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HYPOTHESIS CONCERNING QUARK STARS

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Attempts at systematization of elementary particles and their reduction to a few objects have led to the hypothesis of subparticles known as "quarks" [1], which are assumed to make up all strongly interacting hadrons, that is, mesons, baryons and their resonances. Quarks should have fractional baryon and electrical charges and a mass considerably exceeding the baryon mass. Quarks may be real particles which for a number of reasons are difficult to observe. In some respects the similar hypothesis of "trions," subparticles with a whole charge, also requires that they have a considerable mass. It is an inviting possibility to search for quarks (or trions, which will not be given special consideration here) in astronomical superdense configurations, especially under conditions when ordinary particles lose their individuality and the material from which nucleons are formed may be the quark field.

As is well known, with further compression of a star after the formation of a degenerate electron gas there is an "imbedding" of electrons into protons, a breakdown of the nuclei and a transition to a neutron star; with still further compression a transition to a degenerate hyperon Fermi gas follows [2]. It is natural to assume that a transition to a still heavier baryon resonance may also favored, and finally to the hypothetical sub-particles: quarks, etc.

The transition to quarks corresponds to a strong internal excitation of the baryons, in the last analysis leading to their disintegration into fundamental subparticles.

We will analyze the conditions for the transition of a baryon star, as the preceding configuration, to a quark star, neglecting temperature. We use B, Q_1, Q_2, Q_3 to denote the baryon and the quarks. The disintegration

$$B \to Q_1 + Q_2 + Q_3 \tag{1}$$

is possible when the baryon has the kinetic energy

$$U_k > \Delta mc^2, \quad \Delta mc^2 = (\alpha - 1)\, mc^2, \tag{2}$$

where Δm is the mass defect in (1), m is baryon mass; the masses of the quarks accordingly will be

$$\begin{gathered} m_j = \alpha_j m \ (j = 1,\ 2,\ 3), \\ \Sigma \alpha_j m = \alpha m, \ \alpha = \alpha_1 + \alpha_2 + \alpha_3 \gg 1. \end{gathered} \tag{3}$$

In the case of a baryon degenerate gas the condition (1) has the form

$$\begin{gathered} U_{\max} = \frac{a_q}{m} n_0^q > (\alpha - 1)\, mc^2; \quad n_0 > \{(\alpha - 1)\, m^2 c^2 a_q^{-1}\}^{1/q} \\ q = {}^1/_3,\ {}^2/_3; \quad a_{^2/_3} = \frac{1}{8}\left(\frac{3}{\pi}\right)^{^2/_3} h^2 \approx 5 \cdot 10^{-54}; \\ a_{^1/_3} = \frac{1}{2}\left(\frac{3}{\pi}\right)^{^1/_3} hcm; \end{gathered} \tag{4}$$

where n_0 is the baryon density, $q = {}^2/_3$ for nonrelativistic and $q = {}^1/_3$ for ultrarelativistic gases. It can be estimated that reaction (1) can occur only at very high densities, as a result of which we can simplify by limiting ourselves to the ultrarelativistic case. Although under the conditions which exist in superdense configurations we were concerned with a system containing all species of baryons and their resonances at similar concentrations, however, due to the complexity of this model we will approximate to it by a single baryon gas with some mean reduced mass $m = \gamma m_0$, where m_0 is the nucleon mass and γ is a factor of the order of $1 < \gamma < 10$. Then we have

$$n_0 > \{\gamma (\alpha - 1)\}^3 10^{40} \text{ cm}^{-3} \qquad a_{^1/_3} = \gamma \cdot 1.7 \cdot 10^{-40}. \tag{5}$$

In this case the equilibrium density of the quarks is determined from the equality of the limiting Fermi energies of the baryons and the three quarks.

Considering the baryons as ultrarelativistic, and quarks as nonrelativistic, the equilibrium condition may be written in the form

$$a_{1/3} n_B^{1/3} = \frac{9}{\alpha} a_{1/3} n_Q^{1/3} + \alpha m^2 c^2. \tag{6}$$

In the case where the quarks are ultrarelativistic, we have

$$\frac{n_B}{n_0} \approx 9/\alpha \lesssim 1. \tag{6.1}$$

This high density, as determined by inequality (5), which is necessary for reaction (1), might be attained, for example, in the interiors of some baryon stars. However, according to present-day concepts, a star of such high central density will be in a quasi-equilibrium state [3].

A baryon star with an initial mass $M = N_0 m$, imparts to the quarks a kinetic energy $E = N_1(\alpha - 1)mc^2$ when the N_1-baryons transform quarks, the pressure decrease will be $\Delta P \approx n_Q \Delta mc^2$, where n_Q is the density of quarks of the same kind. Since when n_1 baryons of the n_0 baryons per unit volume transform into quarks, the gravitational energy of the system does not change, such a transition leads to a further compression of the star.

Now we will assume that there is a stellar configuration with the mass $M_0 = (N_Q\alpha + N_B)m$, where αm is the mass of the three quarks, N_Q is the total number of quarks of the same kind, N_B is the total number of baryons (neglecting the gravitational mass defect). Due to the possibility of local density fluctuations such a configuration will be unstable. As a result of density fluctuations in a relatively small volume ΔV, the baryon density can become less than that determined by the inequality (5). Then the process becomes unidirectional and the transformation of quarks into baryons with the release of an enormous kinetic energy begins—$E \approx N_Q(\alpha - 1)mc^2$, where N_Q is the number of quarks in ΔV. This creates a pressure drop $\approx E\Delta V$ and leads to a further expansion of the region of density fluctuation, so that the local density fluctuations can expand in an unlimited way with time. The total kinetic energy released in this case will be

$$\bar{\varepsilon} = (\alpha - 1) N_Q mc^2 = 6(\alpha - 1)\left[1 - \frac{N_B}{N_B + N_Q}\right]\frac{GM^2}{R_g}, \tag{7}$$

$$R_g = \frac{2GM}{c^2},$$

where $M = (N^B + N_Q)m$ is the mass of a star whose initial mass is $(M_B + \alpha N_Q)m$, after all the quarks have transformed back into baryons, R_g is the gravitational radius. In this case the relased kinetic energy is

$$\bar{\varepsilon} > \frac{GM^2}{R_g}$$

and this is adequate in principle for a configuration of mass M, in a state close to the gravitational radius, to expand to an unlimited size. If at the same time the transformation of a quark star into a baryon star occurs quite rapidly, the expansion will have the character of an explosion. Of course, in a quark star formed by compression the fluctuations cannot lead back to a baryon star, but in a quark configuration formed in some other way the fluctuations can apparently lead to an explosion.

It is not impossible that in the central regions of some of the recently discovered astronomical objects, which are releasing enormous amounts of energy (quasars, exploding galaxies), some part is played by processes in which quarks (or other subparticles) participate. Configurations of the quark type may be useful for analysis of the superdense prestellar states proposed by V. A. Ambartsumyan, or for analysis of the initial state of the entire expanding universe.

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