_1Z_2}{A_{12}}\right)^{1/3}T^{-2/3}e^{-3\left(\frac{\pi^2}{2}\alpha^2 Z_1^2 Z_2^2 \frac{m_{12}}{T}\right)^{1/3}}, \tag{13}$$

where m_{12} is the reduced mass of the particles, A_{12} is the same quantity in fractions of the proton mass, $\alpha = 1/137$, $C_{1,2}$ are the particle concentrations, C_{12} is a constant for the particular reaction. If we take as the reaction cross section parameter that for deuterium and express T in ergs, $C_{12} \approx 2 \times 10^{-20}$. From equations of the type of (7) and from (13) we find the concentration of the remaining quarks

$$C(t) \approx \frac{2}{F_{qq}(t)}, \tag{14}$$

if, of course, the initial concentration was higher.

For quarks with $Z = +\frac{2}{3}$ and $A \approx 5$ the concentration after 10^9 years for $T = 10^6$ °K will be $C_q \leq 10^{15}\,\mathrm{cm}^{-3}$, which amounts to 10^{-9} of the hydrogen concentration in the Sun's layers at this temperature. At higher temperatures the consumption of quarks increases markedly. For $T = 10^7$ °K, $C_q \lesssim 10^6\,\mathrm{cm}^{-3}$, i.e., 10^{-18} per gram in the corresponding layers.

For quarks with $Z = -\frac{1}{3}$, it follows from (13) that burnup occurs much faster. But these quarks can combine with nuclei to form a stable system. The charge of the quark-proton system is $+(\frac{2}{3})e$ and the burnup of the quarks should now occur at approximately the same rate as for the case treated above. But at temperatures where annihilation is possible, the quarks will first be detached from the protons and joined to He or heavier nuclei. The burnup will already be unimportant in this case because of the large values of Z and A. We make a quantitative estimate.

The binding energy of a quark to a nucleus is $Q = 2.76\, Z_n^2 A$ keV, where Z_n is the charge number of the nucleus and A is the reduced mass of the system in units of the proton mass. According to the Saha formula, the relative concentration of free and bound quarks is

$$\frac{C_q}{C_{qn}} = \frac{1}{C_n}\left(\frac{Am_nT}{2\pi}\right)^{3/2}e^{-Q/T}.$$

At $T = 10^6$ °K the concentration of quarks attached to protons is 10^9 times as great as that of the free quarks. But equilibrium is reached after 10^{-4}—10^{-5} sec, so that even with a small fraction of free quarks, after $t \sim 10^5$ sec they all go over to the heavier nuclei, in this case He. At higher temperatures the quarks will separate from the He but will attach to heavier elements. In all cases the time for

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*It was already pointed out in[45] that in theories in which the baryons are regarded as composites, at sufficiently high density one cannot regard the gas as consisting of the experimentally known particles (p,N,Λ, Σ, Ξ). One must instead speak of a gas of the "really" elementary particles, the p,N,Λ of the Sakata model, or the quarks, according to the present view.

going over to the heavier nuclei is much less than the burnup time.

At $T = 10^7\,°K$ the fraction of quarks attaching to He is 10^9 times greater than that of the free quarks. Using the concentrations of C, N, and O one can estimate that the time for all the quarks to go over to these nuclei is less than 10^7 sec. Detachment from these nuclei requires a very high temperature. For example, for $T = 5 \times 10^7\,°K$, which exceeds the temperature in the interior of stars of the main sequence, the fraction of free quarks as compared with the quarks attached to O is 10^{-100}. Thus, transfer to heavier nuclei such as Fe practically does not occur; the fractions of Fe and O atoms having quarks are the same, but the Fe content is small compared to the O. If during explosion the temperature is raised above 10^9, the quarks go over to the Fe.

Summarizing, we may say that quarks with $Z = +\frac{2}{3}$ impinging on a star are largely annihilated; the concentration stays less than 10^{-18} per gram. Only those are left that stayed on the surface all the time. This is possible in stars having no convective zone, but since in the early and late stages almost all stars are convective, retention is improbable. Quarks with $Z = -\frac{1}{3}$, falling into a star, attach to the elements C, N, O and heavier ones. One should therefore look for spectra of atoms and molecules with C, N, O, and heavier atoms, whose nuclei contain quarks. The atomic spectra should differ from the usual ones because of the change in the nuclear charge (the isotope shift is small) while the molecular spectra will be different because of the change in the vibration-rotation parameters of the system.

