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Possible production of "collapsed" hadronic matter in very-high-energy nucleon-nucleon collisions

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We speculate on the possible production of "collapsed" hadrons, i.e., color-singlet, electrically uncharged (or with small integral charge) clusters of quarks and antiquarks, in very-high-energy proton-proton collisions, the intermediate states of which contain relatively large numbers of quarks q, antiquarks $\bar{q}$, and gluons g. Using a thermodynamic model, we crudely estimate the numbers and kinetic energies of the q, $\bar{q}$, and g in the intermediate-state gas mixture, and indicate how the properties of collapsed hadrons might depend on the quantum numbers of the q and $\bar{q}$. A brief discussion of experimental signatures for identification of collapsed hadrons is presented, along with mention of the consequences of possible collapsed-hadron production in the early Universe.

INTRODUCTION

There have been a number of speculations on the possible existence of phases of hadronic matter differing from ordinary hadronic matter in some fundamental property, e.g., the ratio of baryon number to volume or baryon number to mass.[1-18] These speculations propose various detailed mechanisms to bring about the formation of the new hadronic phase, but are similar one to another in that most of them visualize the new phase as being formed in the collisions of heavy ions with heavy ions at energies sufficiently large to overcome the short-range repulsion between nucleons. Further, in many of these speculations, the basic units of the new hadronic phase are still assumed to be composed of ordinary nucleons, although the ratios of baryon number to volume and baryon number to mass are supposed to be considerably larger in these basic units than in ordinary hadronic matter.

We consider here the possibility of the existence of a new phase of hadronic matter which is different, at least as regards the mechanism of its formation, from those mentioned above. As did most previous authors, we conclude that the new phase of hadronic matter is likely to be characterized by ratios of baryon number to volume and baryon number to mass that are larger than in ordinary hadronic matter, but we suppose that this "collapsed" hadronic matter can result from very energetic proton-proton (or pion-proton) collisions which produce intermediate states containing large numbers of quarks (q), antiquarks ($\bar{q}$), and gluons (g) with relatively small forces among them, as dictated by asymptotic freedom.[4]

The final states that evolve from this almost ideal gas mixture, as it expands and the q, $\bar{q}$, g confining forces come into play, will principally be those containing ordinary hadrons and antihadrons, i.e., nucleons and hyperons, antinucleons and antihyperons, and π and K mesons,[19] and very infrequently, ordinary nuclei, hypernuclei, antinuclei, and antihypernuclei. Another possibility, however, is that clusters of many quarks (or many antiquarks) in color-singlet and zero- (or integral-) electric-charge configurations, will occasionally condense out of the gas mixture. These clusters, which can be considered as the basic units of collapsed hadronic matter, are likely (see below) to possess zero (or relatively small) electric charge and hypercharge, this last implying a negative strangeness numerically of the order of the baryon number.[20] Also, the masses and radii of the clusters are expected to be less than those of ordinary hadrons with the same baryon number, a rough limit to the mass being specified by the gas temperature.

In general, the condensation upon expansion of the q, $\bar{q}$, g gas mixture into collapsed as well as ordinary hadrons can be viewed as analogous to the condensation upon expansion of, e.g., an α particle, electron gas mixture into ^{12}C, ^{16}O,... atoms as well as ^{4}He atoms. The relative number of collapsed hadrons will depend on their baryon numbers and masses, and also on the q-q ($\bar{q}$-$\bar{q}$) and q-$\bar{q}$ collision rates, and the expansion rate of the q, $\bar{q}$, g gas mixture.

Following current ideas on very-high-energy nucleon-nucleon collisions, we take the volume containing the q, $\bar{q}$, g gas mixture to be appropriately Lorentz-contracted with respect to the volume of a single nucleon, and estimate the numbers and kinetic energies of the q, $\bar{q}$, g in the gas mixture on the assumption that the mixture is in thermal equilibrium. We also indicate how the properties of collapsed hadrons formed in the expansion of the q, $\bar{q}$, g gas mixture depend on the quantum numbers of the q and $\bar{q}$, and how these properties suggest experimental signatures for identification of the collapsed hadrons. Finally, we mention some consequences of the production of collapsed hadrons in the condensation of a cosmological q, $\bar{q}$, g gas mixture which might have been present in the very early Universe.

