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PRODUCTION OF STRANGE CLUSTERS IN RELATIVISTIC HEAVY ION COLLISIONS

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ABSTRACT

We address a number of issues related to the production of strangeness in high energy heavy ion collisions, including the possibility that stable states of multi–strange hyperonic or quark matter might exist, and the prospects that such objects may be created and detected in the laboratory. We make use of events generated by the cascade code ARC to estimate the rapidity distribution dN/dy of strange clusters produced in Si+Au and Au+Au collisions at AGS energies. These calculations are performed in a simple coalescence model, which yields a consistent description of the existing data on non–strange cluster (d, ^{3}He, ^{3}H, ^{4}He) production at these energies. If a doubly strange, weakly bound $\Lambda\Lambda$ dibaryon exists, we find that it is produced rather copiously in Au+Au collisions, with $dN/dy \sim 0.1$ at mid–rapidity. If one adds another non–strange or strange baryon to a cluster, the production rate decreases by roughly one or two orders of magnitude, respectively. For instance, we predict that the hypernucleus $_{\Lambda\Lambda}^{6}$He should have $dN/dy \sim 5 \times 10^{-6}$ for Au+Au central collisions. It should be possible to measure the successive $\Lambda \to p\pi^-$ weak decays of this object. We comment on the possibility that conventional multi–strange hypernuclei may serve as "doorway states" for the production of stable configurations of strange quark matter, if such states exist.

Invited talk presented at HIPAGS '93
Cambridge, MA
January 13–15, 1993

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We address a number of issues related to the production of strangeness in high energy heavy ion collisions, including the possibility that stable states of multi–strange hyperonic or quark matter might exist, and the prospects that such objects may be created and detected in the laboratory. We make use of events generated by the cascade code ARC to estimate the rapidity distribution dN/dy of strange clusters produced in Si+Au and Au+Au collisions at AGS energies. These calculations are performed in a simple coalescence model, which yields a consistent description of the existing data on non–strange cluster (d, ^{3}He, ^{3}H, ^{4}He) production at these energies. If a doubly strange, weakly bound $\Lambda\Lambda$ dibaryon exists, we find that it is produced rather copiously in Au+Au collisions, with $dN/dy \sim 0.1$ at mid–rapidity. If one adds another non–strange or strange baryon to a cluster, the production rate decreases by roughly one or two orders of magnitude, respectively. For instance, we predict that the hypernucleus $_{\Lambda\Lambda}^6$He should have $dN/dy \sim 5 \times 10^{-6}$ for Au+Au central collisions. It should be possible to measure the successive $\Lambda \to p\pi^-$ weak decays of this object. We comment on the possibility that conventional multi–strange hypernuclei may serve as "doorway states" for the production of stable configurations of strange quark matter, if such states exist.

1. Introduction and Motivation

There are a number of motivations for the study of multi–strange matter. For instance, one would like to explore the rôle of the strangeness degree of freedom in baryon–baryon interactions. Most of our empirical knowledge relates to the properties of the nucleon–nucleon system, with more rudimentary information on the ΛN interaction from the analysis of hypernuclear spectroscopy,[1,2] and a hint of an attractive $\Lambda\Lambda$ matrix element from the very sparse data on double hypernuclei.[3] The existing NN, ΛN and ΣN scattering data can be accommodated in a conventional meson exchange picture in which SU(3) symmetry relations are applied to meson–baryon coupling constants, and SU(3) is broken through the use of observed masses for the exchanged mesons.[4,5] However, the lack of any data on spin observables for hyperon–nucleon scattering renders this prescription non–unique. For instance, the approach of the Bonn–Jülich group[6] is to impose the stronger constraints of SU(6) symmetry on the coupling constraints; the data can still be reproduced by suitable adjustments in the short range behavior of the potentials. Thus the question of the degree to which SU(3) symmetry is broken, and the mechanism for this breaking, remains somewhat open. To extend our knowledge of baryon–baryon forces to

the hyperon–hyperon sector ($\Lambda\Lambda$, $\Xi\Lambda$), it is necessary to obtain information on the binding energies of multi–hyperon systems, since the corresponding scattering experiments are not feasible. Relativistic heavy ion collisions offer the only practical method to produce multi–strange bound systems, since a bath of several dozen Λ's, Σ's and Ξ's typically results from an encounter at low impact parameter.

Strangeness is also crucial in distinguishing between various approaches to non–perturbative QCD. For instance, there are several "QCD–inspired" models which yield substantially equivalent results for the strange and non–strange baryon spectra, but differ completely in their predictions for the stability of strange dibaryons. For instance, Jaffe[7] predicts a stable strangeness $S = -2$ dibaryon with $J^\pi = 0^+$, $I = 0$ (the H) on the basis of the Bag Model, while Kunz and Mulders[8] and Kopeliovich et al.[9] use alternate versions of the Skyrme model to arrive at dramatically different conclusions. For instance, Kopeliovich[9] obtains a $\Sigma^-\Sigma^-$ bound state ($^1S_0$, $I = 2$) which might even be stable against first order weak decay. As we indicate later, if any such stable strange dibaryons exist, they should be produced at measurable rates in heavy ion collisions at the AGS.

Another basic question is whether there exist two branches of strange matter, one composed of bound nucleons and hyperons, and another composed of a mixture of strange and non–strange quarks bound together in a single large bag (the "strangelets" of Witten[10] and Farhi/Jaffe[11]). Using mean field theory,[12–15] one can confidently predict the existence of the first branch, based on a reasonable extrapolation of known NN and ΛN interactions, and some fragmentary information on the $\Lambda\Lambda$ and ΞN systems. This extrapolation yields systems which are stable in the bulk limit ($A \to \infty$), with charge $Z/A \to 0$, large strangeness $|S|/A \sim 0.5 - 1$, densities $\rho \simeq 2\rho_0$ (ρ_0 = nuclear matter density) and binding energy per baryon $E_B/A \simeq 10 - 40$ MeV. These conventional hyperonic systems share all the properties of "strangelets",[10,11] except E_B/A. For hyperonic matter, E_B/A is limited by the depths of the mean fields (~ 30 MeV for a Λ in a nucleus, for instance), which are much smaller than the $\Lambda - N$ mass difference $m_\Lambda - m_N \simeq 175$ MeV. Thus bound multi–hyperon systems will always enjoy the possibility of weak decays, dominantly via non–mesonic processes $\Lambda N \to NN$, $\Lambda\Lambda \to \Lambda N$, etc. The hypothetical "strangelets", on the other hand, might conceivably be stable even against weak decays. There are a number of experiments underway to search for long–lived "strangelets", the most sensitive of which is E864 at the AGS,[16] which offers a sensitivity of $\sim 3 \times 10^{-11}$ per collision. There has been much less emphasis on searches for multistrange objects with weak lifetimes of order $\tau_\Lambda \sim 260$ psec. We argue here that such searches are also worthwhile, since these conventional hyperonic systems can be produced with observable rates, at least for small A. If such systems are observed through weak decays, one obtains a constraint on the existence of a "second branch" of deeply bound strange states (for example, the observation of $_{\Lambda\Lambda}^6$He weak decays constrains the allowed mass range of the putative H dibaryon, which could be produced via the strong process $_{\Lambda\Lambda}^6$He $\to$ ^{4}He $+ H$).

