Production and detection of drops of strange matter

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The theoretical possiblity that strange matter is more stable than nuclear matter has enormous implications. It has been suggested to search for the possible formation of metastable strange matter with a relatively small baryon number A, S drops, in present fixed-target relativistic heavy-ion collisions at BNL and CERN. In this paper we estimate the sensitivity required for the above experiments to be successful. These estimates of the production (and lifetimes) of S drops as a function of A, strangeness S, and electric charge, Z, should be useful in designing and evaluating searches for S drops, ${}^{S}A^{Z}$. For example, the production estimates for metastable S drops with $A \lesssim 30$ indicate that they could be detected with dedicated experiments having high sensitivity. Furthermore, specific searches for metastable S drops with $Z<0$ would have the advantage of a low intrinsic background.

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I. INTRODUCTION

The possibility that S drops may not only be metastable [1–12] but could be absolutely stable if they were large enough [6], could have consequences of the greatest importance. While it may require an astrophysical event [13–23] to produce strange matter of sufficient size for absolute stability, we can consider producing smaller, metastable S drops at presently available fixed-target heavy-ion accelerators at BNL and CERN. In fact, earlier, it has been suggested [3,7,9,11] to look for the formation of relatively-small-A strange matter (S drops) in relativistic heavy-ion collisions. It was proposed [12] that these small metastable S drops could be isolated and rapidly grown to a large stable size. The present paper continues the work of Liu and Shaw [7] on the production probability of S drops from a hot quark-gluon droplet via the mechanism of fragmentation and recombination, extending it to include the calculation of detection probabilities under best-guess scenarios. The spirit of this work is to provide a simple framework in which to calculate production and detection probabilities given various values of the relevant parameters. The results presented here should be useful in designing and evaluating future accelerator searches for S drops.

We note that there are other experimental approaches to determining the existence of strange matter that provide new impetus for performing the suggested accelerator experiments as complements to the astrophysical investigations. Witten in his seminal paper [6] discussed the possible astrophysical and cosmological consequences of strange matter. Although it [14] is not clear that strange matter could have survived to the present from the big bang, it is possible that there might be strange stars. In particular, Glendenning [21] has advanced arguments, based on the work of Dewey *et al.* [22], that there is an experimental bias against finding fast pulsars, expected to result from stellar evolution to a strange-matter state. In fact, a single submillisecond pulsar, say below 0.5 ms, would provide strong evidence for the existence of strange stars [21]. (A recent report based on a balloon-borne particle investigation suggests evidence for strange matter in the galactic cosmic radiation [23].)

In this paper we address the question of the production probability of S drops, ${}^{S}A^{Z}$, and the necessary experimental sensitivity required to detect them in relativistic heavy-ion fixed-target collision experiments. The production of S drops which have lifetimes τ_s greater than 3×10^{-8} sec is investigated for small A ($A \lesssim 30$), where we find their production to be experimentally accessible. Specific searches for metastable S drops with $Z<0$ would have the advantage of low intrinsic background, coming mainly from antinuclei and free quarks [24]. Included here are features such as the "cooling" of the S drop (where we introduce the concept of the "super compound state") and the possible momentum distribution of the S drop formed in the collisions. Although, admittedly, our calculations are rough they will nevertheless serve to indicate the viability of the present-day high-sensitivity experiments in search of this exotic form of matter.

II. CALCULATIONS

We discuss the formation of drops of quark-gluon (QG) gas in central collisions occurring in relativistic fixed-target nucleus-nucleus collisions at the BNL Alternate Gradient Synchrotron (AGS) or the CERN Super Proton Synchrotron (SPS). We first determine the probable quark content of matter in the participant region of such collisions, based on experimentally available numbers.

We then discuss regions of metastability in the strangeness S and electric charge Z plane for the various typical A values, based on the Berger-Jaffe [10] mass formula. We then investigate the energy content of this matter, introducing a mechanism for cooling it to an energy where weak decay processes may dominate its further evolution. Finally, we present a simple model for the kinematic properties of this matter which suggest experimental techniques for the investigation. The notation is as follows.

(1) P_{QG} is the probability for the formation of quark-gluon drop.

(2) P_{sp} is the probability of the "spatial factor."

(3) $P({}^{S}A^{Z})$ is the probability for the formation of an S drop, ${}^{S}A^{Z}$.

(4) P_{sum} is the probability for the formation of an S drop [in step (b) below] with baryon number A and electric charge Z (and S not detected).

(5) P_{cool} is the probability for the excited S drop to "cool" down to the "ground" state.

(6) P_{prod} is the total probability for the production of an S drop with baryon number A and electric charge Z.

(7) P_a is the probability for the momentum of the S drop to be in the range of acceptance of the experiment.

Our basic scenario for producing the S drops is summarized in Fig. 1. The spirit of this paper is to make very simple physical estimates for each of the steps.

A relativistic large heavy-ion A_{beam} collides with a fixed-target heavy nucleus to form large hot nonequilibrium quark-gluon (QG) drop. We assume that the QG drop is formed in the center of mass system (c.m.s.) consisting of equal numbers of beam and target nucleons. There is probably a threshold for producing the QG drop both in size A^0_{beam} and in beam energy E^0_{lab}. Above these thresholds, we will take the probability for forming the QG drop, P_{QG}, as

$$P_{QG}=P_{CC}\Theta(A_{beam}-A^0_{beam})\Theta(E_{lab}-E^0_{lab}) , \quad (1)$$

where P_{CC} is the probability for central collision; we take $P_{CC}=0.1$.

(a) The next step is the fragmentation of the large QG drop of size $2A_{beam}$ into smaller QG drops, again in nonequilibrium states. Perhaps a similar breakup is described by van Hove [25]. The probability of this spatial factor P_{sp} to produce a drop of size A will be taken as

$$P_{sp}=(A/2A_{beam}) , \quad (2)$$

where we expect this ratio to be much less than 1: Perhaps we need a Au or Pb beam to produce the initial QG drop, and as we will see below, only small QG drops with A from 10 to 30 can be expected to have appreciable probabilities of producing an S drop.

