Strangeness enhancement in the parton model

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Strangeness enhancement in heavy-ion collisions is studied at the parton level by examining the partition of the new sea quarks generated by gluon conversion into the strange and non-strange sectors. The CTEQ parton distribution functions are used as a baseline for the quiescent sea before gluon conversion. By quark counting simple constraints are placed on the hadron yields in different channels. The experimental values of particle ratios are fitted to determine the strangeness enhancement factor. A quantitative measure of Pauli blocking is determined. Energy dependence between CERN-SPS and relativistic heavy-ion collider energies is well described. No thermal equilibrium or statistical model is assumed.

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I. INTRODUCTION

The production of strange particles in heavy-ion collisions has been a subject of intense study in the past twenty years, ever since the proposal that it may reveal a signal of quark-gluon plasma formation [1,2]. Various approaches to the problem have been adopted, ranging from a statistical thermal model [3,4] to a simple quark coalescence model [5,6] to a dual parton model [7]. Despite differences in diverse viewpoints, the major theme is to explain the phenomenon of strangeness enhancement in nuclear collisions [8]. Although the experimental definition of strangeness enhancement is the increase of the strangeness content of the produced hadrons with an increasing number of participants from pp to AA collisions, a more appropriate theoretical description of strangeness enhancement is in terms of the increase of strange quarks before hadronization. In this paper we present a quantitative treatment of the enhancement factor in the framework of the parton model, and obtain a numerical measure of Pauli blocking.

The point stressed in the original explanation for strangeness enhancement [1,2] is that when the quark degrees of freedom are liberated, it is easier to create strange quark pairs than strange hadrons because the $s\bar{s}$ threshold is lower. Deconfinement then leads naturally to the possibility of plasma formation. In our view the quarks have always been the basis for understanding hadron production even in pp collisions for c.m. energy $\sqrt{S}$ a little above 10 GeV. The recombination model has been able to reproduce the low-p_T inclusive distributions in the fragmentation region by treating the hadronization processes at the parton level [9,10]. Thus the relevance of the quark degrees of freedom in heavy-ion collisions at SPS is nothing new. In collisions at such energies the nucleons are broken up and thus deconfined, but it does not mean that there is thermalized quark-gluon plasma, which no one would associate with pp collisions.

Once one descends to the parton level, the notion of strangeness enhancement (SE) can take on a quantitative description in terms of the strange quark population. The baseline for the unenhanced s quark distribution in the quiescent sea should be pinned down by the parton distribution functions of the nucleon studied exhaustively by several groups [11–13]. We shall use the distribution functions of the CTEQ global analysis [11] that fits some 1300 data points obtained for many reactions in 16 experiments. Their extrapolations to $Q^2=1$ (GeV/c)^2 are presented in the form of graphs available on the web in CTEQ4LQ [14]. Since gluons do not hadronize directly, there being no glueballs found, they are converted to quark pairs which subsequently hadronize by recombination. How much the conversion goes into the strange sector gives us a measure of SE.

Gluon conversion is not a new process that we must consider for heavy-ion collisions. Even in hadronic collisions gluons must convert in order to hadronize. Such conversion has been included in the study of inclusive distributions of hadrons produced in the fragmentation region in the framework of the valon-recombination model [10], and more recently using the CTEQ4LQ parton distribution functions [14] to reproduce various hadronic spectra [15]. Our attention in this paper is shifted from the fragmentation region in hadronic collisions, where the x dependence is an issue, to the central region in nuclear collisions, where the relative yields of particles produced are the focus.

Clearly, there is no way to study SE from first principles. Our investigation here is phenomenological. Our goal is very modest. It is not possible to compute particle ratios from the parton model alone. We shall use a large set of particle ratios as experimental inputs to guide us in the determination of the SE factor. The effect of Pauli blocking in the nonstrange sector is included in those inputs, and are not amenable to first-principle calculations. Our theoretical input is essentially the counting of quarks and antiquarks in their partition into the various hadronic channels. In that sense the physics involved is basically the same as in the coalescence model [5,6], which is a simplified version of the recombination model [9]. The emphasis in Refs. [5,6] is in the multiplicative aspect of the probabilities of having quarks and antiquarks in the same region of phase space in their formation of hadrons. That results in an undesirable feature of s and $\bar{s}$ imbalance in the linear version [5], which is not satisfactorily resolved in the nonlinear version [6] by the introduction of unknown factors. Our emphasis here is on the partition of the

q, $\bar{q}$,s, $\bar{s}$ quarks into the hadronic channels and on the enhancement of their populations from gluon conversion. We shall not investigate the implications of the hadron probabilities being products of the quark probabilities.