2. Multi–strange Hyperonic Systems

The lightest bound strange objects are of greatest interest from the point of view of their production in heavy ion collisions. The lightest $S = -1$ hypernucleus is $_\Lambda^3$H ($\Lambda + d$), followed by $_\Lambda^4$H, $_\Lambda^4$He and $_\Lambda^5$He. For $S = -2$, the lightest bound system is likely to be $_{\Lambda\Lambda}^4$H, although this is not certain, followed by $_{\Lambda\Lambda}^5$H, $_{\Lambda\Lambda}^5$He and $_{\Lambda\Lambda}^6$He. We will focus on some of these systems in our later coalescence estimates. From the known well depth $V_\Lambda \approx 28$

MeV for a Λ in nuclear matter,[2] we know that a Λ first binds in a p–state for an $A = 12$ core ($^{13}_{\Lambda}$C). Due to the Pauli principle, a third Λ cannot occupy the s–state, and hence $_{3\Lambda}^{A}$Z systems will be unstable with respect to Λ emission for $A \lesssim 13$. As we see later, systems like $_{3\Lambda}^{13}$C and heavier will not be produced with observable rates in heavy ion collisions, at least via the coalescence process envisaged here.

A relevant question is the following: What is the lightest system containing a Ξ hyperon which is likely to be stable against strong decay? Normally, one would expect a Ξ to encounter a nucleon, and convert strongly to two Λ's. In free space, the energy release would be

$$Q_{\mathrm{op}}\left(\Xi^{-}p \to \Lambda\Lambda\right) = 28 \text{ MeV}$$
$$Q_{\mathrm{on}}\left(\Xi^{0}n \to \Lambda\Lambda\right) = 23 \text{ MeV} \tag{1}$$

In a nuclear medium, however, binding effects and Pauli blocking can change this conclusion. For instance, consider the system $_{\Xi^{0}\Lambda\Lambda}^{7}$He ($\Xi^{0} + 2\Lambda + {}^{4}$He). Since the $1s$ Λ shell is occupied, the additional Λ's produced in (1) must be ejected into the continuum. The Q value for the strong decay $_{\Xi^{0}\Lambda\Lambda}^{7}$He $\to 2\Lambda + {}_{\Lambda\Lambda}^{5}$He is then

$$Q \approx Q_{\mathrm{on}} - B_{n}\left({}^{4}\text{He}\right) - B_{\Xi^{0}} + 2\left(B_{\Lambda}\left({}_{\Lambda}^{4}\text{He}\right) - B_{\Lambda}\left({}_{\Lambda}^{5}\text{He}\right)\right) \tag{2}$$

where we have assumed that the $\Lambda\Lambda$ interaction is about the same in $_{\Lambda\Lambda}^{6}$He and $_{\Lambda\Lambda}^{5}$He. We note that the sizeable binding energy $B_{n}({}^{4}\text{He}) \simeq 20.6$ MeV of a neutron in ^{4}He largely cancels out the free space Q–value, and we find

$$Q \simeq 1.17 \text{ MeV} - B_{\Xi^{0}} \tag{3}$$

For a Woods–Saxon potential with radius $R = r_{0}A^{1/3}$ ($r_{0} = 1.3$ fm), a modest well depth $V_{\Xi} \geq 18$ MeV will produce a binding energy $B_{\Xi^{0}} > 1.2$ MeV, and hence stabilize the $_{\Xi^{0}\Lambda\Lambda}^{7}$He system. These considerations are given in more detail in Ref. 14, where it is shown that $_{\Xi^{0}\Lambda\Lambda}^{7}$He is likely to be the lightest stable system containing a Ξ hyperon.

A Σ hyperon, on the other hand, cannot be stabilized by binding and Pauli effects against $\Sigma N \to \Lambda N$ conversion, since $Q(\Sigma N \to \Lambda N) \approx 75 - 80$ MeV considerably exceeds the Σ, Λ and N well depths. However, one can evade strong decay in some cases because of charge conservation, for instance by considering composites of $\{\Sigma^{-}n\Xi^{-}\}$, $\{\Sigma^{+}p\Xi^{0}\}$, $\{\Lambda\Xi^{-}n\}$, $\{\Lambda\Xi^{0}p\}$, and $\{\Lambda\Xi^{-}\Xi^{0}\}$. A possible $\Sigma^{-}\Sigma^{-}$ bound dibaryon falls in this class of objects.

A few words are in order considering the possible existence of a weakly bound $S = -2$ dibaryon. This would be a deuteron–like object, rather than the deeply bound H dibaryon proposed by Jaffe[7], which corresponds to a six quark SU(3) singlet. From the three $\Lambda\Lambda$ hypernuclear events observed in emulsion experiments,[17] one extracts a strongly attractive $\Lambda\Lambda$ interaction matrix element in the $^{1}S_{0}$ state of

$$V_{\Lambda\Lambda} \simeq -(4 - 5) \text{ MeV} \tag{4}$$

This is to be compared to the $^{1}S_{0}$ matrix elements $V_{\Lambda N} \simeq -(2\text{--}3)$ MeV and $V_{NN} \simeq -(6\text{--}8)$ MeV. Although it is known that there is no two–body ΛN bound state, the possibility of binding arises for $\Lambda\Lambda$ because of the stronger attraction and the larger mass, which
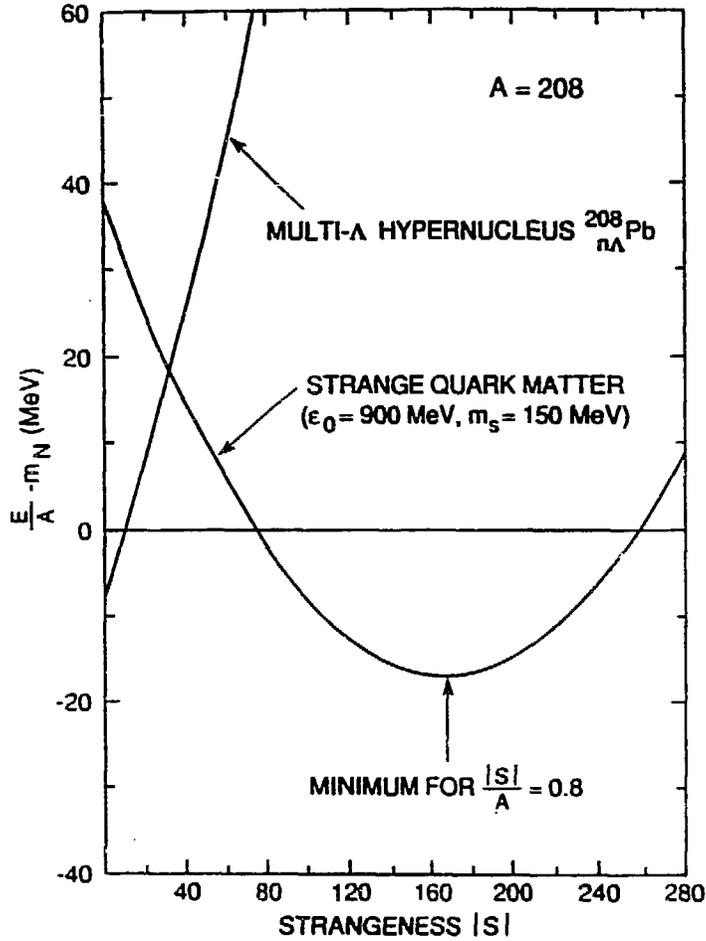
Figure 1: Energy per particle E/A relative to the nucleon mass m_N as a function of strangeness $|S|$ for a multi-Λ hyprnucleus and for a droplet of strange quark matter, both with $Z = 82$, $A = 208$. The hypernuclear binding was estimated in mean field theory[12] and the strangelet energy was obtained from the Berger–Jaffe mass formula with $\epsilon_0 = 900$ MeV, $m_s = 150$ MeV.

decreases the kinetic energy. Assuming such a $\Lambda\Lambda$ state exists, it will be copiously produced in heavy ion collisions, and it should be detectable through its $2(p\pi^-)$ weak decay mode.

