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Production and detection of metastable strange-quark droplets in heavy-ion collisions

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Considerable theoretical interest has focused on the possibility that not only may multiquark droplets S with large strangeness be metastable, but large extended such objects might be absolutely stable. We calculate the production probability of the S's in heavy-ion collisions by fragmentation and recombination of quarks in baryon-rich, hot quark-gluon matter. Although the results are quite model dependent, we propose a very sensitive detection scheme in which the S's should be able to be seen in the scheduled fixed-target, high-energy, heavy-ion facilities.

Considerable theoretical interest[1-6] has focused on the possibility that not only may high-density multiquark droplets with large strangeness be very long-lived, but large-A, extended such objects might be absolutely stable. Roughly, neglecting the strange-quark mass, the number of strange quarks n_s should be $\approx A$, the baryon number, since $n_s = n_u = n_d$ in order to lower the Fermi energies of the u and d quarks. In particular, Chin and Kerman[3] calculated, using the MIT bag model, that droplets (which we will call S) with $A \gtrsim 10$ and $n_s/A \gtrsim 0.8$ would be metastable with lifetimes $\tau_S \gtrsim 10^{-4}$ sec. They proposed producing S's in relativistic heavy-ion collisions. Recently Witten[5] has suggested that finite, but large-A quark matter with $n_s/A \sim 1$ would be stable. Clearly this is of enormous interest. The purpose of this paper is to calculate the production of S's and propose a sensitive detection scheme. Even if S's produced in the *scheduled* fixed-target, high-energy ion facilities[7] are not stable, study of their properties should shed considerable light on these new states of matter.

We consider, as an example, the collision of relativistic ions on a large-A fixed target. Scheduled[7] for 1986 at BNL are $A \leq 32$ ions at $E_{\rm lab}/A \leq 15$ GeV, and for 1986 at CERN are $A \leq 16$ ions at $E_{\rm lab}/A \leq 200$ GeV. We assume that in a fair fraction of the collisions, a quark-gluon plasma is formed.[8] We calculate the subsequent production probability P of the metastable strange droplets S by fragmentation and recombination of quarks. The results are quite model dependent and vary over a large range. However, our calculated P are such that the S's should be seen in the following very sensitive detection scheme summarized in Fig. 1. Basically our idea is that since there will be a huge number of fragments, in addition to a possible S, produced in the primary collision, the *secondary* interactions of the S's should be examined. Particles produced in the initial collision in target T_1 then pass through a "spectrometer" ST that both identifies (on-line) the S particles having $A \gtrsim 10$ and small or negative electric-charge ratio Z/A, and separates them from other fragments. This physical separation of background particles from the S's by the ST need not be complete since the ST will then trigger the counters C surrounding the secondary heavy-liquid target T_2. Since the collision of the relativistic S with a heavy nucleus in the target T_2 would have center-of-mass energies >> the binding energy of the S, it would disintegrate into a *huge* number of hyperons. The observation of multiple Λ decays would be a readily detected and *striking* signature.

Consider the primary collisions of the high-energy ion with the fixed-target heavy nucleus in which a hot quark-gluon plasma droplet[8] (or perhaps two) with baryon number A (presumably the A of the incident ion) is formed. We calculate the increment of the strangeness ratio of the droplet n_s/A, from its zero initial value based on three mechanisms: (F0) fragmentation of u and d quarks into strange mesons and baryons just outside the surface; (R) recombination of u and d quarks with $\bar{s}$ quarks inside the droplet; and (FI) fragmentation inside the droplet. The first mechanism is dominant. We find that the probability P of producing the metastable strange droplet with $n_s/A \geq 0.8$ from the initial quark-gluon droplet is quite model dependent, but favoring *small-A* droplets where it may be very large.

