Dibaryons with Strangeness: Their Weak Nonleptonic Decay Using SU(3) Symmetry and How to Find Them in Relativistic Heavy-Ion Collisions

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Weak SU(3) symmetry is successfully applied to the weak hadronic decay amplitudes of octet hyperons. Weak nonmesonic and mesonic decays of various dibaryons with strangeness, their dominant decay modes, and lifetimes are calculated. Production estimates for the Brookhaven Relativistic Heavy Ion Collider are presented employing wave-function coalescence. Signals for detecting strange dibaryon states in heavy-ion collisions and revealing information about the unknown hyperon-hyperon interactions are outlined.

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Relativistic heavy-ion collisions provide a prolific source of strangeness: dozens of hyperons and kaons are produced in central collisions at Brookhaven Alternate Gradient Synchrotron (BNL AGS) and at CERN Super Proton Synchrotron (SPS) (see, e.g., [1]). This opens the exciting perspective of forming composites with multiple units of strangeness hitherto unachievable with conventional methods.

Exotic forms of deeply bound objects with strangeness have been proposed by Bodmer [2] as collapsed states of matter, consisting of either baryons or quarks. A six-quark bag state, the H dibaryon, was predicted by Jaffe [3]. Other bound dibaryon states with strangeness were proposed using quark potentials [4,5] or the Skyrme model [6]. On the hadronic side, hypernuclei are known to exist already for a long time. The double Λ hypernuclear events reported so far are closely related to the H dibaryon [7]. Metastable exotic multihypernuclear objects (MEMOs) as well as purely hyperonic systems of Λ's and Ξ's were introduced in [8,9] as the hadronic counterparts to multistrange quark bags (strangelets) [10,11]. Most recently, the Nijmegen soft-core potential was extended to the full baryon octet, and bound states of $\Sigma\Sigma$, $\Sigma\Xi$, and $\Xi\Xi$ dibaryons were predicted [12].

One major uncertainty for the detection of such speculative states is their (meta)stability. MEMOs, for example, consist of nucleons, Λ's, and Ξ and are metastable by virtue of Pauli-blocking effects. Only two investigations about the weak decay of dibaryons exist so far: In [13], the H dibaryon was found to decay dominantly by $\mathrm{H} \to \Sigma^- + p$ for moderate binding energies. The $(\Lambda\Lambda)_b$, which has exactly the same quantum numbers as the H dibaryon, was studied in [14]. Here, the main nonmesonic channel was found to be $(\Lambda\Lambda)_b \to \Lambda + n$.

In the following, we will revive an "old" approach to calculate weak decay channels and lifetimes of various strange dibaryons using SU(3) symmetric contact interactions. Finally, we present production estimates for the BNL Relativistic Heavy Ion Collider (RHIC) combining transport simulations using relativistic quantum molecular dynamics, which is widely used for simulations of relativistic heavy-ion collisions, with wave-function coalescence.

The weak decays of the octet hyperons (Λ, Σ, and Ξ) can be described by an effective SU(3) symmetric interaction with a parity-violating (A) and a parity-conserving (B) amplitude [15]. The weak operator is assumed to be proportional to the Gell-Mann matrix λ_6 which ensures hypercharge violation $|\Delta Y| = 1$, the $\Delta I = 1/2$ rule, and the Lee-Sugawara relation for the A amplitudes. There are three $\mathcal{CP}$ invariant terms for the A amplitude. One contributes to $\Sigma^+ \to n + \pi^+$ and can be ignored. The two remaining parameters can be well fitted to the experimental data (see below).

The problem is to describe correctly the B amplitudes which defy a consistent explanation. Traditionally, one uses the pole model which in its basic version is not able to describe the experimentally measured amplitudes [16]. Various solutions have been proposed to remedy the situation like including the vector meson pole [17] or hyperon resonances [18]. On the other hand, as pointed out in [16], there is no serious consideration about a contact interaction for the B amplitudes in the literature.

