Realistic Quark Models and Astrophysics

As is well known, quark models using 12 types of quarks give rather satisfactory descriptions of all properties of numerous and proliferating families of hadrons:† their symmetries, spin, mass, strong, electromagnetic and weak interactions (for a review see the book and lectures cited[1]).

The number 12 is composed of four types (p, n, strange λ and charmed C) times three colours (for example, p-red, p-yellow and p-blue and the same for other types).

Compared with the first guess of Gell-Mann and Zweig with 3 quarks, the most important single gain due to color is that no violation of the Pauli principle is needed. But simultaneously a freedom of choice appears: the charges (electric and baryonic) of individual quarks could be chosen integral or fractional at will.[2] This freedom of choice leads further to the possibility of various answers concerning the stability of individual quarks.

The most fashionable at the moment are "infrared jail" models: colored fractionally charged quarks are confined inside hadrons, so that they do not exist as free particles.

However, as long as the theory of quark confinement is still under construction, the realistic quark models are well worth considering in detail. The realistic quarks are assumed to exist in a free state as well as a bound state. It is assumed further that they have integer electric charges.‡

We discuss the following variants of realistic theories:

1) Fractional baryonic charges of quarks ($B = 1/3$) and exact conservation of baryonic charge lead to the absolute stability of one quark type at least.

2) Fractional baryonic charges of quarks ($B = 1/3$) and violation of baryonic charge conservation lead to unstable quarks.[4,5] The stability of "stable" nuclei, and particularly of protons, is no longer absolute. Their practical stability

† Provided the new ψ (3.1 GeV, 3.7 GeV etc.) particles contain charmed quarks.

‡ The detection of fractional charges being rather easy, the experiment rules out this possibility with certainty (see, e.g., Ref. 3).

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($\tau \gtrsim 10^{30}$ years) is explained by the fact that the decay is possible only in the third order of weak interactions.

3) Integer baryonic charges of quarks and exact baryonic charge conservation lead to fast decay of all individual quarks and simultaneously to the absolute stability of protons. In this scheme two colors of quarks, for example, yellow and blue, have positive baryonic charge ($B = +1$) while the red quarks have $B = -1$. Free yellow or blue quarks (independently of type) can decay into baryons, the red ones into antibaryons. The latter scheme is widely believed to be the most simple and natural. In this paper we add some astrophysical arguments (based on the hot Big Bang theory) to somewhat arbitrary feelings about what is "natural" and what is "artificial".

We shall show below that the first variant leads to the prediction of extremely high concentration of stable quarks in the matter surrounding us: the predicted concentration is of the order of the gold (!) concentration.

The second variant, with baryon charge nonconservation, solves the problem of how to get rid of nondesirable free quarks. But, having in mind the Big Bang picture of the Universe, the theory shows that baryons are also lost even before they are formed from quarks.

It is only the third variant, combining the baryon charge conservation and unstable integrally charged quarks, which is "astroproof", i.e. which survives under the impact of cosmological reasoning.

The modern cosmology cannot escape the idea of a hot singularity. We are interested in the "hadronic period" – its early phase – characterized by temperatures of the order of $T = 100$ to 10 GeV $= 10^{15}$ to 10^{14} °K. The corresponding density, proportional to T^4, is $\cong 10^{27}$ to 10^{23} g/cm^3, much higher than the nuclear density. On the other hand, the time (measured from the singularity) is $t \cong 10^{-10}$ to 10^{-8} sec, the expansion rate is equal to $t^{-1} \cong 10^{10}$ to 10^{8} sec^{-1}.†

At a temperature higher, or of the order of, the quark mass there must be plenty of free quarks. Because of a relatively slow expansion rate, full thermodynamical equilibrium is established.

Starting from this period we must investigate the kinetics of processes during expansion and cooling of the Universe in order to make predictions concerning the contemporary situation.