We now consider the quarks which do not remain in stars. They should either be free ($Z = +\frac{2}{3}$) or attached to hydrogen ($Z = -\frac{1}{3}$). We should mention that in the interstellar gas quarks and quark nuclei should attach to dust particles because of the presence of the charge. Thus their lines may also not be present in the spectrum of instellar gas. Besides, the present methods of investigating the instellar medium cannot in general give information about elements with low concentration.

We now estimate the probability that during the process of formation of the galaxy and the building up of stars no quarks entered the stars. In each process of star formation about half the condensing gas is converted into stars of low mass, which evolve slowly. The other half is converted into massive stars which go through their cycle rapidly and finally eject about half their mass into the interstellar space. The remainder collapses or forms a superdense star. Let us assume that $\frac{1}{4}$ of the mass converted initially into stars is again ejected into the interstellar gas and mixes with the residue of the primary gas, after which star formation proceeds once more (cf., for example, the survey [33]). Such a gradual emission of gas is indicated by the gradual change in the chemical composition of stars and clusters with changes in their spatial and kinematic characteristics. Suppose that the fraction α of all the remaining gas is converted into stars in one cycle. This quantity is unknown; it may be of the order of 0.1—0.3, but its precise value is irrelevant. After n cycles, $(1 - \frac{3}{4}\alpha)^n$ of the gas remains, of which the fraction $a = [1 - \alpha/1 - (3\alpha/4)]^n$ did not pass through the star stage. At the present time 2% of the initial mass of the Galaxy is left in the form of gas. Thus $n\alpha \approx 5$ and $a \approx 0.25$—0.20 over the wide range of values of α from 0.1 to 0.3. Despite its naiveté, the computation shows that the gas in interstellar space should contain a considerable admixture of the original gas, and consequently the percentage content of quarks in the interstellar gas should be 10—20% of the initial value. As already pointed out, however, to detect them there is hardly possible.

The best conditions for experimental detection occur on planets like the earth. The solar system apparently was formed during the process of contraction of a nebula whose central part became the sun. The planets, in particular the inner ones, were formed mainly from dust.[34,35] Thus the fraction of quarks in them should be reasonable. During the period of formation of the earth, the temperature of the main mass of the sun must have been low, since this was still during the stage of compression. The physical conditions during this period have not been carefully studied; it is difficult to judge the probability of mixing with deep layers and annihilation of quarks, if they have positive charge. The negative quarks would have gone into He nuclei or heavier elements. It is more probable, however, that there was no significant burnup, since $T \sim 10^6$ deg was attained only at the very center of the condensing sun, while the envelope was mainly convective. In addition the gas around the earth was rarefied, and did not completely draw away the dust out of which the Earth was formed. Thus, if the quarks are negative they should be sought in hydrogen or heavier elements, and their content in these should be comparable to the initial value; if they are positive, their content can be either large or small, depending on the conditions of convection on the sun during the period of formation of the earth.

We should mention that the farther a planet is from the sun, the higher the probability that quarks are retained in it. Meteorites that are the products of decay of comets are of great interest from this point of view. According to present notions, comets are retained on the periphery of the solar system, go over under the influence of perturbations into orbits closer to the sun, after which they gradually disintegrate.[36] Meteorites from such comets in all probability were not in the depths of the Sun during the period of formation of the solar system.

Since the annihilation of positive quarks occurs under the same conditions as the burning of deuterium, the deuterium content should serve as a check. However, its paucity on Earth is explained, as already mentioned, by the activity of the sun during the period of condensation, when many of the cosmic rays were formed.

5. POSSIBLE WAYS OF SEARCHING FOR NEW PARTICLES

In searching for new particles one should consider the possibility of enriching or depleting samples by taking advantage of their physico-chemical properties.* Let us therefore consider some of the physicochemical properties of the quarks and the hypothetical stable particles with integer charge, and discuss possible ways of searching for these particles.

Particles with integral charge $Z = +1(i^+)$ do not differ physico-chemically from the hydrogen isotopes. They are concentrated during the production of heavy water. Mass spectrometric investigation of heavy water samples gives a relative concentration $C < 10^{-10}$ based on hydrogen in the original water (before separation).[37,38] There is an important possibility of lowering this limit by several factors of ten. Optical spectroscopic methods for detecting such "hydrogen" under terrestrial conditions are not as good as the mass spectroscopic method. Optical searches extraterrestrially, using the isotope shift, are also very difficult, since the isotope shift is usually very much smaller than the line width. The example of the search for deuterium in the sun's spectrum shows that the sensitivity is no better than 10^{-3} of the content of the main isotope.[39] The molecular spectrum of hydrides depends strongly on the masses of the atoms, but is is observed only within a narrow interval of spectral classes, limited above by molecular dissociation and below by the low luminous intensity of stars.