(b) The small QG drop will cool mainly by meson emission. From the results of Liu and Shaw [7], we take the main process for the buildup of s quarks (and decrease in electric charge) in the drop to form an S drop ${}^{S}A^{Z}$ to be the emission of K^+ and K^0 mesons, and we will ignore baryon emission in our specific calculations below.

(c) Following the strong process of cooling and formation of the S drop, there follows a rapid further cooling by emission of gammas of perhaps the last 100 MeV of excitation (again see van Hove [25]). We introduce below the concept of the supercompound state (SCS) to understand this.

(d) Finally, using the Berger-Jaffe mass formula [10], we examine the energy levels of each state ${}^{S}A^{Z}$ to see which ones will live long enough for the relevant experiments to detect them.

We define the production probability P_{prod} as

$$P_{prod}=P_{QG}P_{sp}P_{sum}P_{cool} , \quad (3)$$

where P_{sum} is the probability for a given A and Z (and S not detected) in step (b) and P_{cool} is the probability for cooling in step (c) and these will be calculated below.

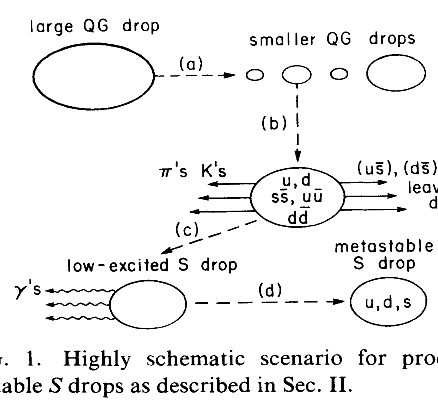

FIG. 1. Highly schematic scenario for producing small, metastable S drops as described in Sec. II.

A. Quark content

Let us consider the relativistic heavy-ion central collision in which a hot quark-gluon (QG) droplet may be formed with a baryon number A and electric charge $Z_i \approx 0.5A$. Here the subscript indicates the initial state of the droplet, assumed to be quite hot and to undergo an evolution to the S drop state. We expect A to represent some fraction of the baryon number of the target and projectile. This QG droplet will have $3A$ u and d valence quarks and many sea-quark pairs $u\bar{u}$, $d\bar{d}$, and $s\bar{s}$. Some of the quarks will leave the QG drop in the form of mesons and baryons in a strong-interaction process, altering the strange-quark content of the drop as well as lowering its energy content. This was calculated in some detail by Liu and Shaw [7] who concluded that for small A there is an appreciable probability of leaving the S drop with a strangeness fraction near the energy minimum required for metastability, namely $n_{s\min} \approx 0.8A$. Further, the dominant process of reaching this state was through the removal of $\bar{s}$ quarks through meson emission. This will form the basis of our simplified model.

We first calculate the strange quark content of the drop. To do this, we need a way to estimate the number of strange quarks left in the S drop by meson emission from the initial QG state. The strange quarks are carried off by K^- and $\bar{K}^0$ mesons, while the antistrange quarks are carried off by K^+ and K^0 mesons, with the net number of s quarks left in the drop as $n_s=(K^+ + K^0)-(K^- + \bar{K}^0)$ where the K^x represent the number of each type of meson. To find this number, we need to know either the total number of each type of meson produced, or, equivalently, the total multiplicity and the ratios of the K/π mesons emitted, as well as the real size of the residual drop A.

It is generally assumed that in a central collision the number of participating nucleons is given by a geometrical argument concerning the number of incident projectile nucleons and the tube in the target that the projectile subtends. For instance, in the recent $E802$ investigation [26,27] of Si+Au, the geometry of the situation suggests that a central collision involves ≈ 100 $(=28+72)$ participating nucleons. Of these, only a fraction will actually form our drop. The relevant question is then what is the relation between the multiplicity of K mesons emitted and the size of the residual droplet formed. This calculation is further complicated by the fact that a certain fraction of the s quarks not emitted as K^- or $\bar{K}^0$ mesons may well leave the volume as hyperons, rather than remain as residual strangeness in our drop. However, in the spirit of this calculation, let us make the following assumption: the mean multiplicity of mesons emitted from the region is proportional to the volume of the residual drop. With this assumption, we can calculate the strangeness fraction of the drop: We can see from the recent $E802$ data (Fig. 3 of Ref. 26) that the mean number of $\bar{s}$ quarks removed from the central participant volume is $n_{\bar{s}} \approx 5$. We arrive at this figure by taking the multiplicity of K^+ mesons from the dN/dy of that figure assuming $dy \approx 1$, multiply by 2 assuming the same probability for forming K^0's, and subtract the equivalent numbers for K^-'s multiplied by 2 to account for the $\bar{K}^0$'s. To estimate the baryon number of the residual drop into which the s excess has been deposited, then, we assume that the partners of the initial nucleon-nucleon collisions will form the likely protodrop, with the other nucleons of the participant region emitted without really entering the region of this residual drop. Based on this simple picture, we arrive at the reasonable conclusion that the strange quark content of the residual S drop may be $\bar{n}_s \approx 0.1A$. As the collision energy increases, we expect the mean meson multiplicity to increase due to increased contributions from the sea quarks [28], but the size of the drop will remain much the same since it is formed primarily of valence quarks. Thus, as the lab energy $E_{\text{lab}}/A_{\text{beam}}$ increases from the BNL value of 14.5 GeV to the CERN values of 60 GeV and 200 GeV, we can reasonably expect the strange quark concentration to increase from our BNL value of $\bar{n}_s \approx 0.1A$, becoming perhaps as large as $\bar{n}_s \approx 0.2A$ [28].

To investigate how a piece of nuclear matter with this quark mixture would evolve, we turn to the Berger-Jaffe mass formula [10]. There are two parameters in the Berger-Jaffe mass formula: m_s, the mass of the strange quark, and ϵ_0, the energy per baryon for a large A strange matter. There is a sensitivity to these parameters [10,12,29] but for purposes of this paper we chose optimistic but reasonable values of $\epsilon_0 = 880$ MeV and $m_s = 150$ MeV [30]. We find then that the number of s quarks, $n_{s\min}$, at the energy minimum, in S, Z space for a given A is $n_{s\min} = 0.8A$. However, we have just seen that the average collision leaves a drop whose s quark content is quite far from this value. Presumably a drop with such low s quark content would simply dissolve into normal hadrons. The drop formation process is statistical in nature and there are fluctuations in the s quark content around this average value that could lead to events in which the drop is near the n_s required for metastability.