General SU(3) symmetry and $\mathcal{CP}$ invariance results in five independent terms for the B amplitudes [15]. We find that one term gives the wrong sign to the B amplitudes for either the Λ or the Ξ's. Hence, it must be small compared to the others. Another term gives a contribution

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to $\Sigma^- \to n + \pi^-$ and can be neglected. Only three terms remain with coupling constants to be adjusted to the seven measured B amplitudes.

The corresponding Lagrangian for both amplitudes reads

$$\mathcal{L} = D\,\mathrm{Tr}\bar{B}B[P,\lambda_6] + F\,\mathrm{Tr}\bar{B}[P,\lambda_6]B + G\,\mathrm{Tr}\bar{B}P\gamma_5 B\lambda_6 + H\,\mathrm{Tr}\bar{B}\lambda_6\gamma_5 BP + J\,\mathrm{Tr}\bar{B}\{P,\lambda_6\}\gamma_5 B\,. \quad (1)$$

B stands for the baryon octet and P for the pseudoscalar nonet. Choosing $D = 4.72$ and $F = -1.62$ for the A amplitudes and $G = 40.0$, $H = 47.8$, and $J = -7.1$ for the B amplitudes in units of 10^{-7} gives a good agreement with the experimental data as shown in Table I. We point out that the B amplitudes do *not* follow a Lee-Sugawara relation [15]. Using this model for the weak hyperon decay, one can calculate the weak mesonic and nonmesonic decay of strange dibaryons using a Hulthén-like wave function [14]. The meson exchange model for the weak nonmesonic decay of hypernuclei has been proven to be quite successful [19]. We include pion and kaon exchange in our model for the nonmesonic decay as they are the dominant contributions. Effects from short-range contributions like vector meson exchange [19] and direct quark-quark contributions [20] have been found to be less important. We find that the p-wave contributions originating from the B amplitudes, the kaon exchange terms, and the interference terms are particularly important for the nonmesonic decay channels. Hence, a consistent scheme of both amplitudes turns out to be a crucial ingredient. Clearly, a more fundamental approach is desirable but is at present not at hand before we understand strong interactions at the confinement scale.

For a detection in heavy-ion experiments we are mainly interested in candidates whose final decay products are charged:

$$(\Sigma^+ p)_b \to p + p\,, \quad (2a)$$

$$(\Xi^0 p)_b \to p + \Lambda\,, \quad (2b)$$

$$(\Xi^0 \Lambda)_b \to p + \Xi^- \quad \text{or} \quad \Lambda + \Lambda\,, \quad (2c)$$

$$(\Xi^0 \Xi^-)_b \to \Xi^- + \Lambda\,. \quad (2d)$$

We find that the decay lengths for all of the above strange dibaryons is between $c\tau \approx 1$–5 cm. Figure 1 shows the

TABLE 1. The hyperon weak decay amplitudes in $\mathrm{SU(3)_{weak}}$ compared to experimental data taken from [16]. All values are in units of 10^{-7}.

	A exp	A SU(3)	B exp	B SU(3)
$\Lambda \to p + \pi^-$	3.25	3.25	22.1	22.1
$\Lambda \to n + \pi^0$	−2.37	−2.30	−16.0	−15.6
$\Sigma^+ \to n + \pi^+$	0.13	0.0	42.2	40.0
$\Sigma^+ \to p + \pi^0$	−3.27	−3.33	26.6	28.3
$\Sigma^- \to n + \pi^-$	4.27	4.71	−1.44	0.0
$\Xi^0 \to \Lambda + \pi^0$	3.43	3.19	−12.3	−11.7
$\Xi^- \to \Lambda + \pi^-$	−4.51	−4.51	16.6	16.6

calculated branching ratios as a function of the binding energy.