CHARACTERISTICS OF THE q, $\bar{q}$, g GAS MIXTURE

To calculate the equation of state of the gas mixture produced in very energetic proton-proton collisions and the number of q, $\bar{q}$, and g in it, we adopt for simplicity a thermodynamic model.[21] This gives, for the relation between the center-of-mass energy of the two colliding protons, $E^* = E_q + E_{\bar{q}} + E_g$, and the temperature T,

$$E^* = \frac{(\frac{4}{3}\pi R_p^3)}{(E^*/2M_p)}(3\times3\times\tfrac{7}{8}+3\times3\times\tfrac{7}{8}+8)(6.6/\pi^2)T^4, \tag{1}$$

where R_p is the proton radius $\cong 4/M_p$ from e-p scattering experiments, $E^*/2M_p$ is the relativistic contraction of the collision distance, and the three terms in parentheses represent the contributions of the q, $\bar{q}$, and g degrees of freedom, respectively, assuming $q = u, d, s$ only. Further, the number of quarks (antiquarks) of a given flavor present in the q, $\bar{q}$, g gas mixture is

$$N_u = N_d = N_s = N_{\bar{u}} = N_{\bar{d}} = N_{\bar{s}} = \frac{\frac{4}{3}\pi R_p{}^3}{E^*/2M_p}[3\times\tfrac{3}{4}\times(2.4/\pi^2)T^3]. \tag{2}$$

Note that in writing Eqs. (1) and (2) we have neglected the effective masses of the quarks compared with T so that, e.g., $N_u = N_q/3$, where N_q is the total number of quarks in the mixture; this involves errors of order $m_q{}^2/(3T)^2$.

Equations (1) and (2) yield[22]

$$T/M_p = 0.10(E^*/M_p)^{1/2} \text{ and } N_q = N_{\bar{q}} = 9.6\,T/M_p\,, \tag{3}$$

from which are obtained the numerical values of T and N_q for several representative values of E^* that are shown in Table I. It is interesting to observe that at the center-of-mass energy of the CERN ISR the value of N_q is rather small and a thermodynamic description may be inaccurate. At the energy of ISABELLE and above, the values of N_q are considerably larger and the thermodynamic model is more reliable quantitatively.

TABLE I. Values of T and $N_q = N_{\bar{q}}$ for different p-p colliding-beam energies E^*.

E^* (GeV)	T (GeV)	$N_q = N_{\bar{q}}$
56 (CERN ISR)	0.77	8
800 (ISABELLE)	2.9	30
5000 ("FUTURA")	7.3	75

PROPERTIES OF THE COLLAPSED HADRONS

We now suppose that the quark (antiquark) system which condenses out of the expanding q, $\bar{q}$, g gas mixture is confined to a spherical region of radius R, the radius of the collapsed hadron, and that the gluonic forces among its quark (antiquark) constitutents are describable by a potential energy extending uniformly over R and proportional in magnitude to the total number of quarks within R. This is certainly a questionable model but we use it only to suggest qualitative conclusions. Again, we assume that the effective masses of the quarks are all small compared with their kinetic energies.