Assuming Poisson statistics, we calculate the probability for a given strange quark content n_s using

$$P(n_s) = \frac{e^{-\bar{n}_s}(\bar{n}_s)^{n_s}}{(n_s)!} \;. \tag{4}$$

We present in Table I the probability of getting a drop of $n_{s\min} = 0.8A$ as a function of A and average values of $\bar{n}_s$ between $0.1A$ and $0.2A$. We conclude from this table that we should concentrate further efforts in our discussion about detectability on values of $A \lesssim 30$.

Once having formed our residual S drop, the drop may evolve via a variety of strong and weak processes depending on its charge as well as on n_s. To find the charge distribution of our drops, we now look at the process by which charge is removed in the emission of the strange mesons. Note that we are assuming that pion emission leaves the net charge unchanged on the average. When an $\bar{s}$ quark pairs with a u quark it removes one unit of charge; while when it pairs with a d quark the charge is not altered. If n_s is the number of s quarks left in the drop then on the average the number of u quarks that paired off with $\bar{s}$ will be $\bar{n}_u = n_s/2.0$. We take our protodrop to have an initial charge $Z_i = 0.5A$ before accounting for the meson emission process. (In this model the charge on the drop cannot increase beyond Z_i.) To arrive at an S drop having a given Z we need, say, $n_u = Z_i - Z$ number of u quarks to pair off with $\bar{s}$. Again, assuming Poisson statistics, we have

$$P(n_u) = \frac{e^{-\bar{n}_u}(\bar{n}_u)^{n_u}}{(n_u)!} \;. \tag{5}$$

We define

$$P({}^S A_Z) = P(n_u)P(n_s) \;. \tag{6}$$

B. Metastability

At this point we have computed the probability distribution in ${}^S A^Z$, Eq. (6) above. The next step is to consider the lifetimes of these ${}^S A^Z$ drops with respect to both strong and weak processes to see which live long enough for observation. The basis for these calculations will be the Berger-Jaffe mass formula [10] used as described in Ref. 12.

We estimate the decay rates for weak decay processes using the following formulas [12]: for β decay,

$$\Gamma_{\Delta Z=1} \approx 10^3 \left[\frac{\Delta E\ (\text{MeV})}{20} \right]^5 \text{sec}^{-1} \;. \tag{7}$$

and, for weak nonleptonic decay [31],

$$\Gamma_{\Delta S=1} \approx 10^9 \left[\frac{\Delta E\ (\text{MeV})}{20} \right]^2 \text{sec}^{-1} \;. \tag{8}$$

TABLE I. Probability $P(n_{s\min})$ of obtaining $n_{s\min}=0.8A$ for different A and $\bar{n}_s$.

A	$n_{s\min}$	$\bar{n}_s=0.1A$	$P(n_{s\min})$	$\bar{n}_s=0.15A$	$P(n_{s\min})$	$\bar{n}_s=0.2A$	$P(n_{s\min})$
10	8	1.0	9.1×10^{-6}	1.5	1.4×10^{-4}	2.0	8.6×10^{-4}
15	12	1.5	6.0×10^{-8}	2.3	3.7×10^{-6}	3.0	5.5×10^{-5}
20	16	2.0	4.2×10^{-10}	3.0	1.0×10^{-7}	4.0	3.8×10^{-6}
30	24	3.0	2.3×10^{-14}	4.5	8.5×10^{-11}	6.0	1.9×10^{-8}
40	32	4.0	1.3×10^{-18}	6.0	7.5×10^{-14}	8.0	1.0×10^{-10}
50	40	5.0	7.5×10^{-23}	7.5	6.8×10^{-17}	10.0	5.6×10^{-13}
60	48	6.0	4.5×10^{-27}	9.0	6.3×10^{-20}	12.0	3.1×10^{-15}
70	56	7.0	2.7×10^{-31}	10.5	6.0×10^{-23}	14.0	1.8×10^{-17}
80	64	8.0	1.7×10^{-35}	12.0	5.7×10^{-26}	16.0	1.0×10^{-19}
90	72	9.0	1.0×10^{-39}	13.5	5.4×10^{-29}	18.0	6.0×10^{-22}
100	80	10.0	6.3×10^{-44}	15.0	5.2×10^{-32}	20.0	3.5×10^{-24}

First, we only *consider S drops* $^SA^Z$ *which are stable against strong neutron decay*. Second, we select those S drops which have no charge change as in Eq. (7) with lifetimes $\tau\geq3\times10^{-8}$ sec. The weak nonleptonic decays, Eq. (8), occur very rapidly. However, the small energy release will go off as γ rays (see Sec. II.D) and thus will not affect the spectrometer experiments which detect Z and A but not S. Results for the weak lifetimes using Eq. (7) for $A=15$ are shown in Table II. In application of these equations, we assume that the S drops have rapidly reached their ground states via energy emission as discussed below in Sec. II D.

TABLE II. Lifetimes via weak beta decay for $A=15.0$, $\epsilon_0=880.0$, and $m_s=150.0$ (MeV).