3. Multi–hyperon States as "doorways" to Strange Quark Matter

A mass formula for "strangelets" has been proposed by Berger and Jaffe.[18] It assumes the form

$$E(A, S, Z) = \epsilon_0 A + \epsilon_1 A^{2/3} + \frac{\epsilon_2}{A}(S - S_{\min})^2$$
$$+ \left(\frac{\epsilon_3}{A} + \frac{\epsilon_4}{A^{1/3}}\right)(Z - Z_{\min})^2 \qquad (5)$$

where the constants ϵ_i can be related to the Bag constant B and the strange quark mass m_s. A similar expression, an extension of the familiar Bethe–Weizsäcker mass formula, has recently been constructed for hyperonic matter.[15] For strange quark matter, E/A displays a minimum for strangeness $S = S_{min}$, for fixed Z and A. For $Z = 82$, $A = 208$, this behavior is shown in Fig. 1 (taken from Ref. 19) for typical parameters $\epsilon_0 = 900$ MeV, $m_s = 150$ MeV. Consider now a conventional hypernucleus $^{208}_{n\Lambda}$Pb, in which n neutrons are replaced by Λ's.[12,13] For this system, E/A is minimum for $S = 0$. As seen in Fig. 1, the two branches, namely hyperonic matter and strange quark matter, will cross at some value of S. This crossing depends strongly on the value of ϵ_0, which is essentially unknown. In Fig. 1, there is an appreciable region of S where $E/A \leq m_N$, i.e., these strange quark systems are stable against weak as well as strong decay. This would of course be somewhat of a miracle!

Now suppose that a crossing of the two branches of strange matter occurs at a small value of A, in the region which is experimentally accessible with heavy ion reactions. As an example, consider again the system $_{\Xi^0\Lambda\Lambda}^{7}$He . We have argued that this object cannot decay strongly, so we anticipate that it will decay weakly with $\tau \sim \tau_\Lambda/3$. This argument holds unless there exists a stable state of strange quark matter of similar A, which would be populated by strong decays, for example

$$_{\Xi^0\Lambda\Lambda}^{7}\text{He} \rightarrow K^+ + X \tag{6}$$

where X is an $A = 7$, $S = -5$, $Z = 1$ strangelet with typical ratios $|S|/A \sim 0.7$, $Z/A \sim 0.1$, which we assume to have a mass of order $7m_N$ (i.e., absolutely stable). Neglecting binding effects, we then have

$$M\left(_{\Xi^0\Lambda\Lambda}^{7}\text{He}\right) - M(X) \simeq m_{\Xi^0} + 2m_\Lambda - 3m_N \simeq 730 \text{ MeV} \tag{7}$$

Thus there is sufficient energy for the emission of a K^+ in reaction (6). We see that the hypernucleus $_{\Xi^0\Lambda\Lambda}^{7}$He serves as a "doorway state" for the production of the strangelet X. On the other hand, if the weak decay of the $_{\Xi^0\Lambda\Lambda}^{7}$He is seen, it would appear to rule out the existence of X, at least in a certain mass regime. This argument assumes that the strong process (6) proceeds much faster than weak decay. The strong lifetime depends on the spatial overlap between the $_{\Xi^0\Lambda\Lambda}^{7}$He state, which consists of quarks localized in baryons (three quark clusters) and X, in which each quark roams in a single large bag. However, both systems have a density $\rho \sim 2\rho_0$, so this distinction is not clear. It is possible that this spatial overlap factor is sufficiently small so that strong and weak decay lifetimes of $_{\Xi^0\Lambda\Lambda}^{7}$He become comparable. It is clearly necessary to provide some rough estimates of this suppression factor before the lifetime argument can be applied to eliminate X.

4. Coalescence Estimates of Strange Cluster Formation

There are several possibilities for producing bound strange clusters in relativistic heavy ion collisions. One hypothesis consists of assuming that quark–gluon plasma (QGP) is formed in the collision, and then adopting some hadronization scenario[20–23] to produce strange matter. For instance, Greiner and Stöcker[20] consider a "strangeness distillation" mechanism in which a QGP droplet radiates K^+ and K^0 mesons (i.e., $\bar{s}$ quarks), leading to an enrichment of the s quark content of the fragment. These droplets can cool down to form
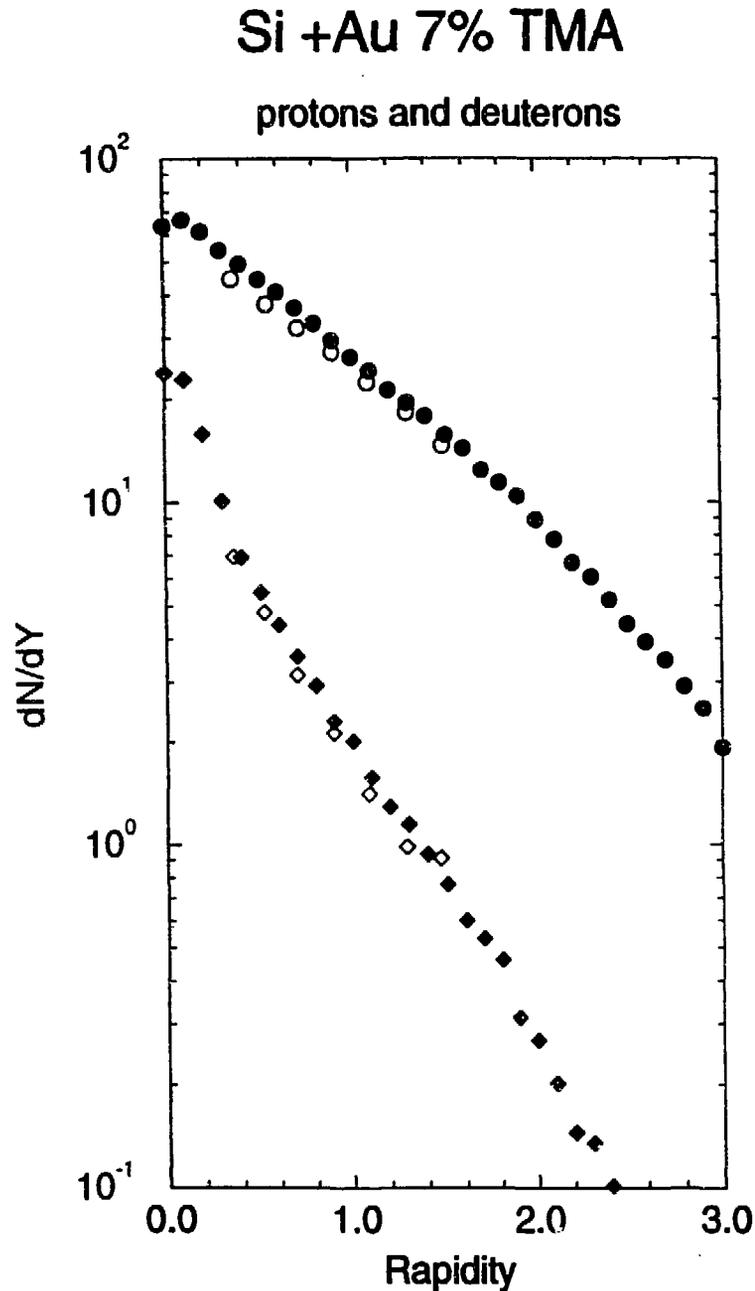
Si +Au 7% TMA