The total energy of the collapsed hadron is then given by

$$E = E^{\text{pot}}_{\text{gluon}} + E^{\text{pot}}_{\text{Coul}} + E^{\text{kin}} \tag{4}$$

with

$$E^{\text{pot}}_{\text{gluon}} = -\tfrac{1}{3}(n_u+n_d+n_s)\epsilon_0\,, \quad \epsilon_0 > 0 \tag{5}$$

$$E^{\text{pot}}_{\text{Coul}} = \frac{\alpha}{2}\sum_{\substack{i,j\\ i\neq j}}\frac{Q_iQ_j}{r_{ij}} \cong \frac{3}{4}\frac{\alpha}{R}\left[\left(\sum_i Q_i\right)^2 - \left(\sum_i Q_i{}^2\right)\right], \tag{6}$$

$$E^{\text{kin}} = \tfrac{3}{4}(\tfrac{3}{4}\pi)^{1/3}\frac{1}{R}(n_u{}^{4/3}+n_d{}^{4/3}+n_s{}^{4/3})\,, \tag{7}$$

where

$$\begin{aligned} n_u &= I^{(3)} + B + Y/2 = I^{(3)} + 3B/2 + S/2\,,\\ n_d &= -I^{(3)} + B + Y/2 = -I^{(3)} + 3B/2 + S/2\,,\\ n_s &= B - Y = -S\,,\\ \sum_i Q_i &= 2n_u/3 - n_d/3 - n_s/3 = I^{(3)} + Y/2\,,\\ \sum_i Q_i{}^2 &= 4n_u/9 + n_d/9 + n_s/9\\ &= \tfrac{1}{3}(I^{(3)}+Y/2) + 2B/3\,, \end{aligned} \tag{8}$$

and where n_u, n_d, and n_s are the numbers of u, d, and s quarks in the collapsed hadron, Q_i is the electric charge on the ith quark, and B, $I^{(3)}$, S, Y, and $\sum_i Q_i$ are the baryon number, third component of isospin, strangeness, hypercharge, and electric charge, respectively, of the collapsed hadron.

For the small numbers of quarks (antiquarks) in the collapsed hadrons contemplated here, we can neglect the Coulomb energy ($\alpha = \frac{1}{137}$) and find from Eqs. (4) to (8)

$$E=-\epsilon_0 B+\frac{3}{4}\left(\frac{3\pi}{4}\right)^{1/3}\frac{3B^{4/3}}{R}\times\left\{1+\frac{1}{9}\left[\frac{4}{3}\left(\frac{I^{(3)}}{B}\right)^2+\left(\frac{Y}{B}\right)^2\right]+\cdots\right\}. \tag{9}$$

The ground state and low-lying energy states given by Eq. (9) obtain when $I^{(3)}$ and Y vanish or are close to zero. Thus, in our model, the lowest-energy states of the collapsed hadron are characterized by approximately equal numbers of quarks of each flavor ($n_u \cong n_d \cong n_s \cong B$), and so by a zero or numerically small electric charge, and by a numerically large, negative strangeness. Thus our collapsed hadrons are hyperhadrons.

If we assume further, again as with ordinary hadrons, that $R=r_0 B^{1/3}$, the masses of the collapsed hadrons are given by

$$E_{\text{ground state}} \cong B\left[-\epsilon_0+\frac{3}{4}\left(\frac{3\pi}{4}\right)^{1/3}\frac{3}{r_0}+\cdots\right]. \tag{10}$$

The value of r_0 may be fairly close to $R_p \cong 4/M_p$, for which value the second term in Eq. (10) is approximately 0.75 GeV. Since both terms in Eq. (10) could be similar in magnitude, the masses of the collapsed hadrons might be less (perhaps significantly less) than the masses of ordinary hadrons with corresponding baryon numbers.

Particularly stable collapsed hadrons would be the analogs of closed-shell nuclei. Thus, the collapsed hadron with $n_u=n_d=n_s=B=6$, with a wave function that could be thought of as a superposition of contributions from very tightly bound configurations corresponding to $[ppnn\Omega^-\Omega^-]$, $[pp\Lambda\Lambda\Xi^-\Xi^-]$, $[\Sigma^+\Sigma^+\Sigma^0\Sigma^0\Sigma^-\Sigma^-]$, etc., would be the analog of an α particle. (We emphasize, however, that reference to such configurations serves solely to make explicit the quantum numbers involved; the constituents of collapsed hadrons are quarks or antiquarks, not elementary baryons.) The lowest-mass state of a collapsed-hadron "multiplet" defined by a given baryon number would, by energy considerations, be stable against nonleptonic and semileptonic weak decay to ordinary hadrons as well as to other collapsed hadrons, in contradistinction to ordinary hypernuclei. Higher-mass states would β decay within the multiplet, but not to ordinary hadrons.