(a) There is only one nonmesonic decay channel for $(\Sigma p)_b \to p + p$ which we find to be dominant above 5 MeV binding energy. The dibaryon should show up in the invariant pp mass spectrum after background subtraction from event mixing at $M = 2.128$ GeV $- \epsilon$, where ϵ is the binding energy. With this method the weak decay of the lightest hypernucleus ${}^3_\Lambda\mathrm{H} \to {}^3\mathrm{He} + \pi^-$ has been detected in heavy-ion collisions by the E864 Collaboration [21].

(b) For the $(\Xi^0 p)_b$ bound state only one mesonic but three different nonmesonic channels contribute. The dominant nonmesonic decay turns out to be $(\Xi^0 p)_b \to \Lambda + p$ already for a binding energy of 2 MeV or more. The decay itself resembles the one for the weak decay of the Ξ^- or Ω^-, which have already been detected by several experiments (see contributions in [1]). Instead of an outgoing π^- or K^- there is a proton leaving the first weak vertex.

(c) The dibaryon $(\Xi^0\Lambda)_b$ decays to $\Xi^- + p$ and, with a small fraction, to two Λ's. Therefore, it can be seen in $\Xi^- p$ or $\Lambda\Lambda$ invariant mass plots. One has indeed seen two-Λ events at the AGS by experiment E896 [22], and experiment WA97 at the SPS has already published two-Λ correlation functions [23]. There are plans to study the correlation of two Λ's on an event-by-event basis at the STAR detector at BNL RHIC [24].

(d) The $(\Xi^0\Xi^-)_b$ dibaryon has been predicted to be bound [12] and its decay to $\Xi^- + \Lambda$ has a branching ratio of a few percent.

The other bound candidates predicted by the Nijmegen model [12] involve weak decays with Σ hyperons in the final state. If one can measure neutrons, one is sensitive to all proposed states:

$$(\Sigma^-\Sigma^-)_b \to \Sigma^- + n + \pi^-\,, \quad (3a)$$

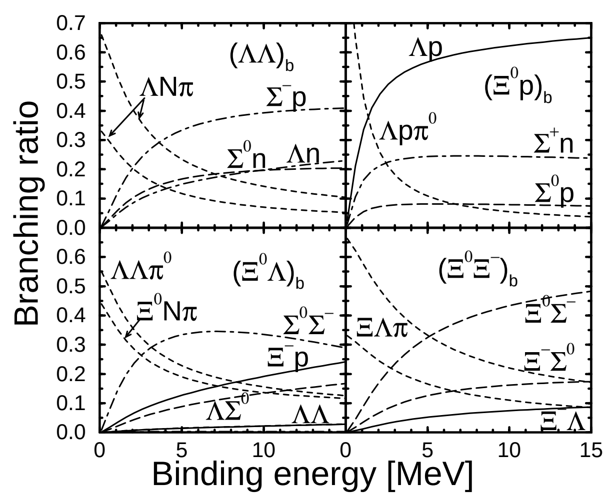

FIG. 1. Weak decay branching ratios for several strange dibaryons versus the binding energy. Solid lines denote ultimately charged final states, while dash-dotted lines indicate final states accessible with a neutron detector.