protons and deuterons

Figure 2: Proton and deuteron rapidity distributions dN/dy for Si+Au collisions at 14 GeV/A. The E802 data for protons[27] are shown as open circles, while the E802 deuteron data[28] corresponds to the open square. The "7% TMA" data refers to central collisions with the highest 7% of multiplicity. The ARC calculations[25] for the proton spectrum (solid circles) were done with an impact parameter $b = 2$ fm. The solid squares represent the ARC coalescence results for deuterons based on Eq. (11), using the parameters given in Table 1.

strangelets of baryon number $A \simeq 10 - 30$, with charge $Z/A \simeq -0.1$ (i.e. large strangeness $|S|/A \geq 1$). Shaw and his collaborators[21,22] have made more schematic estimates in which the production probability $P(A, Z)$ of strangelets per collision event is written as

$$P(A, Z) = P_{\text{QGP}} \cdot P_A \cdot \sum_S P(A, Z, S) \cdot P_{\text{cool}} \tag{8}$$

in which P_{QGP}, P_A, and P_{cool} are the probabilities for producing QGP in a collision, assembling a cluster of baryon number A, and cooling a cluster to the ground state, respectively. We sum over the strangeness S of clusters corresponding to bound states. It is assumed, somewhat arbitrarily, that $P_{\text{QGP}} = 0.1$, $P_A = A/2A_{\text{beam}}$, $P_{\text{cool}} = c/A$, with $c = 6 \times 10^{-2}$ for collisions at 15 GeV/A, and

$$P(A, Z, S) = P(n_u) \cdot P(n_s)$$
$$P(n_{u,s}) = e^{-\bar{n}_{u,s}} \frac{(\bar{n}_{u,s})^{n_{u,s}}}{n_{u,s}!} \tag{9}$$

The functions $P(n_{u,s})$ are Poisson distributions which specify the deviations from the average initial strangeness ($|S|/A \simeq 0.1 - 0.2$) and charge of the droplet. That is, the idea is to build up the strangeness S and lower the charge Z by fluctuations from these starting values. Taking $\epsilon_0 = 880$ MeV, $m_s = 150$ MeV in a Berger-Jaffe strangelet mass formula, Crawford et al.[22] estimate

$$P(A, Z) \approx \begin{cases} 2 \times 10^{-9} & (A{=}10, Z{=}{-}1) \\ 7 \times 10^{-9} & (A{=}10, Z{=}1) \\ 2 \times 10^{-11} & (A{=}20, Z{=}{-}1) \\ 8 \times 10^{-11} & (A{=}20, Z{=}1) \end{cases} \tag{10}$$

for Au+Au collisions at AGS energies. Thus in a very high sensitivity experiment such as E864,[16] it would be possible to detect stable strangelets up to $A \sim 20$.

We mention these rather crude quark estimates to emphasize the point that the predicted rates[21,22] of formation of strangelets from QGP are many orders of magnitude larger (for fixed A, Z, S) than the estimates we now present based on the coalescence model. Thus coalescence provides a rather conservative approach which probably represents a lower limit for strangelet production, and a realistic estimate for light single and multiply–strange hypernuclei. That is, if deeply bound strangelets exist, they could be formed at earlier stages of the collision, and not be broken up again by subsequent interactions. The coalescence picture, on the other hand, is appropriate for rather weakly bound clusters, which are formed late in the collision process, at "freezeout".

The preliminary results of the coalescence calculations shown here were obtained[24] using events for Si+Au and Au+Au collisions at AGS energies generated by the cascade code ARC,[25,26] due to Pang, Schlagel and Kahana. ARC yields phase space densities of protons, neutrons and Λ hyperons, which serve as input for our calculations. The single particle p and Λ rapidity distributions dN/dy from ARC are shown in Figures 2 and 3, together with experimental data from AGS experiments E802.[27,28] The agreement of ARC results with data for baryon inclusive distributions is seen to be excellent.
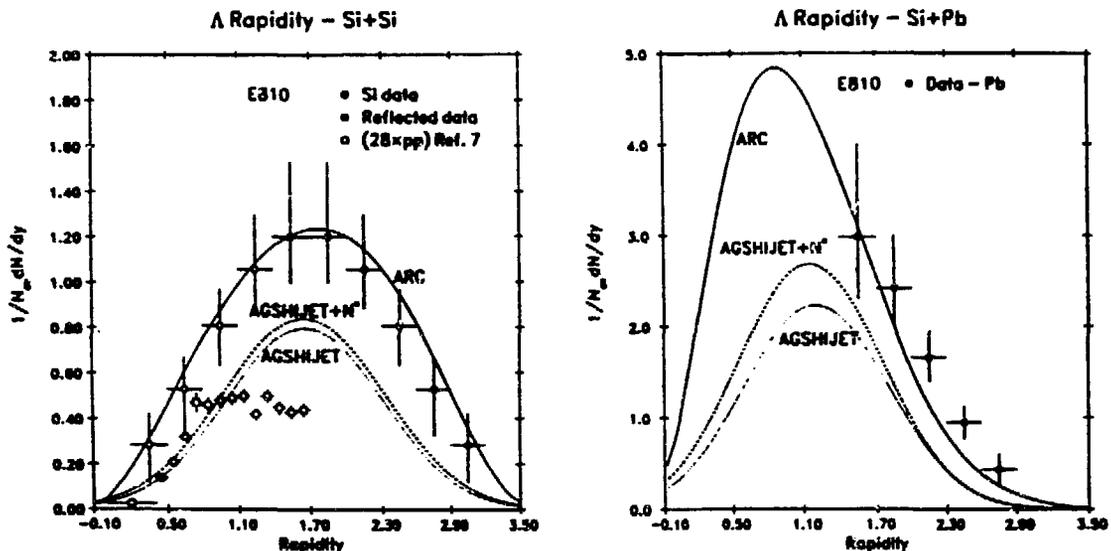
Figure 3: Rapidity distributions for Λ hyperons in Si+Si (left) and Si+Pb (right) collisions at 14.6 GeV/A taken from Eiseman et al.[29]. The ARC results are seen to be in good agreement with the E810 data.