EXPERIMENTAL IDENTIFICATION OF COLLAPSED HADRONS

We recall that most high-energy p-p collisions are of the peripheral type. In a colliding-beams machine such collisions will show "projectile" fragmentation, i.e., jets of particles in the directly forward and directly backward directions. On the other hand, we would expect that collisions leading to the high-temperature intermediate states described above would be central collisions showing heavy "target" fragmentation, i.e., rough isotropy or wide-angle jets with relatively few particles. Hence collapsed-hadron production should be sought in those collisions without appreciable forward-backward jet structure.

Condensation of the expanding q, $\bar{q}$, g gas mixture following the p-p collision will in general lead to ordinary hadrons in much larger numbers than collapsed hadrons. Nevertheless, the properties of the collapsed hadrons described above provide specific experimental signals by means of which they may be identified. In summary, these properties are (i) zero or small electric charge, (ii) large negative (positive) strangeness for matter (antimatter), approximately equal in magnitude to the baryon number, (iii) radii and masses probably less than the radii and masses of ordinary hadrons with equivalent baryon numbers, and (iv) approximately equal numbers of collapsed hadrons and antihadrons.

The collision of an energetic collapsed hadron having these properties with an ordinary nucleon of a particle detector would be similar in some respects to the collision of a Ξ^0 or Ξ^- (Ω^-) with ordinary matter. Depending on the precise values of B and S, the final states of a collapsed-hadron–nucleon collision would contain several strange baryons which would appear in the detector as distinct vees. Even taking into account secondary interactions, such final states would be noticeable by the size of the hyperon population relative to the size of the meson population.

Since collapsed antihadrons should occur about as often as collapsed hadrons, we would expect to observe interactions resulting in a number of final-state antihyperons of positive strangeness. These would be a striking signature of collapsed-antihadron–nucleon collisions. Another striking signature of certain collapsed-antihadron–nucleus collisions would be the production of many mesons with a $(K^-, \bar{K}^0)/\pi$ ratio of order unity.

A stable collapsed hadron (or antihadron) with momentum comparable to its mass would move slowly enough to permit an accurate time-of-flight measurement of its velocity to be made by present techniques. For collapsed hadrons (or antihadrons) with unit electric charge, a velocity measurement in conjunction with a momentum measurement would unambiguously determine the mass. Masses of neutral collapsed hadrons would be more difficult to obtain.

Finally, a collapsed hadron or antihadron that condenses out of the gas mixture formed in the initial p-p collision will tend to leave behind ordinary hadronic matter of opposite baryon number and strangeness. That imbalance in the residue would serve as a signal of the production of a new particle type, if it were shown that large numbers of particles from the p-p collision did not escape detection.

In this connection, an interesting example of a possible new particle type are the noteworthy "Centauro" events,[17,23] with primary energies $\sim 10^3$ TeV, observed in emulsion studies of cosmic rays by the Brazil-Japan collaboration. The two main features of these events are (1) the absence of π^0 and e among their secondaries (the absence of charged mesons among the $\sim 10^2$ total secondaries per event is not established), and (2) the relatively large average transverse momentum $\langle p_t \rangle$ of the secondaries, estimated to be $\langle p_t \rangle \sim 1.7 \pm 0.7$ GeV.