We begin by considering a basic hypothesis used in the fragmentation mechanism just out the surface of the droplet. In general, the fragmentation of quarks emitted from the surface with an average kinetic energy $\sim$0.2–0.4 GeV is quite different from the usual jet, and, hence, the usual jet mechanism, including, e.g., the chromoelectric-flux-tube model, cannot be applied to this case. However, in the usual Monte Carlo jet-generation programs,[9] there is one hypothesis which should be equally true in the present case, namely, the fragmentation process into pions stops if the energy of the leading quark becomes smaller than some small-energy cut $E_c \sim 0.1$ GeV. This hypothesis implies that a u or d quark emitted from the surface of the droplet

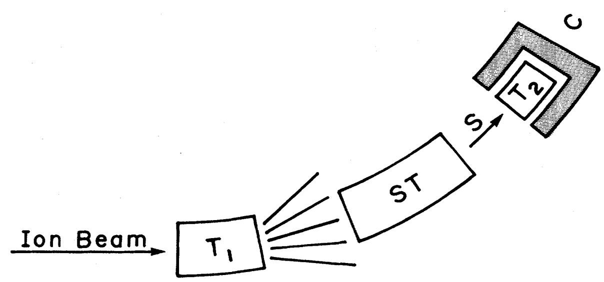

FIG. 1. Schematic diagram of a proposed experiment to detect the quasistable strange-quark droplets S. The relativistic heavy-ion beam hits a Pb target T_1. In addition to a possible S, *many* particles are produced in each primary interaction. The spectrometer-trigger ST would be designed to *both* separate out and identify (on-line) S's by its properties of baryon number $A \gtrsim 10$ and small or negative electric-charge ratio Z/A. The identification of an S by the ST would trigger the counters C surrounding the large-A target T_2. The observation of multiples Λ's in C emitted in the interaction of a S in T_2 would be a striking, readily observed signature.

produces in its color field a $(u,\bar{u})$ or $(d,\bar{d})$ pair and forms a pion, if its kinetic energy relative to the anticolor quark induced on the surface is larger than the rest energy of a pion. We note that this is just one implicit hypothesis, among others, used in Ref. 10 to calculate the pion energy radiation by hot quark-gluon plasma.

We need to calculate the kaon-number radiation by hot quark-gluon plasma. The naturally corresponding hypothesis is that a u or d [s] quark, emitted from the surface of the droplet, produces in its color field $(u,\bar{u})$, $(d,\bar{d})$, and $(s,\bar{s})$ pairs with the same relative probabilities, i.e., 4:4:2, as in usual jets,[9,11] and forms a strange meson, if the produced pair is $(s,\bar{s})$ [$(u,\bar{u})$ or $(d,\bar{d})$], and if the energy of the emitted quark relative to the anticolor quark induced on the surface is greater than the sum of the rest energies of the strange meson and the s [u or d] quark. (Note that an additional hypothesis for the calculation of the energy of the kaons radiated would be required just as in the calculation of the pion energy radiation.)

In order to estimate the increment of strangeness in the droplet with baryon number A due to the above three mechanisms, we need only consider the contribution from the initial $3A$ u and d quarks, since the contribution of the produced quarks to the strangeness is canceled by that of an equal number of produced antiquarks. In the fragmentation mechanism an emitted u or d quark may produce several mesons. However, the last remaining quark must retract into the droplet. The probability for the last remaining quark being an s quark is $\frac{1}{5}$. Thus, on the average, each emitted u or d quark contributes $\frac{1}{5}$ s quark to the droplet.

The chemical potential μ of the u and d quarks is determined by

$$3A/V = g\int\frac{d^3p}{(2\pi)^3}\rho(p)\quad(g=12)\ ,$$
$$\rho(p)=\{\exp[(p-\mu)/T]+1\}^{-1} - \{\exp[(p+\mu)/T]+1\}^{-1}\ , \tag{1}$$

where A/V is the baryon density of the compressed droplet and is independent of A. Using Eq. (1), we calculate μ as a function of T for two different values of the baryon density A/V as parametrized by the minimum radius equal to $r_M A^{1/3}$. The results are given in Table I. The values $r_M=0.75$ and 0.56 fm correspond to maximum densities of 4 and 10 times nuclear density, respectively.

