

Suppression of p -wave baryons in quark recombination

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We show that the observed suppression of the $\Lambda(1520)/\Lambda$ ratio in central Au+Au collisions at the BNL Relativistic Heavy Ion Collider can be naturally understood in the constituent quark recombination model.

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Recent data from nuclear collisions observed at the BNL Relativistic Heavy Ion Collider (RHIC) show that the emission of excited hadronic states is differentially suppressed in central Au+Au collisions [1,2]. Similar results were also found in central collisions of Pb+Pb at the CERN Super Proton Synchrotron (SPS) [3]. The yields of some hadrons are suppressed in comparison with both those measured in $p+p$ collisions and those predicted by statistical models. Curiously, not all excited hadrons are suppressed. For example, the ratio Σ^*/Λ shows no suppression at RHIC, and the ratio ϕ/K appears to be even slightly enhanced. The ratio K^*/K is modestly suppressed, and the strongest suppression is seen in the ratio Λ^*/Λ , where Λ^* stands for the negative-parity partner of the Λ hyperon with a mass of 1520 MeV.

The differences of the relative yields of these strange hadrons compared with yields measured in $p+p$ collisions is not very surprising, because the production of hadrons containing strange quarks is known to be strongly enhanced in nuclear collisions at RHIC energies. What is noteworthy is that the measured yield ratios deviate from the predictions of the thermal statistical model, which generally explains the observed hadron yields well [4–6]. The tentative explanation for the observed deviation proposed by Adams *et al.* [1] is that some fraction of the short-lived excited hadrons decays before the medium has become so dilute that the decay fragments can escape unscattered. It is then possible to estimate the duration of the dense hadronic phase from the known lifetime of the hadronic state and the observed suppression [7]. The problem with this explanation is that it yields vastly different estimates for the duration of the dense hadronic phase. For example, the K^*/K ratio demands a time span $\Delta\tau \approx 2.5$ fm/c, whereas the Λ^*/Λ ratio would require a much longer duration of $\Delta\tau \approx 9$ fm/c. Such a long time span is difficult to reconcile with the values of the duration of the emission process derived from two-pion intensity interferometry measurements, which give values for $\Delta\tau$ in the range 2–3 fm/c [8].

The discrepancy can possibly be explained by including the effect of partial regeneration of excited hadronic states in the evolving dense medium [9] if its lifetime is sufficiently long. However, quantitative predictions of this effect depend on various unknown cross sections, and it is not clear whether a simple compelling picture emerges that can explain all the measured ratios [1].

In this article, we propose a simple explanation for the observed strong suppression of the Λ^*/Λ ratio, compared with the observed K^*/K ratio and the thermal model predictions. Our argument is based on the fact that the $\Lambda(1520)$ has a different internal quark structure than that of all other hadrons that have been detected in the final state of relativistic heavy ion reactions. In the framework of the constituent quark model, the $\Lambda(1520)$ is described as an orbital excitation of the ground-state Λ hyperon, where one quark is in a p -wave orbital [10]. In the calculations, the $\Lambda(1520)$ is a mixture of flavor-SU(3) singlet and octet, which corresponds to a spatial wave function with the strange quark being predominantly in the p -wave state, specifically,

$$|\Lambda(1520)\rangle \approx 0.91|1\rangle + 0.40|8\rangle \approx -0.37|s\rangle + 0.93|p\rangle, \quad (1)$$

where $|1(8)\rangle$ denotes the flavor-SU(3) state, and $|s(p)\rangle$ the symmetry of the internal spatial wave function of the s quark. For simplicity, we shall neglect the minor component of the spatial wave function and approximate the Λ^* state as a pure p -wave excitation of the strange quark with the (ud) quark pair being in a spin and isospin singlet state configuration.

The internal structure of the emitted hadron is assumed to be of no relevance in the statistical (thermal) model of particle emission; only the mass and the quantum degeneracy matter. The assumption underlying the statistical model is that all S -matrix elements for hadron production are of roughly equal magnitude. This assumption may be justified for the emission of ground-state hadrons, which all have similar spatial quark wave functions. The insensitivity to the hadronic wave function can be demonstrated in the framework of the sudden recombination model in the high-temperature limit, when the source is homogeneous over the size of the hadron [11]. In practice, however, the prevailing conditions at hadronization do not correspond to this limit. The formation temperature of hadrons, $T_{\text{ch}} \approx 160$ MeV, is comparable to the energy scale of hadronic excitations, and the coherence length of quarks just before hadronization is also expected to be similar to the size of a hadron. It is therefore plausible that details of the spatial wave function of the emitted hadron should have an effect on the production yield, leading to deviations from the predictions of the statistical model.