Z	E (MeV)	ΔE (MeV)	$\tau_{\Delta Z=1}$ (sec)
-11.0	14439	150	4.3×10^{-8}
-10.0	14289	137	6.6×10^{-8}
-9.0	14152	125	1.1×10^{-7}
-8.0	14027	112	1.8×10^{-7}
-7.0	13915	100	3.2×10^{-7}
-6.0	13815	87	6.3×10^{-7}
-5.0	13728	75	1.4×10^{-6}
-4.0	13653	62	3.4×10^{-6}
-3.0	13591	50	1.0×10^{-5}
-2.0	13541	38	4.4×10^{-5}
-1.0	13503	25	3.3×10^{-4}
0.0	13478	12	1.1×10^{-2}
1.0	13466		
2.0	13466	0.03	$1.3\times10^{+11}$
3.0	13478	12	1.0×10^{-2}
4.0	13503	25	3.3×10^{-4}
5.0	13541	38	4.3×10^{-5}
6.0	13591	50	1.0×10^{-5}
7.0	13653	62	3.4×10^{-6}
8.0	13728	75	1.4×10^{-6}
9.0	13816	87	6.3×10^{-7}
10.0	13915	99	3.2×10^{-7}
11.0	14028	113	1.8×10^{-7}
12.0	14153	125	1.1×10^{-7}
13.0	14290	137	6.6×10^{-8}
14.0	14440	150	4.2×10^{-8}

C. Production probabilities for observable *S* drops

We now can calculate the production probabilities $P(^SA^Z)$ for $^SA^Z$ using Eq. (6) for those S drops which have β-decay lifetimes $>3\times10^{-8}$ sec as discussed in Sec. II B. The values of S and Z have also been restricted by taking account of strong neutron decay. Furthermore we consider values of Z which satisfy the greater of either $|Z|\leq0.2A$ or $|Z|\leq3.0$; for higher values of positive Z the intrinsic background will be large and thus make it difficult to detect large-positive-Z S drops, while for lower negative Z the probability $P(^SA^Z)$ is low. From Table I we see that for $A>40.0$ the probability is too low to be observable for the existing experiments. But for $A\leq30$ it is appreciable enough for the present-day experiments to look for these metastable states. Results for $A=10,15$, and 20 are shown in Table III for $\bar{n}_s=0.1A$ suggested for the BNL case and in Table IV for $A=10,15$, and 20 for $\bar{n}_s=0.2A$, which might be appropriate for the CERN energies. We have included the $A=10$ calculations, although the formalism may not be applicable for this small an A. Note that the probability of forming a positively charged drop with $Z=1$ to 3 is less than three orders of magnitude greater than for forming a negatively charged drop with $Z=-1$ to -3 when the probabilities are summed over the metastable n_s combinations. This will prove relevant when discussing experimental detectability in Sec. III.

D. Cooling of *S* drop to its ground state

Here we calculate P_c, the probability for rapidly cooling of the initially formed S drop, $^SA^Z$, to near its ground state. As discussed above, we have assumed that the drop A was formed via the initial interactions among equal numbers of projectile and target nucleons in a high-energy nucleus-nucleus collision. Thus, for a lab energy $E_{\rm lab}/A_{\rm beam}=\gamma_{\rm lab}$GeV the c.m.s. energy of the S drop is $E_i=A\sqrt{(\gamma_{\rm lab}/2)}$ GeV. The initial S drop that is formed in an excited state will decay into its "ground" state through various processes that could be allowable from energetic considerations. For an $\epsilon_0=880$ MeV and $m_s=150$ MeV we find a ground state energy of $E_0\approx910A$ MeV in the mass range from $10\leq A\leq30$ near the energy minimum in Z, S space. Thus we are interest-

TABLE III. (a) Probability $P({}^{S}A^{Z})$ for $A=10.0$ and $\bar{n}_s=0.1A$. (b) Probability $P({}^{S}A^{Z})$ for $A=15.0$ and $\bar{n}_s=0.10A$. (c) Probability $P({}^{S}A^{Z})$ for $A=20.0$ and $\bar{n}_s=0.10A$. $P_{\rm sum}$ is the total probability for a given Z. Included are only those S and Z for which the weak lifetimes of the metastable S drop is greater than 3×10^{-8} sec. Strong neutron decay also constrains the range of S and Z. Furthermore the Z values have been restricted to the greater of the following conditions: $|Z|\le3$ or $|Z|\le0.2A$.

S \ Z	-3	-2	-1	0	1	2	3
					(a)		
-11	7.8×10^{-10}	1.1×10^{-9}	1.4×10^{-9}	1.6×10^{-9}	1.4×10^{-9}	1.0×10^{-9}	5.7×10^{-10}
-10	6.6×10^{-9}	1.1×10^{-8}	1.5×10^{-8}	1.8×10^{-8}	1.8×10^{-8}	1.4×10^{-8}	8.5×10^{-9}
-9	4.7×10^{-8}	8.4×10^{-8}	1.3×10^{-7}	1.7×10^{-7}	1.9×10^{-7}	1.7×10^{-7}	1.1×10^{-7}
-8	2.7×10^{-7}	5.4×10^{-7}	9.5×10^{-7}	1.4×10^{-6}	1.8×10^{-6}	1.8×10^{-6}	1.3×10^{-6}
-7	1.2×10^{-6}	2.8×10^{-6}	5.6×10^{-6}	9.6×10^{-6}	1.4×10^{-5}	1.6×10^{-5}	1.4×10^{-5}
-6	4.1×10^{-6}	1.1×10^{-5}	2.6×10^{-5}	5.2×10^{-5}	8.6×10^{-5}	1.1×10^{-4}	1.1×10^{-4}
-5	9.5×10^{-6}	3.0×10^{-5}	8.5×10^{-5}	2.0×10^{-4}	4.1×10^{-4}	6.6×10^{-4}	7.9×10^{-4}
-4	1.3×10^{-5}						4.2×10^{-3}
$P_{\rm sum}$	2.8×10^{-5}	4.4×10^{-5}	1.2×10^{-4}	2.6×10^{-4}	5.1×10^{-4}	7.9×10^{-4}	5.1×10^{-3}
					(b)		
-14				1.1×10^{-10}	1.1×10^{-10}	1.1×10^{-10}	
-13	3.0×10^{-10}	4.9×10^{-10}	7.1×10^{-10}	9.3×10^{-10}	1.1×10^{-9}	1.1×10^{-9}	9.1×10^{-10}
-12	1.9×10^{-9}	3.3×10^{-9}	5.2×10^{-9}	7.3×10^{-9}	9.2×10^{-9}	9.9×10^{-9}	9.1×10^{-9}
-11	9.9×10^{-9}	1.9×10^{-8}	3.3×10^{-8}	5.0×10^{-8}	6.9×10^{-8}	8.1×10^{-8}	8.1×10^{-8}
-10	4.4×10^{-8}	9.2×10^{-8}	1.7×10^{-7}	3.0×10^{-7}	4.5×10^{-7}	5.8×10^{-7}	6.4×10^{-7}
-9	1.6×10^{-7}	3.7×10^{-7}	7.9×10^{-7}	1.5×10^{-6}	2.5×10^{-6}	3.6×10^{-6}	4.4×10^{-6}
-8	4.6×10^{-7}	1.2×10^{-6}	2.9×10^{-6}	6.1×10^{-6}	1.1×10^{-5}	1.8×10^{-5}	2.5×10^{-5}
-7	9.9×10^{-7}	3.0×10^{-6}	8.1×10^{-6}	2.0×10^{-5}	4.2×10^{-5}	7.8×10^{-5}	1.2×10^{-4}
$P_{\rm sum}$	1.7×10^{-6}	4.7×10^{-6}	1.2×10^{-5}	2.8×10^{-5}	5.6×10^{-5}	1.0×10^{-4}	1.5×10^{-4}