In order to calculate the increment $N_s^{\rm F0}$ of the number of s quarks due to the emission of u and d quarks from the initial A baryons, we note that the anticolor quark induced on the surface by the emitted u or d quark would move along the surface due to the pulling color force from the emitted quark. However, its velocity may be significantly smaller than the emitted quark, since it has an effective mass. We take $m_s=0.15$ GeV (Ref. 12). According to the hypothesis mentioned above, the minimum momentum for the creation of a strange meson from a u or d quark emitted along the normal line of the surface is $|p_m|=0.65$ GeV, and should be larger if emitted along a direction with a larger angle to the normal line, due to the velocity $\vec{v}_0$ of the induced anticolor quark along the surface. Let $p_{\perp m}$ and $p_{\parallel m}$ be the components of $\vec{p}_m$ of the emitted quark along the normal and parallel direction such that $\vec{p}_m{}^2=p_{\parallel m}{}^2+p_{\perp m}{}^2$. One sees that $(p_{\parallel m},p_{\perp m})$ can be considered approximately as lying on an ellipse with parallel major axis equal to a and perpendicular major axis equal to $b=0.65$ GeV/c, where a depends on $|\vec{v}_0|$ and $a\geqslant b$. For $\vec{v}_0=0$, $a=b$, and for $\vec{v}_0\rightarrow$ velocity of light, $a\rightarrow\infty$. In general, the minimum value

$$p_{\parallel m}=a[1-(p_\perp/b)^2]^{1/2}\ . \tag{2}$$

The increment $N_s^{\rm F0}$ of the number of s quarks due to the fragmentation of u and d quarks from the initial A baryons is given by

$$N_s^{\rm F0}=N(a,b)P_s\ , \tag{3}$$

$$N(a,b)=\frac{d^3N}{d^2A\ dt}4\pi r^2 t\ , \tag{4}$$

$$\frac{d^3N}{d^2A\ dt}=\frac{g}{(2\pi)^2}\left[\int_0^b\frac{p_\perp dp_\perp}{(p_\parallel{}^2+p_\perp{}^2)^{1/2}}\int_{p_{\parallel m}}^\infty\rho(p)p_\parallel\,dp_\parallel + \int_b^\infty\frac{p_\perp p_\perp}{(p_\parallel{}^2+p_\perp{}^2)^{1/2}}\int_0^\infty\rho(p)p_\parallel\,dp_\parallel\right]\ , \tag{5}$$

where $g=12$, r is the radius of the strange droplet, t is the persisting time of the quark-gluon plasma, $\rho(p)$ is given by Eq. (2),

$$p_\perp/(p_\parallel{}^2+p_\perp{}^2)^{1/2}=v_\perp\ ,$$

$N(a,b)$ is the total number of u and d quarks emitted from the surface as a function of a and b, P_s is the probability of the formation of a primary strange meson with the emitted u and d quarks, and $d^3N/d^2A\ dt$ is the number of u and d quarks emitted per unit surface per unit time. P_s is estimated to be $\frac{1}{5}$.

Similar to Eq. (3), the decrement $N_B^{\rm F0}$ of the number of baryons, due to the probability P_B of the formation of leading baryons with the emitted u and d quarks from the A baryons, is given by

$$N_B^{\rm F0}=N(a_B,b_B)P_B\ , \tag{6}$$

with P_B estimated to be $\sim\frac{1}{6}$. We note that $N_s^{\rm F0}$ and $N_B^{\rm F0}$ are proportional to A, since they depend on A only through the factor r^2t with $t\propto A^{1/3}$ (Ref. 13) and $r^2\propto A^{2/3}$.

Numerical results are tabulated in Table II for $T=0.20$ and 0.25 GeV and for three sets of values of (a,b) in Eq. (2). The other very important parameter varied in Table II is r_M which determines the minimum radius of the droplet $=r_M A^{1/3}$ as in Table I. These r_M also determine the u- and d-quark chemical potential μ. Now clearly as time increases from the initial formation of the droplet and the (net) number of strange quarks n_s increases from 0, the number of u and d quarks must decrease to $3A-n_s$. We have not taken this explicitly into account. However, a correct treat-

TABLE I. Calculated chemical potential μ (in GeV) as a function of T for $r_M=0.56$ and 0.75 fm (where the minimum radius of the droplet equals $r_M A^{1/3}$).