$$(\Sigma^+\Sigma^+)_b \rightarrow \Sigma^+ + p\,, \tag{3b}$$

$$(\Xi^0\Sigma^+)_b \rightarrow \Sigma^+ + \Lambda\,, \tag{3c}$$

$$(\Xi^-\Sigma^-)_b \rightarrow \Sigma^- + \Sigma^-, \tag{3d}$$

$$(\Xi^0\Xi^0)_b \rightarrow \Sigma^+ + \Xi^-, \tag{3e}$$

$$(\Xi^-\Xi^-)_b \rightarrow \Sigma^- + \Xi^-. \tag{3f}$$

In addition, one can see the nonmesonic decay involving a direct neutron in the final state, like $(\Lambda\Lambda)_b \rightarrow \Lambda + n$ and $(\Xi^-\Lambda)_b \rightarrow \Xi^- + n$. Thus, a possible Λn or $\Xi^- n$ invariant mass distribution might reveal important information about the unknown hyperon-hyperon interactions hitherto unaccessible by experiment. We find that the dominant nonmesonic decay for $(\Lambda\Lambda)_b$ is the same as for the H dibaryon, i.e., $(\Lambda\Lambda)_b \rightarrow \Sigma^- + p$. This means that the two dibaryons are indistinguishable experimentally. Note, that the nonmesonic decay of the $(\Lambda\Lambda)_b$ always involves a neutral particle in the final state. Searches for the H dibaryon in heavy-ion collisions are indeed sensitive for a weak decay with a Σ^- in the final state [25] and may be utilized to look for other exotic candidates. Especially the weak decay (3b) looks very similar to the weak decay of the H dibaryon one is already looking for, but with the opposite sign for the Σ hyperon.

Let us now focus on formation probabilities for strange baryon clusters $\Lambda\Lambda$, $p\Sigma^+$, $p\Xi^0$, $\Xi^0\Lambda$, and $\Xi^0\Xi^-$. The coalescence model provides estimates by simple phase-space arguments. Momentum coalescence has been successful in describing data at low energies (see, e.g., [26]). At relativistic bombarding energies, however, expansion of the source and collective flow have been shown to strongly modify the production rates [27,28]. Therefore, we will combine source distributions for baryons borrowed from microscopic transport calculations [29] with a coalescence prescription in phase space as detailed in [30]. This procedure has been successful to describe deuteron yields and momentum distributions [30,31] and is in accord with studies of proton-deuteron correlations [32]. Assuming uncorrelated emission the formation rate can be expressed as

$$\frac{dN}{d\vec{P}} = g \int f_A(\vec{x}_1, \vec{p}_1) f_B(\vec{x}_2, \vec{p}_2) \rho_{AB}(\Delta\vec{x}, \Delta\vec{p}) \times \delta(\vec{P} - \vec{p}_1 - \vec{p}_2)\, d^3x_1\, d^3x_2\, d^3p_1\, d^3p_2\,, \tag{4}$$

where $\Delta\vec{x} = \vec{x}_1 - \vec{x}_2$ and $\Delta\vec{p} = (\vec{p}_1 - \vec{p}_2)/2$ are given in the respective two-body c.m. system (i.e., $\vec{P} \equiv 0$). One has to multiply the rate with a symmetry factor of $1/2$, if the outgoing particles are identical. For the wave function we assume a Hulthén shape as for the calculations of weak decay properties $\Psi(r) = c/r(e^{-\kappa r} - e^{-\alpha\kappa r})$. The statistical prefactors g account for the lack of information about two-body correlations with respect to internal degrees of freedom. It includes the spin average and the projection on one particular final isospin state of the dibaryon. All strange dibaryons are assumed to be formed in spin-singlet states. The reduction to the correct "number" of possible quantum states depends crucially on the assumption of uncorrelated emission and the nature of the bound state. Since the multiparticle correlations during the breakup are not well known we consider the g values as estimates which need further guidance and insight. The predictions for strange dibaryons are depicted in Fig. 2. Variations in the wave-function parameters $E_b = 1$–20 MeV ($\kappa = \sqrt{2\mu E_b}$) and $\alpha = 2$–6 lead only to minor changes in the final result ($\pm 20\%$). Therefore, we have chosen to present calculations for the two most extreme parameter sets ($E_b \approx 5$ MeV, $\alpha = 2$) and ($E_b \approx 1$ MeV, $\alpha = 2$). The formation of $\Lambda\Lambda$ states and deuterons (see also [33,34]) is diminished by the volume expansion close to midrapidity. For nucleon-hyperon bound states the rapidity shift towards projectile and target is somewhat stronger due to enhanced nuclear freeze-out densities at forward/backward rapidities. Note, that strange dibaryons produced at these rapidities have substantially longer decay lengths which opens the possibility of detecting them at small forward or backward angles. The B parameter $B_{AB} \propto \frac{1}{g_{AB}} N(A,B)/N(A)N(B)$ measuring the production rates of dibaryons increases by a factor of 2 to 3 comparing $\Lambda\Lambda$ and $\Xi\Xi$ states. This enhancement is compatible with an "early" freeze-out scenario for multiple strange baryons as argued in [35]: Clusters with high strangeness might be formed more likely as they decouple earlier from the collisions zone.