(c)

S \ Z	-4	-3	-2	-1	0	1	2	3	4
-16							5.9×10^{-11}	5.9×10^{-11}	5.2×10^{11}
-15		7.2×10^{-11}	1.2×10^{-10}	2.0×10^{-10}	2.9×10^{-10}	3.9×10^{-10}	4.7×10^{-10}	5.0×10^{-10}	4.6×10^{-10}
-14	1.8×10^{-10}	3.6×10^{-10}	6.7×10^{-10}	1.1×10^{-9}	1.8×10^{-9}	2.6×10^{-9}	3.3×10^{-9}	3.8×10^{-9}	3.8×10^{-9}
-13	7.4×10^{-10}	1.6×10^{-9}	3.2×10^{-9}	5.9×10^{-9}	9.9×10^{-9}	1.5×10^{-8}	2.1×10^{-8}	2.6×10^{-8}	2.8×10^{-8}
-12	2.6×10^{-9}	6.0×10^{-9}	1.3×10^{-8}	2.6×10^{-8}	4.8×10^{-8}	8.0×10^{-8}	1.2×10^{-7}	1.6×10^{-7}	1.9×10^{-7}
-11	7.5×10^{-9}	1.9×10^{-8}	4.5×10^{-8}	9.9×10^{-8}	2.0×10^{-7}	3.6×10^{-7}	5.9×10^{-7}	8.6×10^{-7}	1.1×10^{-7}
-10	1.8×10^{-8}	5.0×10^{-8}	1.3×10^{-7}	3.1×10^{-7}	6.9×10^{-7}	1.4×10^{-6}	2.5×10^{-6}	4.0×10^{-6}	5.6×10^{-6}
-9	3.4×10^{-8}	1.1×10^{-7}	3.1×10^{-7}	8.1×10^{-7}	2.0×10^{-6}	4.4×10^{-6}	8.8×10^{-6}	1.6×10^{-5}	2.4×10^{-5}
-8	4.8×10^{-8}								9.0×10^{-5}
$P_{\rm sum}$	1.1×10^{-7}	1.9×10^{-7}	4.6×10^{-7}	1.1×10^{-6}	2.8×10^{-6}	5.9×10^{-6}	1.1×10^{-5}	2.0×10^{-5}	1.2×10^{-4}

ed in calculating the probability for rapid cooling of the S drop from the initial energy E_i to near its ground-state value by emission of an amount of energy whose maximum is set by $\Delta E_{\rm max}=E_i-E_0$.

Now we calculate the probability that the excited protodrop having energy E_i will emit energy ΔE in a short enough time (by meson and baryon emission) to have its further evolution dominated by rapid γ emission and then by the weak decay processes. We will assume that the probability $P_{\rm cool}$ to cool within a window dE_s of our ground state is simply

$$P_{\rm cool}=dE_s/\Delta E_{\rm max}\ . \qquad (9)$$

We estimate dE_s to be the excitation energy at which rapid gamma emission dominates. Here we introduce the concept of the *supercompound state* (SCS) in which the energy dE_s is shared among many excited quark configurations. This is in analogy with the compound state in moderate and large A nuclei where at low excitation energies, γ emission dominates over neutron emission. In the SCS, neutron emission is *greatly inhibited* by the further requirement that three quarks with the correct energy, spin, flavor, and color must combine before emission is possible. Thus we suggest that a value (less than mass of pion) $dE_s\approx100$ MeV is reasonable for the SCS to decay by a rapid series of γ emissions to the ground-state configuration of the quarks which can then decay by the weak interaction. We use this value of dE_s with Eq. (9) to estimate $P_{\rm cool}$ in Table V.

E. Kinematics

Let the incident particle have a laboratory energy $E_{\rm lab}/A_{\rm beam}=\gamma_{\rm lab}$ GeV. We assume that the S drops are produced with a certain momentum distribution in the center-of-momentum (c.m.s.) frame such as shown below. After a Lorentz boost we obtain the distribution of momentum in the laboratory frame. We then integrate this distribution over the experimental acceptance to determine the acceptance probability.

We assume the distribution in the center of mass to be [32]

$$\frac{d^3N(p)}{dy\,dp_t^2} = ae^{-p_t/\bar{p}_t}e^{-c(y-\bar{y})^2}, \tag{10}$$

where a is a normalization constant, p_t is the transverse momentum, $\bar{p}_t$ is the average transverse momentum, y is the rapidity, $\bar{y}$ is the laboratory rapidity of the c.m.s., and c is a measure of the width of the rapidity distribution. At BNL, the c.m.s. for a nucleon-nucleon system has $\bar{y}=1.7$, while at CERN, $\bar{y}=3$. The mean transverse momentum is thought to scale with the particle mass as $\bar{p}_t \approx 0.5\sqrt{A}$ GeV/c at low values of Feynman x near the

TABLE IV. (a) Probability $P({}^SA^Z)$ for $A=10.0$ and $\bar{n}_s=0.2A$. (b) Probability $P({}^SA^Z)$ for $A=15.0$ and $\bar{n}_s=0.20A$. (c) Probability $P({}^SA^Z)$ for $A=20.0$ and $\bar{n}_s=0.20A$. P_{sum} is the total probability for a given Z. Included are only those S and Z for which the weak lifetimes of the metastable S drop is greater than 3×10^{-8}sec. Strong neutron decay also constrains the range of S and Z. Furthermore the Z values have been restricted to the greater of the following conditions: $|Z|\le3$ or $|Z|\le0.2A$.