T (GeV)	0.15	0.18	0.2	0.25	0.30
$r_M=0.56$ fm	0.397	0.344	0.309	0.225	0.164
$r_M=0.75$ fm	0.229	0.181	0.152	0.101	0.071

TABLE II. Calculated results for $T=0.2$ and 0.25 GeV and $r_M=0.75$ and 0.56 fm. N_s^{F0} and N_B^{F0} denote, respectively, the number of strange mesons and baryons emitted through fragmentation of quarks just outside the surface; N_s^R, N_{sB}^R, and $(N_{B1}^R+N_{B2}^R)$ denote, respectively, the number of strange mesons, strange baryons, and nonstrange baryons emitted through recombination mechanism; and N_s^{FI} denotes the number of strange mesons through fragmentation of quarks inside the surface. $\langle f_s\rangle$ is the average of the strange-quark fraction f_s, D is the fluctuation of f_s, i.e., $D=\langle(\Delta f_s)^2\rangle^{1/2}/\langle f_s\rangle$, and P is the probability for $f_s \geq 0.8$. In case 1, $a=b=0.65$ GeV/c for N_s^{F0} and $a=1$, $b=1$ GeV/c for N_B^{R0}. In case 2, $a=1$, $b=0.65$ GeV/c for N_s^{F0} and $a=1.5$, $b=1$ GeV/c for N_B^{F0}. In case 3, $a=\infty$, $b=0.65$ GeV/c for N_s^{F0} and $a=\infty$, $b=1$ GeV/c for N_B^{F0}.

	r_M (fm)	T (GeV)	N_s^{F0}/A	N_B^{F0}/A	N_s^R/A	N_{sB}^R/A	N_{B1}^R/A	N_{B2}^R/A	N_s^{FI}/A	$\langle f_s\rangle$	D ($A=32$)	D ($A=150$)	P ($A=32$)	P ($A=150$)
Case 1	0.75	0.2	0.31	0.087	0.029	0.0033	0.0073	0.0027	0.053	0.45	0.28	0.13	9.4×10^{-3}	3.6×10^{-8}
		0.25	0.41	0.16	0.099	0.011	0.0080	0.0073	0.067	0.76	0.23	0.11	4.1×10^{-1}	3.3×10^{-1}
	0.56	0.2	0.45	0.13	0.020	0.0027	0.017	0.0013	0.053	0.64	0.24	0.11	1.7×10^{-1}	1.4×10^{-2}
		0.25	0.55	0.23	0.085	0.0093	0.025	0.0060	0.067	1.04	0.21	0.10	8.8×10^{-1}	0.99
Case 2	0.75	0.2	0.21	0.053	0.029	0.0033	0.0073	0.0027	0.053	0.33	0.32	0.15	1.7×10^{-4}	4.0×10^{-16}
		0.25	0.31	0.11	0.099	0.011	0.0080	0.0073	0.067	0.61	0.25	0.12	1.2×10^{-1}	5.2×10^{-3}
	0.56	0.2	0.31	0.073	0.020	0.0027	0.017	0.0013	0.053	0.44	0.28	0.13	4.9×10^{-3}	1.4×10^{-8}
		0.25	0.43	0.14	0.085	0.0093	0.025	0.0060	0.067	0.77	0.23	0.11	4.4×10^{-1}	3.6×10^{-1}
Case 3	0.75	0.2	0.14	0.029	0.029	0.0033	0.0073	0.0027	0.053	0.24	0.37	0.17	6.4×10^{-7}	2.6×10^{-26}
		0.25	0.21	0.062	0.099	0.011	0.0080	0.0073	0.067	0.45	0.28	0.13	9.4×10^{-3}	1.0×10^{-7}
	0.56	0.2	0.21	0.04	0.0020	0.0027	0.017	0.0013	0.053	0.34	0.32	0.15	2.3×10^{-4}	9.0×10^{-16}
		0.25	0.29	0.087	0.085	0.0093	0.025	0.0060	0.067	0.55	0.26	0.12	6.8×10^{-2}	2.7×10^{-4}

ment of this should lie between the results for the two values of r_M.