We show below in the framework of the nonrelativistic constituent quark model that the internal p -wave structure of the $\Lambda(1520)$ hyperon leads to a significant suppression of its creation by quark recombination, compared with s -wave baryons. For reasonable choices of the parameters, we find that the suppression is approximately one-half, similar to the experimental observation. The amount of the suppression is quite insensitive to the parameters of our model. Our result suggests that the observed suppression of $\Lambda(1520)$ production in central Au+Au collisions is not the consequence of final-state interactions, but of the production mechanism (quark recombination) itself. The insight that the internal p -wave structure of a hadron can reduce its yield in nuclear reactions was also reached in the framework of a quark-diquark model of baryons [12]. Our work differs from this earlier study by our use of a more realistic internal wave function of the emitted baryon, and it is based on the recombination model rather than the direct reaction model. These qualitative differences have important quantitative consequences; in particular, the use of a proper internal wave function of the baryon is essential for the magnitude of the predicted suppression.

Adopting the convention of Isgur and Karl [10], we denote the positions of the u and d quark by \mathbf{x}_1 and \mathbf{x}_2 , respectively, and the position of the s quark by \mathbf{x}_3 . We assume that the u and d quarks have the same mass m , and the s quark has mass m_s . The Jacobi coordinates are given by

$$\begin{aligned} \mathbf{r}_{\text{c.m.}} &= \frac{m(\mathbf{x}_1 + \mathbf{x}_2) + m_s \mathbf{x}_3}{M}, \\ \mathbf{r} &= (\mathbf{x}_1 - \mathbf{x}_2)/2, \\ \mathbf{r}' &= (\mathbf{x}_1 + \mathbf{x}_2)/2 - \mathbf{x}_3, \end{aligned} \quad (2)$$

where $M = 2m + m_s$ denotes the total mass. We assume that the internal wave functions of the Λ and Λ^* can be written as

$$\begin{aligned} |\Lambda\rangle &= 2^{-1/2} \Phi^s(b_{u/d}, \mathbf{r}) [\chi_u \times \chi_d]^{(0)} \\ &\times \Phi^s(b_s, \mathbf{r}') \chi_s^{(1/2)} |ud - du\rangle s, \end{aligned} \quad (3)$$

$$\begin{aligned} |\Lambda^*\rangle &= 2^{-1/2} \Phi^s(b_{u/d}, \mathbf{r}) [\chi_u \times \chi_d]^{(0)} \\ &\times [\Phi^p(b_s, \mathbf{r}') \times \chi_s]^{(3/2)} |ud - du\rangle s, \end{aligned} \quad (4)$$

where Φ^s and Φ^p are the lowest s - and p -wave eigenstates of the harmonic oscillator:

$$\begin{aligned} \Phi^s(b, \mathbf{r}) &= (\pi b^2)^{-3/4} e^{-r^2/2b^2}, \\ \Phi^p(b, \mathbf{r}) &= (\pi b^2)^{-3/4} \frac{\sqrt{2}\mathbf{r}}{b} e^{-r^2/2b^2}. \end{aligned} \quad (5)$$

We take the radius parameter of the constituent u, d -quark wave functions as $b \approx 0.6$ fm [13] and assume that the parameter scales as usual with the reduced mass: $b_{u/d} = b\sqrt{2}$, $b_s = b\sqrt{M/2m_s}$.

We further assume that the quarks just before hadronization can be described by Gaussian wave packets of the form

$$\Psi(R, \mathbf{D}, \mathbf{k}; \mathbf{x}) = (\pi R^2)^{-3/4} \exp\left(-\frac{1}{2R^2}(\mathbf{r} - \mathbf{D})^2 + i\mathbf{k} \cdot \mathbf{r}\right), \quad (6)$$

where \mathbf{D} denotes the position and \mathbf{k} the momentum of the center of the wave packet. The width parameter R describes the

coherence properties of the initial quarks, which is determined by their mean free path in the hadronizing medium. Such Gaussian wave packets have been used, e.g., in the framework of quark molecular dynamics [14]. Because the magnitude of R is not well known from phenomenological considerations, we shall explore a range of values for R in the vicinity of the confinement radius. We allow R^2 to scale inversely with the quark mass to ensure that quarks become localized in the limit of infinite mass. We further assume that the initial quark momenta \mathbf{k} are given by a thermal distribution with temperature $T = T_{\text{ch}}$. Finally, we assume that the hadrons are formed by recombination in a surface region, which we model as a plane with a Gaussian thickness profile of half-width a . The ensemble distribution for the initial-state wave packet thus has the form

$$F(\mathbf{D}, \mathbf{k}) = \prod_{i=1}^3 \exp\left(-\frac{D_{i,x}^2}{2a^2} - \frac{\mathbf{k}_i^2}{2m_i T}\right). \quad (7)$$