In this first set of calculations, we have used a particularly simple form of the coalescence model. Refinements will be reported on later.[24] As an example, consider deuteron production. Given an ARC event, we follow the progress of each neutron–proton (n, p) pair until after their last interactions with other nucleons or mesons. We then stipulate that a deuteron is formed if the relative two–body center of mass (c.m.) momentum Δp and the relative spatial separation Δr of the np pair satisfy the conditions

$$\Delta p \leq (\Delta p)_{\text{max}} \quad , \quad \Delta r \leq (\Delta r)_{\text{max}} \tag{11}$$

where Δr is computed at the time of closest approach. Eq. (11) corresponds to the condition that the np pair fits into the deuteron wave function, in both momentum and coordinate space. In Eq. (11), we have essentially approximated the square of the wave function in terms of a square well. This crude approximation will be improved upon.[24] Since the deuteron is a $^3S_1$ np bound state, we supply a spin factor of 3/4, according to the statistical weight of the spin triplet configuration for a pair of uncorrelated spins. For a more general cluster of spin J and baryon number A, the spin factor[30] becomes $(2J + 1)/2^A$. We take care to avoid double counting. Heavier clusters are built up by sequential coalescence. For instance, to obtain ^{3}He, we first coalesce a deuteron–like np pair, and then look for another proton which satisfies Eq. (11), where Δp and Δr are now the relative momentum and coordinate of the proton with respect to the c.m. of the deuteron.

In addition to $d(J = 1)$, ^{3}He, ^{3}H$(J = 1/2)$, and ^{4}He$(J = 0)$ clusters, we also calculate the rates for the production of the following strange clusters:

$$(\Lambda\Lambda)_b(J = 0), \quad {}^{3}_{\Lambda}\text{H}(J = 1/2), \quad {}^{5}_{\Lambda}\text{He}(J = 1/2), \quad {}^{4}_{\Lambda\Lambda}\text{H}(J = 1), \quad {}^{6}_{\Lambda\Lambda}\text{He}(J = 0) \tag{12}$$

Table 1: Parameters for Coalescence Calculations

Process	$(\Delta p)_{\max}$	$(\Delta r)_{\max}$
$p + n \to d$, $\Lambda + \Lambda \to (\Lambda\Lambda)_b$	120 MeV/c	2.4 fm
$d + n \to {}^3\text{H}$, $d + p \to {}^3\text{He}$, $d + \Lambda \to {}_\Lambda^3\text{H}$	160	3.2
${}^3\text{H} + p$, ${}^3\text{He} + n \to {}^4\text{He}$	180	3.6
${}^4\text{He} + \Lambda \to {}_\Lambda^5\text{He}$	190	3.6
$d + (\Lambda\Lambda)_b \to {}_{\Lambda\Lambda}^4\text{H}$	240	3.6
${}^4\text{He} + (\Lambda\Lambda)_b \to {}_{\Lambda\Lambda}^6\text{He}$	320	3.6

The values of $(\Delta p)_{\max}$ and $(\Delta r)_{\max}$ which we have used for the various coalescence processes are collected in Table 1. Using these parameters, we obtain good agreement with the available data on d, ${}^3\text{He}$, ${}^3\text{H}$ and ${}^4\text{He}$ production from experiments E814 and E886.[31,32] The comparison with the preliminary E886 data[32] is shown in Fig. 4, and that with the E802 deuteron data is displayed in Fig. 2.

For the ${}^1S_0$ $\Lambda\Lambda$ bound state $(\Lambda\Lambda)_b$, we assume the same $(\Delta p)_{\max}$ and $(\Delta r)_{\max}$ as for the deuteron. As $(\Lambda\Lambda)_b$ becomes more deeply bound, the value of $(\Delta p)_{\max}$, and hence the production rate, increases strongly. From Fig. 5, we see that $(\Lambda\Lambda)_b$ is produced fairly copiously, with dN/dy approaching 0.1 at mid–rapidity for Au+Au collisions at the AGS. Thus $(\Lambda\Lambda)_b$, if it indeed exists, is more abundant than the $\bar{p}$!

If other hyperon–hyperon bound states exist, for example the $\Sigma^-\Sigma^-$ or $\Xi^-\Xi^-$ states predicted by Kopeliovich,[9] their rates can be similarly obtained. For instance, we estimate

$$N\left(\Sigma^-\Sigma^-\right)_b / N\left(\Lambda\Lambda\right)_b \simeq 1/10 \tag{13}$$

in heavy ion collisions at AGS energies.

Our results for light $S = -1$ and -2 hypernuclei are shown in Figs. 6 and 7. The rates for these objects are large enough to be measured, as we argue in the next section.

In Table 2, we list the number $N = \int dy\, dN/dy$ of particles of each species produced per event in central Si+Au and Au+Au collisions at AGS energies. Here δp and δn represent the change in the initial proton and neutron numbers which occur during the collision process. Since baryon number is conserved, and $B\bar{B}$ production is relatively rare, hyperons come into existence at the expense of nucleons, mostly neutrons. The final observed neutron and proton numbers for Au+Au collisions are

$$\tilde{N}_n = N_n + \delta n \simeq 186 \quad , \quad \tilde{N}_p = N_p + \delta p \simeq 167 \tag{14}$$

The coalescence probability for deuterons is then

$$N_d / \tilde{N}_p \tilde{N}_n \simeq 4 \times 10^{-4} \tag{15}$$

A consequence of the approximate equality of $\tilde{N}_p$ and $\tilde{N}_n$ is a comparable amount of ${}^3\text{He}$ and ${}^3\text{H}$ production in Au+Au collisions. For light projectiles, the ${}^3\text{H}/{}^3\text{He}$ ratio is closer to the N/Z ratio in the initial state.

From Table 2, we see that the N values for clusters decrease rapidly as the baryon number and strangeness increase. We can express this decrease in terms of a penalty
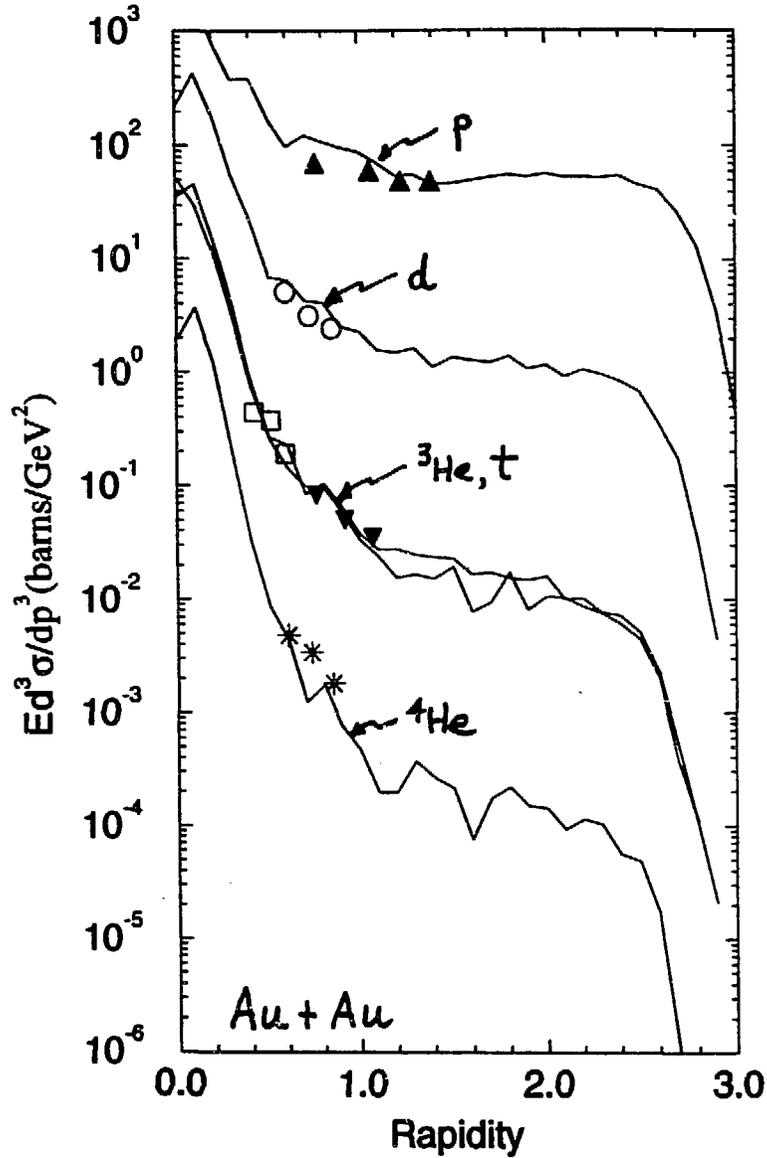
Figure 4: ARC coalescence calculations (solid curves) of the invariant cross sections for light non–strange clusters formed in Au+Au collisions at 11.7 GeV/c. The preliminary data of AGS experiment E886 are shown as solid triangles (protons), open circles (deuterons), open squares (tritons), solid triangles (^{3}He) and stars (^{4}He) [G. Diebold, private communication]. The E886 measurements are minimum bias, and correspond to a lab angle of 5°. The ARC events were generated with a impact parameter $b = 9$ fm.