S \ Z	−3	−2	−1	0	1	2	3
				(a)			
−13	2.1×10^{-8}	2.6×10^{-8}	2.8×10^{-8}	2.6×10^{-8}	2.0×10^{-8}	1.2×10^{-8}	5.7×10^{-9}
−12	1.2×10^{-7}	1.6×10^{-7}	1.9×10^{-7}	1.9×10^{-7}	1.5×10^{-7}	1.0×10^{-7}	5.2×10^{-8}
−11	5.9×10^{-7}	8.6×10^{-7}	1.1×10^{-6}	1.2×10^{-6}	1.1×10^{-6}	7.9×10^{-7}	4.3×10^{-7}
−10	2.5×10^{-6}	4.0×10^{-6}	5.6×10^{-6}	6.7×10^{-6}	6.7×10^{-6}	5.4×10^{-6}	3.2×10^{-6}
−9	8.8×10^{-6}	1.6×10^{-5}	2.4×10^{-5}	3.3×10^{-5}	3.6×10^{-5}	3.2×10^{-5}	2.1×10^{-5}
−8	2.6×10^{-5}	5.1×10^{-5}	9.0×10^{-5}	1.3×10^{-4}	1.7×10^{-4}	1.7×10^{-4}	1.3×10^{-4}
−7	5.8×10^{-5}	1.3×10^{-4}	2.7×10^{-4}	4.5×10^{-4}	6.5×10^{-4}	7.4×10^{-4}	6.4×10^{-4}
−6	9.7×10^{-5}	2.6×10^{-4}	6.1×10^{-4}	1.2×10^{-3}	2.0×10^{-3}	2.7×10^{-3}	2.7×10^{-3}
−5	1.1×10^{-4}	3.6×10^{-4}	1.0×10^{-3}	2.4×10^{-3}	4.8×10^{-3}	7.7×10^{-3}	9.3×10^{-3}
−4	7.8×10^{-5}						2.4×10^{-2}
P_{sum}	3.8×10^{-4}	8.2×10^{-4}	2.0×10^{-3}	4.2×10^{-3}	7.7×10^{-3}	1.1×10^{-2}	3.7×10^{-2}
				(b)			
−18	3.3×10^{-10}	3.8×10^{-10}	4.0×10^{-10}	3.8×10^{-10}	3.2×10^{-10}	2.3×10^{-10}	1.4×10^{-10}
−17	1.8×10^{-9}	2.2×10^{-9}	2.4×10^{-9}	2.4×10^{-9}	2.2×10^{-9}	1.7×10^{-9}	1.1×10^{-9}
−16	8.8×10^{-9}	1.2×10^{-8}	1.4×10^{-8}	1.5×10^{-8}	1.4×10^{-8}	1.1×10^{-8}	7.6×10^{-9}
−15	3.9×10^{-8}	5.5×10^{-8}	6.9×10^{-8}	7.9×10^{-8}	7.9×10^{-8}	6.8×10^{-8}	5.0×10^{-8}
−14	1.6×10^{-7}	2.3×10^{-7}	3.2×10^{-7}	3.9×10^{-7}	4.1×10^{-7}	3.8×10^{-7}	3.0×10^{-7}
−13	5.5×10^{-7}	8.9×10^{-7}	1.3×10^{-6}	1.7×10^{-6}	2.0×10^{-6}	2.0×10^{-6}	1.7×10^{-6}
−12	1.7×10^{-6}	3.0×10^{-6}	4.7×10^{-6}	6.7×10^{-6}	8.4×10^{-6}	9.1×10^{-6}	8.3×10^{-6}
−11	4.5×10^{-6}	8.6×10^{-6}	1.5×10^{-5}	2.3×10^{-5}	3.1×10^{-5}	3.7×10^{-5}	3.7×10^{-5}
−10	1.0×10^{-5}	2.1×10^{-5}	4.0×10^{-5}	6.8×10^{-5}	1.0×10^{-4}	1.3×10^{-4}	1.5×10^{-4}
−9	1.8×10^{-5}	4.2×10^{-5}	9.0×10^{-5}	1.7×10^{-4}	2.8×10^{-4}	4.1×10^{-4}	5.0×10^{-4}
−8	2.6×10^{-5}	6.9×10^{-5}	1.6×10^{-4}	3.5×10^{-4}	6.5×10^{-4}	1.1×10^{-3}	1.5×10^{-3}
−7	2.8×10^{-5}	8.5×10^{-5}	2.3×10^{-4}	5.6×10^{-4}	1.2×10^{-3}	2.2×10^{-3}	3.5×10^{-3}
P_{sum}	8.9×10^{-5}	2.3×10^{-4}	5.4×10^{-4}	1.2×10^{-3}	2.3×10^{-3}	3.9×10^{-3}	5.7×10^{-3}