With these model assumptions, the (sudden) transition matrix elements from an uncorrelated three-quark state to the hadronic states (3) and (4) can be easily evaluated. The thermal average and the integration over the hadronization zone can also be performed analytically. We denote the averaged transition probabilities as $W^{(s)}$ and $W^{(p)}$,

$$W^{(s)} = \int \prod_i d\mathbf{D}_i d\mathbf{k}_i F(\mathbf{D}, \mathbf{k}) |\langle \Lambda | \Psi_i \rangle|^2, \quad (8)$$

and the analogous equation giving $W^{(p)}$ for Λ^* formation. The final result for the ratio of the transition probabilities into the Λ and Λ^* states, correcting for their spin(J_Λ, J_{Λ^*}) degeneracies, is

$$\begin{aligned} \frac{(2J_\Lambda + 1)W^{(p)}}{(2J_{\Lambda^*} + 1)W^{(s)}} &= \frac{2b^2}{3(R^2 + b^2)} \left[1 + \left(2 + \frac{R^2 + b^2}{a^2} \right)^{-1} \right. \\ &\quad \left. + 3R^4 \left(2b^2 R^2 + \frac{R^2 + b^2}{mT} \right)^{-1} \right]. \end{aligned} \quad (9)$$

We first note that the ratio tends to one in the limit $R, T \rightarrow \infty$. This is not unexpected as it confirms the result obtained by Fries *et al.* [11]. For finite values of R and T , the ratio is always less than unity, i.e., the production of the p -wave hadron (the Λ^*) is suppressed. This is explored in Fig. 1, which shows the suppression factor (9) as a function of the hadronic size parameter b for several different choices of the quark coherence length R . Remarkably, in the range of realistic values for $b \approx 0.6$ fm, the suppression is insensitive to the precise value of R . This is gratifying, because R is by far the most uncertain parameter in our model. In the large- a limit for the surface thickness, which corresponds to a volume-dominated quark recombination, the suppression factor is found to be slightly (about 10%) enhanced.

Figure 1 shows that the formation of p -wave baryons is suppressed by a factor of 0.5–0.6 in the realistic range of parameters in our model. This is quite close to the suppression, compared with the statistical model prediction, of the $\Lambda(1520)/\Lambda$ ratio in central Au+Au collisions [1]. We do not need to adjust the hadron size parameter b to fit the

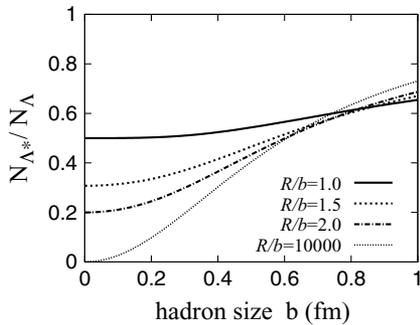


FIG. 1. Suppression factor for the formation of a p -wave baryon by recombination of three quarks from a thermal medium, as a function of the hadron size parameter b for four different choices of coherence length R of the initial-state quarks ($R/b = 1, 1.5, 2, 10^4$). Temperature $T = 160$ MeV; ud -quark mass $m = 330$ MeV; hadronization surface thickness $a = 0.5$ fm.

observed suppression value, because we are using a realistic hadron wave function. We emphasize that this suppression is a formation effect, not an effect of final-state interactions. Within our model, it is predicted that the suppression should be independent of the momentum of the baryon. If high-quality spectra of Λ and Λ^* hyperons can be obtained in future high-statistics runs, this property could perhaps be used to distinguish between the suppression mechanism proposed here and final-state suppression mechanisms. On general grounds, one expects that a suppression effect due to rescattering will diminish with increasing hadron momentum, because the particle spends less time in the medium. Of course, this argument applies only to the momentum range in which recombination is thought to be the dominant hadronization

process ($p_T \leq 4$ GeV/c). Also, relativistic effects may modify our prediction.

In conclusion, we have shown that under the conditions prevailing at hadronization of a quark-gluon plasma, the recombination model predicts that the yield of hadrons with an internal p -wave excitation is suppressed compared with the yield of ground-state hadrons. For the example of $\Lambda(1520)$ versus Λ formation, the suppression factor is calculated to be in the range 0.5–0.6. This prediction is found to be rather insensitive to the precise choice of model parameters. We suggest the mechanism pointed out here may be the origin of the relative suppression, compared with statistical model expectations, of $\Lambda(1520)$ production in central Au+Au collisions at RHIC.

The present work is based on the idea of the recombination model. It extends previous work by taking into account the internal structure of the emitted baryon and obtains the new insight that an internal p wave may result in a reduced hadron yield. We note that the same mechanism affects the production of all p -wave hadrons. It would be interesting to confirm this experimentally, but unfortunately it seems unlikely that the p -wave excitation of any other baryon or meson can be identified in the final state of a heavy ion collision.

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