factor P for adding a nucleon to a cluster or a factor λ for changing a nucleon into a Λ.
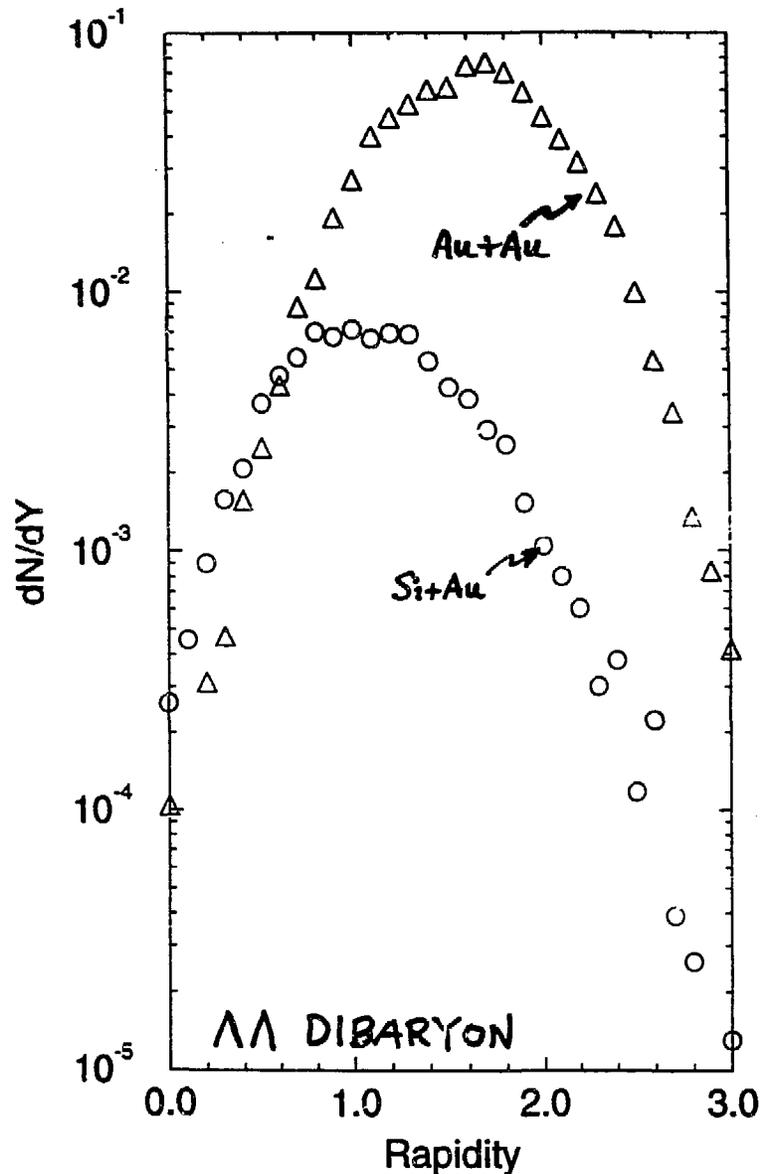
Figure 5: ARC coalescence predictions for the rapidity distribution dN/dy of a hypothetical bound $\Lambda\Lambda$ dibaryon state in Si+Au and Au+Au central collisions at AGS energies. We have assumed the same parameters $(\Delta p)_{max}$ and $(\Delta r)_{max}$ as for the deuteron, and used $b = 2$ fm.

As a rough estimate (e.g. for Au+Au), we take

$$P \approx \frac{N\left(^3\text{He}\right)/2}{N\left(d\right)/3} \simeq \frac{1}{20} \qquad \text{or} \qquad \frac{N\left(^4\text{He}\right)}{N\left(^3\text{He}\right)/2} \simeq 0.08 \qquad (16)$$
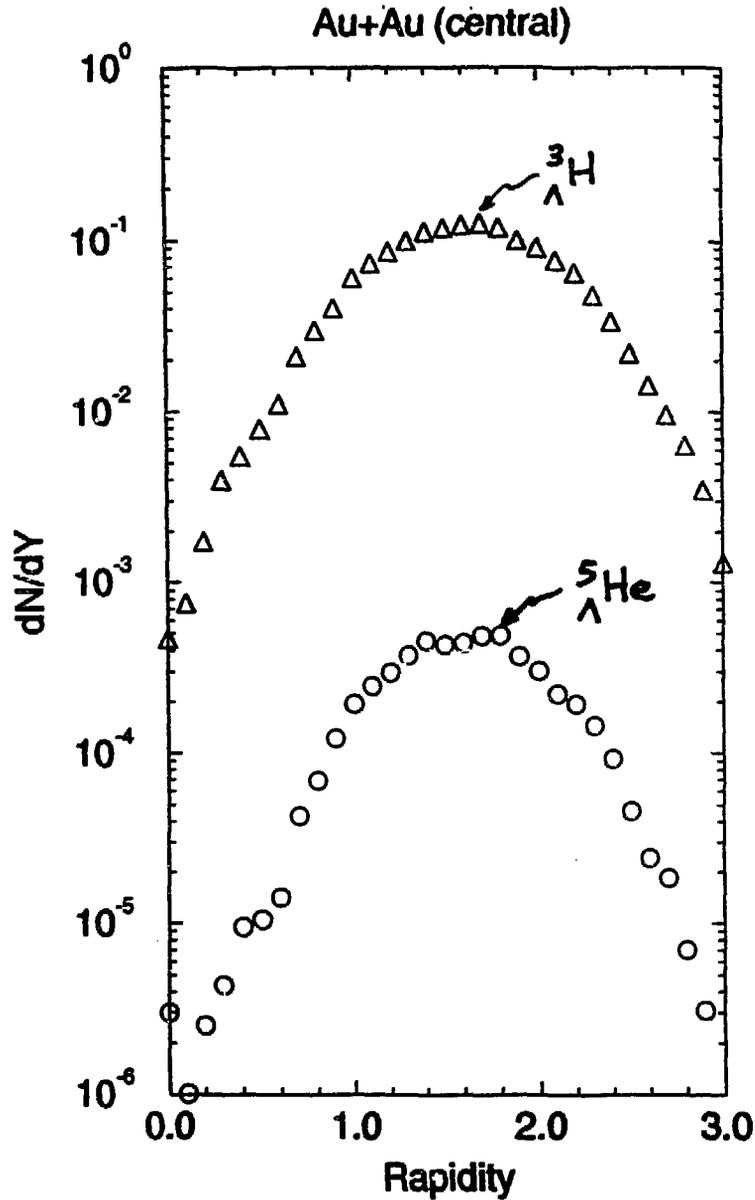
Figure 6: Rapidity distributions for the single hypernuclei $^3_\Lambda$H and $^5_\Lambda$He for central Au+Au collisions at 11.7 GeV/c, calculated in the ARC coalescence model, using $b = 2$ fm and the parameters of Table 1.