S \ Z	−4	−3	−2	−1	0	1	2	3	4
					(c)				
−17	2.1×10^{-8}	3.5×10^{-8}	5.3×10^{-8}	7.5×10^{-8}	9.8×10^{-8}	1.1×10^{-7}	1.2×10^{-7}	1.1×10^{-7}	9.4×10^{-8}
−16	6.4×10^{-8}	1.1×10^{-7}	1.8×10^{-7}	2.7×10^{-7}	3.7×10^{-7}	4.7×10^{-7}	5.2×10^{-7}	5.2×10^{-7}	4.6×10^{-7}
−15	1.7×10^{-7}	3.2×10^{-7}	5.5×10^{-7}	8.8×10^{-7}	1.3×10^{-6}	1.7×10^{-6}	2.1×10^{-6}	2.2×10^{-6}	2.1×10^{-6}
−14	4.0×10^{-7}	8.0×10^{-7}	1.5×10^{-6}	2.5×10^{-6}	4.0×10^{-6}	5.7×10^{-6}	7.4×10^{-6}	8.4×10^{-6}	8.4×10^{-6}
−13	8.2×10^{-7}	1.8×10^{-6}	3.5×10^{-6}	6.5×10^{-6}	1.1×10^{-5}	1.7×10^{-5}	2.3×10^{-5}	2.9×10^{-5}	3.1×10^{-5}
−12	1.4×10^{-6}	3.3×10^{-6}	7.2×10^{-6}	1.4×10^{-5}	2.6×10^{-5}	4.4×10^{-5}	6.6×10^{-5}	8.8×10^{-5}	1.0×10^{-4}
−11	2.1×10^{-6}	5.3×10^{-6}	1.3×10^{-5}	2.7×10^{-5}	5.5×10^{-5}	1.0×10^{-4}	1.6×10^{-4}	2.4×10^{-4}	3.0×10^{-4}
−10	2.5×10^{-6}	7.0×10^{-6}	1.8×10^{-5}	4.4×10^{-5}	9.6×10^{-5}	1.9×10^{-4}	3.5×10^{-4}	5.5×10^{-4}	7.7×10^{-4}
−9	2.4×10^{-6}	7.3×10^{-6}	2.1×10^{-5}	5.6×10^{-5}	1.4×10^{-4}	3.1×10^{-4}	6.1×10^{-4}	1.1×10^{-3}	1.7×10^{-3}
−8	1.7×10^{-6}								3.1×10^{-3}
P_{sum}	1.2×10^{-5}	2.6×10^{-5}	6.4×10^{-5}	1.5×10^{-4}	3.3×10^{-4}	6.7×10^{-4}	1.2×10^{-3}	2.0×10^{-3}	6.0×10^{-3}

TABLE V. Probability of cooling, P_{cool}, to within dE_s of 100.0 MeV for various A and γ_{lab}.

A	γ_{lab}	P_{cool}
10.0	14.5	5.6×10^{-3}
15.0	14.5	3.7×10^{-3}
20.0	14.5	2.8×10^{-3}
10.0	60.0	2.2×10^{-3}
15.0	60.0	1.5×10^{-3}
20.0	60.0	1.1×10^{-3}
10.0	200.0	1.1×10^{-3}
15.0	200.0	7.3×10^{-4}
20.0	200.0	5.5×10^{-4}

production peak [33]. The constant $c \approx 2$ from $\bar{p}$ data at the AGS [34]. Using Eq. (10) we can calculate the laboratory rapidity distribution for an S drop having an arbitrary A.

We define the experimental sensitivity of a new particle search in terms of this production model as

$$S_A = \frac{1}{N_{\text{ints}} P_a} , \tag{11}$$

where N_{ints} is the number of interactions sampled and P_a is the fraction of the particle spectrum that is accepted by the experiment. Two different experimental approaches have been approved for new particle searches at the AGS, a focusing spectrometer and a nonfocusing spectrometer, which have overlapping regions of sensitivity in both rapidity and rigidity space.

A typical focusing spectrometer operated at 0 deg can have a geometrical acceptance of ≈ 15 mrad or a solid angle of 0.2 msr, and a momentum acceptance of $\approx \pm 3\%$ in $\delta p/p$. This means that a single setting of the spectrometer can provide an acceptance $P_{a,i} \approx 0.01$ for a given A/Z particle, or if N_i interactions are sampled at this setting, then $S_{A,i} = (0.01 N_i)^{-1}$. The spectrometer can be tuned to different rigidities in a series of measurements covering a rigidity range from 1 to 30 GV using standard magnets, with each setting having acceptance optimized for a given A/Z S drop. We obtain the total sensitivity by summing the acceptance over the number of settings of the spectrometer weighted by the N_i sampled at each setting as

$$S_A = \left[\sum_i N_i P(A)_{a,i} \right]^{-1} . \tag{12}$$

If we sample the same number of interactions at each rigidity setting, we can take N_i out of the sum as N_{ints} leaving the acceptance probability as

$$P(A)_a = \sum_i P_{a,i}^{-1} . \tag{13}$$

This allows the spectrometer to cover the A/Z range up to 10 or more with the integral sensitivity greater than 10% as shown in Fig. 2. Since the focusing spectrometer can run at higher singles rate using a very selective Cherenkov trigger, it is possible to sample more than 10^8 collisions per second. This means it can sample over 10^{11} interactions per hour at the AGS. Assuming each setting integrates for 10 h or 10^{12} interactions, this approach yields a search sensitivity of better than *1 particle in* 10^{11} *interactions* or a sensitivity of better than 10^{-11} in searching for new particles over a broad A/Z range.

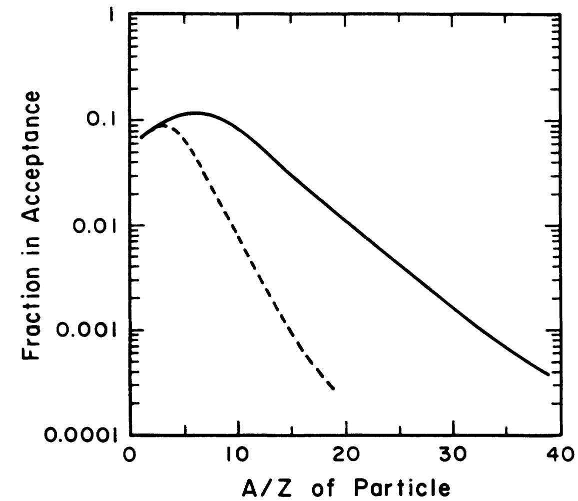

FIG. 2. Integral acceptance for S drops at BNL energies for a focusing spectrometer calculated using Eqs. (10)–(13). The dotted curve corresponds to the spectrometer having a range (GeV) in rigidity R of $1<R<15$, and the solid curve corresponds to $1<R<30$.

A nonfocusing or open-geometry spectrometer can be configured to accept much higher rigidity particles, even neutrals, and will thus extend the A/Z range beyond that of the focusing system; however, this approach requires a significant increase in detector and trigger complexity. It may be possible to run such a system at interaction rates in excess of 10^6 per spill. Since there are no focal conditions to change, this allows the nonfocusing spectrometer to perform a broadband search without changing experimental conditions for perhaps 1000 h, again leading to a sample size of 10^{12} total interactions. Acceptance may be as high as 30% depending on specific geometry and particle type, again leading to sensitivities for new particle production in the range of 10^{-11} to 3×10^{-12}. The sensitivity of any experimental setup is clearly specific to that experiment but can be easily calculated with a model such as this once the geometrical and momentum acceptances are specified.