We remark that the residual hadronic matter accompanying a collapsed hadron (or antihadron), heavily depleted in quarks (or antiquarks) as we have noted, would as a consequence be depleted in either case in mesons relative to baryons. Furthermore, a large value of $\langle p_t \rangle$ of the residual hadronic matter might follow from its recoil against a massive unit of collapsed hadronic matter. Our treatment of the model discussed above, involving a very energetic proton-proton collision that gives rise to a collapsed hadron in company with ordinary antibaryons is too crude to apply directly to a quantitative explanation of the Centauro events, but we observe that the model may be qualitatively consistent with one feature, and possibly both features, of the Centauro events.

SUMMARY AND CONCLUSIONS

Certain properties of the collapsed hadrons that are obtained here follow more or less directly from the values of the quark quantum numbers and may be independent of the particular model in which the energy of the hadronic states is calculated, and even of the specific nature of the resultant multiquark matter. Thus, for example, Chin and Kerman[16] use the MIT bag model of hadrons to describe in some detail possible extended massive multiquark states, formed in the collisions of relativistic heavy ions, which are quite different from the states described here. Nevertheless, they find important attributes of their states to be metastability combined with large strangeness. These attributes are also suggested by infinite-quark-matter calculations.[5,11,12,14,24,25]

There is, as we have noted, much wider variation among model calculations of the values anticipated for the masses and radii of possible new phases of quark matter, and also of the means of production of such new phases. We emphasize here that very-high-energy p-p collisions[21] may be an effective mechanism for collapsed-hadron production, especially if ordinary nuclear substructure is not necessary to either the formation or the stability of the new hadronic phase. Apart from very-high-energy nucleon-nucleus interactions in cosmic rays, no adequate test of this mechanism has been made or will be possible until the forthcoming hadron-hadron colliding-beam machines are available with center-of-mass energies near or greater than 10^3 GeV.

We have not attempted to consider at what stage in the expansion of a cosmological $q, \bar{q}, g$ gas mixture, which might have been present in the early Universe, there would have occurred condensation of collapsed hadrons. If, however, we assume that they were produced at an early time in very energetic collisions (or at some later evolutionary stage), there is no specific reason to suppose that they would have subsequently disappeared. Despite a large numerical value of strangeness, a collapsed hadron appearing as a color singlet with zero or small integral electric charge would be stable, and its dominant interaction with ordinary matter at low energy would be elastic scattering. Collapsed hadrons of this type with nonzero electric charge might be observed, if of sufficient natural abundance, in very sensitive mass spectroscopic analyses of very light elements.[26] On the other hand, collapsed hadrons of zero electric charge would not be discovered by this means; their observation would clearly have to be based on properties other than electric charge, e.g., nonzero magnetic moment. Alternatively, collapsed hadrons with zero (or negative) electric charge may have a nonvanishing cross section even at small kinetic energy to snatch one or more nucleons from a target nucleus; the resultant deexcitation of the mutilated target nucleus could then be observed.

Finally, there is the possibility that a neutron star might burn or explode by conversion to a collapsed-hadron star, and that the conversion might be observed and appropriately interpreted. Such a phenomenon, however, is apart from the primary consideration of this paper because it would involve low n-n relative velocities in a very large gravitational field in contrast to high p-p relative velocities in a negligible gravitational field in the collisions discussed above.

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[19]Even at the very high energies under consideration, the large masses of the charm and heavier quarks relative to the temperature of the gas mixture keep their numbers very small at thermal equilibrium.

[20]Bodmer, Ref. 1, was the first to point out that collapsed hadrons are likely to have negative strangeness numerically of the order of their baryon number.

[21]In this model the manner of formation of the intermediate-state gas mixture is not of primary importance. Hence our comments on the production of collapsed hadrons may apply equally well to π-p, $\bar{p}$-p, e^+-e^-, etc. collisions at very high energy. Of course, in p-p collisions there is present an excess of six quarks which may in the subsequent condensation of the q, $\bar{q}$, g gas mixture aid in the nucleation of collapsed hadronic matter clusters.

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