where we have divided out a factor $(2J + 1)$. For λ, we have

$$\lambda \simeq \frac{N\left(^3_\Lambda H\right)}{N\left(^3H\right)} \simeq 0.4 \qquad \text{or} \qquad \left(\frac{N\left(_{\Lambda\Lambda}^4 H\right)/3}{N\left(^4He\right)}\right)^{1/2} \simeq 0.3 \tag{17}$$
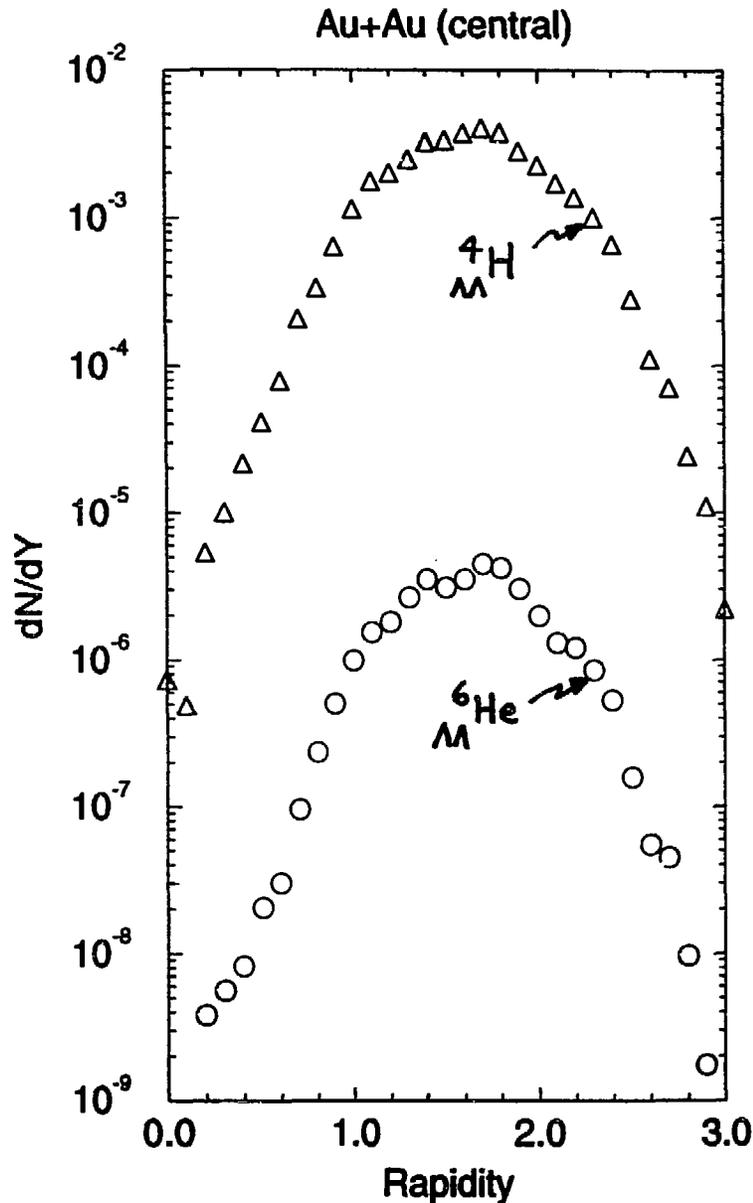
Figure 7: ARC coalescence predictions for the production of the double hypernuclei $_{\Lambda\Lambda}^{4}$H and $_{\Lambda\Lambda}^{6}$He in Au+Au central collisions ($b = 2$ fm).

Note that λ is larger than the value $N_\Lambda/\bar{N}_n \approx 0.1$ that one might naively guess. The penalty factor λP for adding a Λ to a cluster is then

$$\lambda P \approx (2-3) \times 10^{-2} \qquad (18)$$

Because of this rather severe penalty factor, we are clearly limited in the size of strange clusters we can produce via coalescence with measurable rates. An interesting case is $_{\Xi^0\Lambda\Lambda}^{7}$He, which we have argued is the lightest system containing a Ξ which is stable against

Table 2: Number of particles N per central collision at AGS energies, from ARC + coalescence model

Particle	N(Si+Au)	N(Au+Au)
Λ	5.3	20.8
Σ^-	1.6	6.9
δp	3.9	9.3
δn	-13.8	-49.9
d	12.3	12.4
^{3}H	1.3	0.4
^{3}He	1.0	0.4
^{4}He	0.13	0.015
$(\Lambda\Lambda)_b$	0.008	0.08
$_\Lambda^3$H	0.04	0.15
$_\Lambda^5$He	6×10^{-4}	5×10^{-4}
$_{\Lambda\Lambda}^4$H	3×10^{-4}	4×10^{-3}
$_{\Lambda\Lambda}^6$He	6×10^{-7}	4×10^{-6}

strong decay. The ARC cascade does not yet contain Ξ production, but an estimate based on the RQMD[33] code yields $N(\Xi^0)/N(\Lambda) \simeq 1/40$. Hence we estimate

$$N\left(_{\Xi^0\Lambda\Lambda}^{7}\text{He}\right) \approx \frac{N\left(\Xi^0\right)}{N\left(\Lambda\right)} \cdot \lambda P \cdot N\left(_{\Lambda\Lambda}^6\text{He}\right) \simeq (2-3) \times 10^{-9} \qquad (19)$$

for Au+Au collisions. This is probably too small a rate to be detectable since $_{\Xi^0\Lambda\Lambda}^{7}$He will have a lifetime of order $\tau_\Lambda/3$, too short to be observed by E864.