III. RESULTS AND DISCUSSION

The search for the production of small metastable S drops at present fixed-target heavy-ion facilities at BNL and CERN is of the greatest importance. Two experiments have been recently approved at BNL [35] which will be searching for S drops in their studies, E864 [36] and E878 [37]; more recently a third experiment, E882 [38] was approved. Potential experiments were discussed in a meeting on "strange matter" held at CERN [39]. Arguments were made that the present fixed target heavy-ion facilities present a "window of opportunity in searching for S drops" since future higher-energy heavy-ion colliders may be worse both from a production and

TABLE VI. Probability for the production of S drop, P_{prod} as given by Eq. (3).

	$\gamma_{\text{lab}}=14.5$					$\gamma_{\text{lab}}=60.0$					$\gamma_{\text{lab}}=200.0$		
A	Z	$\bar{n}_s$	P_{prod}	A	Z	$\bar{n}_s$	P_{prod}	$\bar{n}_s$	P_{prod}	A	Z	$\bar{n}_s$	P_{prod}
10	-3	$0.1A$	2.6×10^{-9}	10	-3	$0.15A$	4.8×10^{-9}	$0.2A$	1.3×10^{-8}	10	-3	$0.2A$	7.0×10^{-9}
	-2		4.1×10^{-9}		-2		9.5×10^{-9}		3.0×10^{-8}		-2		1.5×10^{-8}
	-1		1.1×10^{-8}		-1		2.3×10^{-8}		7.3×10^{-8}		-1		3.7×10^{-8}
	0		2.5×10^{-8}		0		5.1×10^{-8}		1.5×10^{-7}		0		7.7×10^{-8}
	1		4.8×10^{-8}		1		9.9×10^{-8}		2.8×10^{-7}		1		1.4×10^{-7}
	2		7.5×10^{-8}		2		1.5×10^{-7}		4.0×10^{-7}		2		2.0×10^{-7}
	3		4.8×10^{-7}		3		6.6×10^{-7}		1.4×10^{-6}		3		6.7×10^{-7}
15	-3	$0.10A$	1.6×10^{-10}	15	-3	$0.15A$	6.8×10^{-10}	$0.2A$	3.3×10^{-9}	15	-3	$0.2A$	1.6×10^{-9}
	-2		4.3×10^{-10}		-2		1.8×10^{-9}		8.6×10^{-9}		-2		4.2×10^{-9}
	-1		1.1×10^{-9}		-1		4.5×10^{-9}		2.0×10^{-8}		-1		9.9×10^{-9}
	0		2.6×10^{-9}		0		1.0×10^{-8}		4.5×10^{-8}		0		2.2×10^{-8}
	1		5.2×10^{-9}		1		2.0×10^{-8}		8.6×10^{-8}		1		4.2×10^{-8}
	2		9.3×10^{-9}		2		3.5×10^{-8}		1.5×10^{-7}		2		7.1×10^{-8}
	3		1.4×10^{-8}		3		5.3×10^{-8}		2.1×10^{-7}		3		1.0×10^{-7}
20	-4	$0.1A$	1.0×10^{-11}	20	-4	$0.15A$	6.6×10^{-11}	$0.2A$	4.4×10^{-10}	20	-4	$0.2A$	2.2×10^{-10}
	-3		1.7×10^{-11}		-3		1.4×10^{-10}		9.5×10^{-10}		-3		4.8×10^{-10}
	-2		4.2×10^{-11}		-2		6.6×10^{-10}		2.3×10^{-9}		-2		1.2×10^{-9}
	1		1.0×10^{-10}		-1		8.8×10^{-10}		5.5×10^{-9}		-1		2.8×10^{-9}
	0		9.3×10^{-10}		0		1.9×10^{-9}		1.2×10^{-8}		0		6.1×10^{-9}
	1		5.5×10^{-10}		1		3.7×10^{-9}		2.5×10^{-8}		1		1.2×10^{-8}
	2		1.0×10^{-9}		2		7.7×10^{-9}		4.4×10^{-8}		2		2.2×10^{-8}
	3		1.9×10^{-9}		3		1.2×10^{-8}		7.3×10^{-8}		3		3.7×10^{-8}
	4		1.1×10^{-8}		4		5.1×10^{-8}		2.2×10^{-7}		4		1.1×10^{-7}

detection perspective. It is with all this in mind that we have presented here a very simple framework in which to calculate production probabilities and detection for S drops in these experiments now being implemented or now being designed. Although our calculations are rough, the results presented in Tables I–VI should be of use in designing and evaluating searches for this exotic and potentially important form of matter. (Furthermore, the calculations have been presented in a transparent manner so that the reader might in any of the several stages substitute an "improved" version.)

We now calculate the production probability P_{prod} defined in Eq. (3) where P_{sum} is tabulated in Table III for $\bar{n}_s=0.1A$ and in Table IV for $\bar{n}_s=0.2A$. P_{cool} is tabulated in Table V. We have evaluated P_{sp}, using Eq. (2), with $A_{\text{beam}}=30$. Our results for P_{prod} are given in Table VI for various γ_{lab}.

We observe from Table VI that an experiment designed to look for S drops at BNL and CERN should have a sensitivity of detecting rates smaller than one S drop produced in 10^7 collisions. The rates for small A (less than 30) look favorable. Specific searches for metastable S drops with $Z<0$ have the advantage of a *much lower intrinsic background* (e.g., $Z=-3$ would have no intrinsic background) and yet have only less than a factor of 1000 smaller production rate than the corresponding case with $Z>0$. See Sec. II E for a discussion of the merits of using a focusing spectrometer versus an open-geometry apparatus.

Experiments at CERN would have the advantage over those at BNL in that the larger expected $\bar{n}_s$ at the higher E_{lab} gives an increase in production rates. However, there will be a decrease in collision times at CERN energies whose consequences are hard to estimate, so that it is crucial to do these searches for S drops at all available energies.

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