We assume the first case, with exact baryonic charge conservation. The Universe has everywhere the same average density of the baryonic charge. In the early hadronic period this means the small predominance of quarks q (with

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† The age t of the Universe and its temperature T are connected by the relation $T^4 \cong (Gt^2)^{-1}$. Here G is Newton's gravitational constant: $G = 6.7 \times 10^{-8}$ dyn cm^2/g^2, or $G = 6 \times 10^{-39} m_p^{-2}$ where m_p is proton mass, $h = c = 1$.

positive $B = 1/3$ for all types) over antiquarks $\tilde{q}$ ($B = -1/3$). We must assume that

$$q:\tilde{q} \cong 1 + 10^{-8} , \qquad q:\gamma \cong \tilde{q}:\gamma \cong 1 .$$

No convincing theoretical approach to the strange ratio $1 + 10^{-8}$ is known; it is taken from the present observations. 10^{-8} is the contemporary ratio of baryons to photons,

$$\frac{B}{\gamma} = \frac{1}{3} \frac{q - \tilde{q}}{\gamma} \cong 10^{-8} .$$

During expansion and cooling most quarks and antiquarks are extinguished by binary collisions:

$$q + \tilde{q} \rightarrow \text{mesons}$$

$$q + q \rightarrow \text{baryon} + \text{mesons} + \tilde{q}$$

$$\tilde{q} + q \rightarrow \text{antibaryon} + \text{mesons} + q .$$

It was shown by S. B. Pikelner and the authors[6] that extinguishing by binary collisions leads to a final concentration

$$\frac{q}{\gamma} \cong \frac{\tilde{q}}{\gamma} \cong \frac{G^{1/2}}{\sigma v m} ,$$

where σ is the quark annihilation cross section, v its velocity and m its mass. With $\sigma v \cong m^{-2}$ and $m \cong$ GeV we obtain $q:\gamma \cong 10^{-18}$.

Different types of quarks can decay spontaneously into one most stable type via weak interaction. This lightest quark is perhaps captured by nuclei due to electromagnetic and strong interactions.

Thus very unusual types of isotopes or particles are predicted in rather high concentration: to the formula given above corresponds

$$q:H \cong 10^{-10} \qquad (H = \text{hydrogen})$$

that is more than the concentration in the Universe of many well-studied isotopes.

The unusual isotopes were searched by the experimentalists, but unsuccessfully. For example, a superheavy isotope of hydrogen with $6m_H < m < 16m_H$ is absent[7] to the level of $q/H \lesssim 10^{-18}$. It is interesting and important to continue this quest further including a wider range of masses and various types of isotopes. Most difficult would be the detection of stable neutral quarks in the case when the strong interaction does not bind them with nuclei.

Our final conclusion is that astrophysical arguments make the first variant improbable although they do not definitely rule it out.

Let us analyze the second possibility (unstable quarks, baryonic charge nonconservation). The quark decay with a small enough characteristic time solves the puzzle of the absence of free quarks in Nature. The short lifetime of the free quark does not contradict the very large lower limit of the proton stability ($\tau \gtrsim 10^{37}$ sec): the point is that all the three quarks constituting a proton must decay simultaneously. In this case protons are, in practice, not lost due to their decay during the cool period but the real disaster takes place earlier during the period of existence of free quarks in thermodynamic equilibrium.

This thermodynamic equilibrium is obtained with a high degree of precision.[†]

But thermodynamic equilibrium without charge conservation leads to baryonic charge symmetry. The situation in the second case is summarized by saying that it explains the absence of free quarks but the explanation is far too good – the free baryons and therefore practically all matter is annihilated (except a tiny fraction $\sim 10^{-18}$, ten orders less than observed).

Attempts[4,9] to use CP violation to explain the predominance of surviving baryons over antibaryons do not work. The equilibrium is symmetric even in the CP violating theory. The kinetic effects of CP violation (which is also *T* violation) seems to be far too weak.

Thus astrophysical arguments definitely rule out the variant of baryonic charge nonconservation and pose serious problems for the variant of stable quarks. Astrophysics has decisively nothing against the third variant of the theory according to which the baryonic charge is conserved and quarks are unstable. According to such theory each baryon contains two quarks with $B = +1$ and one quark with $B = -1$. Taken literally, this theory predicts that, using energetic enough hadrons, we achieve the reaction

$$p + p \rightarrow 3q + p + \text{mesons} ,$$

with subsequent characteristic spontaneous decay of quarks

$$3q \rightarrow 2 \text{ nucleons} + \text{antinucleon} + \text{mesons}$$

$$q \rightarrow \text{nucleon} + \text{mesons for yellow and blue quarks}$$

and $$q \rightarrow \text{antinucleon} + \text{mesons for the red quark.}$$

Thus an experimental search for unstable colored quarks with integer electric charges becomes most important.

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† The dynamical equilibrium is due not only to decay reversal q → leptons, leptons → q, but also to all kinds of induced processes, leptons + mesons + q → leptons + mesons. Due to induced processes the rate of equilibrium establishment grows at high temperature, just as in the case of N ⇄ P equilibrium (Hayashi[10]).