There are some uncertainties in estimating the number of emitted strange mesons through the recombination mechanism inside the droplet. We assume that the average volume density of the number n_s of $\bar{s}$ quarks is equal to the equilibrium one at the temperature $T=0.25$ GeV. The number density n_A of u and d quarks from the A baryons is $n_A \sim 1.68/\text{fm}^3$, and that not from the A baryons is, for $T=0.25$ GeV, calculated to be $n_A'=1.54/\text{fm}^3$. One sees that the number density of u and d quarks from the A baryons is large enough for the formation of a strange meson of volume $\sim 0.7\ \text{fm}^3$ and a strange baryon of volume $\sim 2.2\ \text{fm}^3$. We assume that an $\bar{s}$ quark will recombine with an u or d quark into either a strange meson or a strange baryon. It will be emitted from the surface, if the normal component $p_\perp$ of its total momentum is positive, it is a color singlet, and its center of mass is inside the outermost surface layer of thickness, 0.3 fm ($\sim$ mean free path of a meson in the quark-gluon plasma). The competition between the u and d quarks from the A baryons and those not from the A baryons is also taken into account. Thus we obtain the number of strange mesons N_s^R and strange baryons N_{sB}^R emitted through the recombination mechanism. Similarly, the numbers of nonstrange baryons N_{B1}^R and N_{B2}^R, emitted, respectively, with three and two of the u and d quarks belonging to the A baryons, are estimated.

In order to estimate the number of strange mesons emitted through the fragmentation mechanism inside the droplet, only a slight change on the basic hypothesis mentioned above is necessary, i.e., the energy of the fragmenting quark is now relative to the surface layer (not "relative to the anticolor quark induced on the surface"). The number density of the u and d quarks with energy greater than $E_k=0.65$ GeV is calculated to be $\sim 0.84/\text{fm}^3$ at $T=0.25$ GeV. Assuming that the mean lifetime of a quark that appears in the outermost surface layer is 0.5×10^{-23} sec, we obtain the number of strange mesons N_s^{FI}, emitted from the outermost surface layer of thickness 0.3 fm through the fragmentation of u and d quarks inside the surface from the A baryons. We again note that all the N's are proportional to A.

Now we can estimate the strange-quark fraction[3]

$$f_s=\frac{n_s}{A'}\ , \tag{7}$$

where n_s is the resultant strangeness and A' is its baryon number. The average values $\bar{n}_s$ of n_s and $\bar{A}'$ of A' are given by

$$\bar{n}_s=N_s^{F0}+N_s^R+N_{sB}^R+N_s^{FI}\ ,$$

$$\bar{A}'=A-N_B^{F0}-\tfrac{1}{3}(N_s^R+2N_{sB}^R+3N_{B1}^R+2N_{B2}^R+N_s^{FI})\ . \tag{8}$$

The average values $\bar{f}_s$ of f_s are given in Table II. As pointed out in Ref. 14, the mean fluctuation of the quark-gluon plasma could be as large as the average value itself. In this case, the probability for the formation of strange matter, i.e., $f_s \gtrsim 0.8$, is close to unity. However, we estimate the fluctuation by assuming that the fluctuation of the related numbers of particles obeys Poisson statistics. As a first approximation we assume that A' is a constant. The probability of $N\equiv n_s \geq 0.8A'\equiv N_c$, i.e., for $f_s\geq 0.8$, is given by

$$P=\sum_{N\geq N_c}\frac{\bar{N}^N e^{-\bar{N}}}{N!}\ , \tag{9}$$

with $\bar{N}=\bar{f}_s A'$. Numerical values of P and also the fluctuation of the f_s defined by $D=\langle(\Delta f_s)^2\rangle^{1/2}/\langle f_s\rangle$, are given in Table II for $A=32$ and 150.

In conclusion, we have calculated the probability P of forming a strange-matter droplet S after the initial formation of a baryon-rich quark-gluon-plasma droplet in a relativistic heavy-ion, fixed-target collision. Although we see that the results for P in Table II are quite model dependent, large probabilities can occur. Furthermore, our proposal for observing the secondary interactions of the S's as summarized in Fig. 1 (and the associated text) should be very sensitive to small production cross sections. The possibility of observing the quasistable S's and shedding light on them and their related stable new strange-matter states[1–6] is of enormous interest.

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