5. Experimental Aspects

Objects with long lifetimes $\tau > 10$ ns can be detected in a high sensitivity search such as E864. The bound hypernuclear clusters considered here will decay weakly, with lifetimes of the order of $\tau \simeq 0.1$ ns. Thus one would have to design an experiment to look for specific weak decay modes. A favorable case corresponds to final states containing only charged particles. The branching ratios BR for decay into such modes will decrease rapidly with increasing A. For a weakly bound $(\Lambda\Lambda)_b$, we expect

$$BR\left((\Lambda\Lambda)_b \to 2\left(p\pi^-\right)\right) \simeq 4/9$$
$$\tau\left((\Lambda\Lambda)_b\right) \simeq \tau_\Lambda/2 \simeq 0.13 \text{ ns} \qquad (20)$$

based on $BR(\Lambda \to p\pi^-) \simeq 2/3$ for free space Λ decay. The experimental signature would be two "vees", from which one could reconstruct the invariant mass of $(\Lambda\Lambda)_b$. As $(\Lambda\Lambda)_b$ becomes more deeply bound, the quasi-free decay $\Lambda \to N\pi$ is turned off, and other modes such as Λn, $\Sigma^- p$, etc. must prevail. The weak decays of the SU(3) singlet H dibaryon are discussed by Donoghue *et al.*[34] As another example, consider $_{\Lambda\Lambda}^6$He. A favorable decay would be

$$_{\Lambda\Lambda}^6\text{He} \to p\pi^- + _\Lambda^5\text{He} \to 2\left(p\pi^-\right) + {}^4\text{He} \qquad (21)$$

For $^5_\Lambda$He, the ratio of non–mesonic ($\Lambda N \to NN$) to mesonic decay widths has been measured to be[35]

$$Q^- = \Gamma_{NM}/\Gamma_{\pi^-} \simeq 1.2 \tag{22}$$

For $_{\Lambda\Lambda}^6$He, we estimate a similar ratio $Q^- \simeq 1.5$. Using $\Gamma_{\pi^0}/\Gamma_{\pi^-} = 1/2$, we find

$$\Gamma_{\pi^-}/\Gamma_{tot} = \frac{1}{1 + Q^- + \Gamma_{\pi^0}/\Gamma_{\pi^-}} \simeq \frac{1}{3} \tag{23}$$

or

$$BR\left(_{\Lambda\Lambda}^6\text{He} \to 2\left(\pi^- p\right) + {}^4\text{He}\right) \simeq \left(\frac{\Gamma_{\pi^-}}{\Gamma_{tot}}\right)^2 \simeq \frac{1}{10} \tag{24}$$

Using $N(_{\Lambda\Lambda}^6\text{He}) \simeq 4 \times 10^{-6}$ for Au+Au from Table 2, we find that a sensitivity of $\sim 4 \times 10^{-7}$ is required to detect $_{\Lambda\Lambda}^6$He. This appears feasible albeit difficult. Using similar arguments, one can estimate that

$$BR\left(_{\Xi^0\Lambda\Lambda}^{7}\text{He} \to \text{all charged}\right) \sim 10^{-2} \tag{25}$$

where we have summed over several charged modes, each with $BR \sim 2 \times 10^{-3}$. Combined with Eq. (19), this implies that a sensitivity approaching 10^{-11} is required to detect $_{\Xi^0\Lambda\Lambda}^{7}$He through its all charged weak decays. This appears beyond reach for an object with $\tau \sim 0.1 ns$.

6. Final Remarks

The existing data on d, ^{3}He, ^{3}H and ^{4}He production at AGS energies are consistent with a calculation based on the ARC cascade code, supplemented by a simple coalescence prediction. Based on this success, we have obtained reasonable estimates of formation rates for Λ and $\Lambda\Lambda$ hyperfragments. We conclude that bound dibaryon states such as $(\Lambda\Lambda)_b$ for $(\Sigma^-\Sigma^-)_b$ should be produced at easily measurable rates in Au+Au collisions at the AGS. Double hyperfragments such as $_{\Lambda\Lambda}^4$H, $_{\Lambda\Lambda}^5$H, $_{\Lambda\Lambda}^5$He and $_{\Lambda\Lambda}^6$He should also be observed.

7. Acknowledgments

8. References

1. E.H. Auerbach *et al.*, Ann. Phys. 148, 381 (1983).
2. R.E. Chrien and C.B. Dover, Ann. Rev. Nucl. Part. Sci. 39, 113 (1989).
3. C.B. Dover, D.J. Millener, A. Gal and D.H. Davis, Phys. Rev. C44, 1905 (1991).
4. M.M. Nagels, T.A. Rijken and J.J. deSwart, Phys. Rev. D12, 744 (1975) and D15, 2547 (1977); D20, 1633 (1979).
5. P.M.M. Maessen, T.A. Rijken and J.J. deSwart, Phys. Rev. C40, 2226 (1989).
6. B. Holzenkamp, K. Holinde and J. Speth, Nucl. Phys. A500, 485 (1989).
7. R.L. Jaffe, Phys. Rev. Lett. 38, 195, 617(E) (1977).
8. J. Kunz and P.J. Mulders, Phys. Lett. B215, 449 (1989).
9. V.B. Kopeliovich, Yad. Fiz. 51, 241 (1990) [Sov. J. Nucl. Phys. 51, 151 (1990)]; V.B. Kopeliovich, B. Schwesinger and B.E. Stern, Phys. Lett. B242. 145 (1990).

10. E. Witten, Phys. Rev. D30, 272 (1984).

11. E. Farhi and R.L. Jaffe, Phys. Rev. D30, 2379 (1984) and D32, 2452 (1985).

12. M. Rufa et al., J. Phys. G13, 143 (1987) and Phys. Rev. C42, 2469 (1990).

13. J. Schaffner, C. Greiner and H. Stöcker, Phys. Rev. C46, 322 (1992).

14. J. Schaffner, C.B. Dover, A. Gal, D.J. Millener and H. Stöcker, to be submitted to Annals of Physics.

15. C.B. Dover and A. Gal, submitted to Nucl. Phys. A.

16. R. Majka and J. Sandweiss, spokesmen, Brookhaven AGS Experiment E864, "Measurements of Rare Composite Objects and High Sensitivity Searches for Novel Forms of Matter Produced in High Energy Heavy Ion Collisions".

17. D.J. Prowse, Phys. Rev. Lett. 17, 782 (1966);
M. Danysz et al., Nucl. Phys. 49, 121 (1963);
S. Aoki et al., Prog. Theor. Phys. 85, 1287 (1991).

18. M.S. Berger and R.L. Jaffe, Phys. Rev. C35, 213 (1987).

19. C.B. Dover, "Strange Quark Matter", BNL–47670, to appear in the Proceedings of the International Conference on the Structure of Baryons and Related Mesons, Yale University, June 1992 (World Scientific).

20. C. Greiner and H. Stöcker, Phys. Rev. D38, 2797 (1988) and D44, 3517 (1991).

21. H.C. Liu and G.L. Shaw, Phys. Rev. D30, 1137 (1984).

22. H.J. Crawford, M.S. Desai and G.L. Shaw, Phys. Rev. D45, 857 (1992).

23. Z.Árvay et al., Proc. Workshop on Relativistic Heavy Ion Collisions at Present and Future Accelerators, Budapest, Hungary, June 1992; Central Research Inst. Report KFKI–1991–28/A.

24. A.J. Baltz et al., manuscript in preparation.

25. Y. Pang, T.J. Schlagel and S.J. Kahana, Phys. Rev. Lett. 68, 2743 (1992).

26. T.J. Schlagel, S.H. Kahana and Y. Pang, Phys. Rev. Lett. 69, 3290 (1992).

27. T. Abbott et al., Phys. Rev. Lett. 64, 847 (1990); 66, 1567 (1991).

28. C. Parsons, doctoral thesis, MIT (1992), unpublished.

29. S.E. Eiseman et al., Phys. Lett. B297, 44 (1992).

30. A.Z. Mekjian, Phys. Rev. C17, 1051 (1978).

31. J. Germani, private communication (E814).

32. G. Diebold, private communication (E886).

33. J. Schaffner, private communication.

34. J.F. Donoghue, E. Golowich and B.R. Holstein, Phys. Rev. D34, 3434 (1986).

35. G. Coremans et al., Nucl. Phys. B16, 209 (1970);
H.G. Miller et al., Phys. Rev. 167, 922 (1968).

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