There are several searches in heavy-ion collisions for the H dibaryon [25,36] and for long-lived strangelets [37,38] with high sensitivities. Hypernuclei have been detected most recently in heavy-ion reactions at the AGS by the E864 Collaboration [21]. The dibaryon states studied here are short lived. They can, in principle, be detected in present and future experiments by the following means:

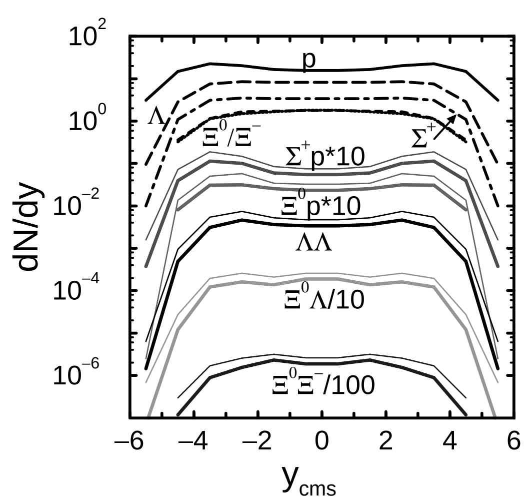

FIG. 2. Rapidity distribution of baryons (upper curves) and strange dibaryons (lower curves) using RQMD2.4 with wave-function coalescence for Au + Au collisions at $\sqrt{s} = 200A$ GeV. Upper curves are for a binding energy of $E_b = 5$ MeV, lower ones for $E_b = 1$ MeV ($\alpha = 2$).

(1) Experiments with a time-projection chamber can track for unique exotic decays like a charged particle decaying to two charged particles or tracks forming a vertex a few centimeters outside the target.

(2) Experiments sensitive to hyperons can look for peaks in the invariant mass spectrum of pp, $p\Lambda$, $\Lambda\Lambda$, $p\Xi^-$, and $\Lambda\Xi^-$ by background subtraction using event mixing.

(3) Resonances (unbound states) can be seen in the correlation function of $\Lambda\Lambda$ [39] and $\Lambda\Xi^-$. Two-particle interferometry is a powerful tool to extract information about their (unknown) strong interaction potential as the correlation function depends sensitively on final-state interactions [40]. The Coulomb potential does not mask the strong interactions at low momenta as pointed out in [41] for Λp so that information about the presently unknown hyperon-hyperon forces can be extracted as shown in [42].

The STAR experiment at the BNL RHIC is able to detect short-lived candidates as well as exotic resonances [43,44]. One $(\Lambda\Lambda)$ resonance can be seen out of 100 uncorrelated Λ's [43]. For the production rates given in Fig. 2 and 10^6 central events, even the bound $(\Xi^0\Xi^-)_b$ dibaryon can be seen by backtracking for a reconstruction efficiency of only 0.2% or better which is indeed feasible for lifetimes around 10^{-10} s [43].

In this paper we have calculated production rates of strange dibaryons via the coalescence mechanism of independently produced baryons. Finally, we want to point out that another mechanism for their formation might be possible. Via the separation and distillation process, a hot quark-gluon plasma gets enriched with strangeness [45] leading to strangelet creation. If strangelets are unstable they can form a doorway state by decaying to strange dibaryons and increase the production rates.

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