The particles with integral charge $Z = -1(i^-)$, in particular, the antiparticles of the preceding ones, are created by energetic cosmic rays in the atmosphere, attach to nuclei in the atmosphere, jump from the protons to heavier nuclei, as in the case of μ^--mesic atoms. It is natural to look for them among the isotopes of carbon (N, i^-), nitrogen (O, i^-) and oxygen (F, i^-). Such atoms are formed as the result of reactions like $O + p, i^- \rightarrow F, i^- + \gamma$. Their binding energy of such nuclei is of the order of several MeV.

The $q^{+2/3}$ or $q^{-1/3}$ quark (depending on which one is the lighter) and the corresponding antiquark are stable and can accumulate in the earth. Atoms containing the quarks have an uncompensated electric charge and behave like ions. Solvation of the ions in polar solutions practically excludes the possibility of evaporation from water of the quarks or of molecules containing quarks. One can cite the example of the Li^+, Na^+, F^+ and Cl^+ ions. All these ions have a noble gas structure, and their solubility in water is small. But the charge on the ions gives an energy of solvation of the order of 1.5 eV, which makes it impossible to drive them out of solution. For quarks the energy of solvation is lower in the ratio Z or Z^2, i.e. it is of order 0.5—1 eV for $Z = 2/3$ and 0.2—0.5 eV for $Z = -1/3$. At 100°C the corresponding value of $e^{-Q/T}$ is $10^{-14} - 10^{-17}$ in the first case and 10^{-3}—10^{-7} in the second. The nonvolatility of the quarks must be considered in mass-spectroscopic searches for them; their concentration in vapors is substantially less than in liquids. Upon distillation of the water the sample is purified of quarks. The experiments of Kohlrausch on the electrical conductivity of pure water[40] apparently give a relative concentration of quarks less than 10^{-9}. Because of our earlier remarks, this estimate is even worse for ordinary water.

Ions containing quarks should be adsorbed from nonpolar materials (petroleums, oils) onto the surface of minerals containing petroleum, or onto filters or the glass and metallic walls of vessels containing oil. Loss of quarks during purification of oil should be considered in interpreting the Millikan experiment, which indicates a relative concentration below 10^{-15}.

The technique of accurate determination of very small periodic forces, which has been successfully developed by V. B. Braginskiĭ,[41] has been proposed by him for use in detecting single fractional charges in samples weighing 10^{-4} g, placed in a periodic electric field. This corresponds to a sensitivity of 10^{-19}.

The optical spectra of atoms containing quarks should be very characteristic. The L_α lines for $(q^{+2/3}e^-)$ and $(q^{-1/3}pe^-)$ atoms fall in the near ultraviolet $\lambda = 2750$ Å. The Hubble red shift for distant galaxies and quasars shifts this line to a convenient region for observation. Atoms of C, N, O, and Fe, which have a quark attached to their nuclei, should have spectra altogether different from the usual spectra of these elements, since all the screening parameters of the electron shells are changed. Calculation of the spectra of such atoms represents a definite quantum mechanical problem. After the calculations have been made, one must make a serious search for these lines and also for the $\lambda = 2750$ Å line and molecular lines for unusual masses* in the spectra of various cosmic objects, entirely independently of all estimates of quark concentrations, which at present pretend to be reliable.

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*In principle it is impossible, for example, to exclude the possibility of biological concentration of quarks by some organisms.

*For the analogous proposals for positronium and antipositronium cf.[42, 43]

6. CONCLUSION

One of the main questions arising in connection with the possible existence of new stable particles, and quarks in particular, is why these particles have so far not been seen by us in nature. As the above arguments show, this is not at all surprising. In the process of the primary Friedmann expansion quarks were consumed extensively and changed into nucleons; their concentration becomes of order 10^{-9}—10^{-18} per nucleon, even if the quarks and nucleons had the same initial concentrations. If the positively charged quarks are lightest, and consequently stable, their burnup continues in the interior of stars. The negatively charged quarks are "conserved," attaching themselves to nuclei. Thus the fact that quarks have so far not been seen can be regarded as an argument that the positive quarks are the stable ones. One should however remember that in the process of evolution part of the matter does not go through the stage of being part of a star, and preserves the quark concentration which was left after the initial stage of the Friedmann expansion.

In searching for thermalized quarks under terrestrial conditions one should take account of their physico-chemical peculiarities, such as solvation in water solutions and precipitation on the walls in nonpolar solvents. Under laboratory conditions the best methods for searching for quarks are to measure the elementary charges on macroscopic bodies and to use mass spectrometry. The latter method is especially effective in looking for new particles with integral charge. Optical spectroscopy can be used for quarks in extraterrestrial objects.

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Translated by M. Hamermesh