II. QUARK COUNTING

We begin by drawing the boundary of our concern here. Since the yields on multistrange hyperons are low compared to K and Λ, we shall in first approximation ignore the production of Ξ and Ω, and aim at results with accuracies not better than 90%. With such simplification we can better exhibit the spirit of our approach to the problem and make more transparent the issues involved in SE. Improvements that include the Ξ and Ω particles can be considered later. We shall also consider an isosymmetric dense medium at midrapidity so that we need not distinguish u and d quarks. Protons and neutrons will be equal in number, as will be π^+ and π^-. The strange quarks s and $\bar{s}$ are produced in equal numbers, but K^+ and K^- will not be produced in equal numbers because of associated production.

Let us use the following notation to denote the numbers of hadrons and nonstrange quarks, e.g., N is the number of nucleons, and q is the number of light quarks:

$$N = p + n, \quad \bar{N} = \bar{p} + \bar{n}, \tag{1}$$

$$\Pi = \pi^+ + \pi^- + \pi^0, \tag{2}$$

$$Y = \Lambda + \Sigma^0 + \Sigma^+ + \Sigma^-, \tag{3}$$

$$K = K^+ + K^0, \quad \bar{K} = K^- + \bar{K}^0, \tag{4}$$

$$q = u + d, \quad \bar{q} = \bar{u} + \bar{d}. \tag{5}$$

Then there are linear relations among these numbers based on counting the number of valence quarks in the various hadrons,

$$3N + \Pi + 2Y + K = q, \tag{6}$$

$$3\bar{N} + \Pi + 2\bar{Y} + \bar{K} = \bar{q}, \tag{7}$$

$$Y + \bar{K} = s, \tag{8}$$

$$\bar{Y} + K = \bar{s}. \tag{9}$$

The right-hand sides of the above equations all refer to the numbers of quarks after enhancement from gluon conversion. Let κ be the fraction of s quarks that recombine with nonstrange antiquarks to form antikaons, and similarly $\bar{\kappa}$ the fraction of $\bar{s}$ to form kaons. That is, we define

$$\bar{K} = \kappa s, \quad K = \overline{\kappa s}. \tag{10}$$

Then on account of Eqs. (8) and (9), we have

$$Y = (1-\kappa)s, \quad \bar{Y} = (1-\bar{\kappa})\bar{s}. \tag{11}$$

We define the hadronic ratios

$$r = K/\bar{K}, \quad R = \bar{Y}/Y. \tag{12}$$

It then follows that

$$\kappa = \frac{1-R}{r-R}, \quad \bar{\kappa} = r\kappa, \tag{13}$$

where $s = \bar{s}$ has been used. For experimental values of r and R, we assume that $K/\bar{K} \approx \overline{K^+}/K^-$ and $\bar{Y}/Y \approx \bar{\Lambda}/\Lambda$. For Pb-Pb collisions at SPS the values are [16–18]

$$r = 1.8, \quad R = 0.13, \tag{14}$$

so we obtain

$$\kappa = 0.52, \quad \bar{\kappa} = 0.94. \tag{15}$$

With these values of κ and $\bar{\kappa}$ we can proceed to consider the nonstrange sector. We define

$$\rho = \bar{N}/N \tag{16}$$

so that we can obtain from Eqs. (6) and (7)

$$N = \frac{1}{3\ (1-\rho)}[q - \bar{q} + 3s(\kappa - \bar{\kappa})], \tag{17}$$

$$\Pi = \frac{1}{1-\rho}\{-\rho q + \bar{q} - s[(1+2\rho) \times \kappa - (2+\rho)\bar{\kappa} + 2(1-\rho)]\}. \tag{18}$$

The particle ratios involving abundant strange and nonstrange hadrons are

$$\frac{N}{K} = \frac{1}{1-\rho}\left[\frac{q_v}{3s\bar{\kappa}} + \frac{1}{r} - 1\right], \tag{19}$$

$$\frac{\Pi}{K} = \frac{1}{(1-\rho)\bar{\kappa}}\left[(1-\rho)\frac{q}{s} - \frac{q_v}{s} - (1+2\rho) \times \kappa + (2+\rho)\bar{\kappa} - 2(1-\rho)\right], \tag{20}$$

where q_v denotes the number of valence quarks, i.e., $q_v = q - \bar{q}$. The right-hand side can be determined from parton distributions, assuming that the parameters κ, $\bar{\kappa}$, and ρ are known from experiments. The left-hand side can be related approximately to p/K^+ and π^+/K^+:

$$\frac{p}{K^+} = \frac{N}{K}, \quad \frac{\pi^+}{K^+} = \frac{2\Pi}{3K}. \tag{21}$$

The experimental values of these ratios at SPS are [19,20]

$$\frac{p}{K^+} = 1.0, \quad \frac{\pi^+}{K^+} = 4.76. \tag{22}$$

The value of ρ is [21]

$$\rho = 0.07. \tag{23}$$

With these experimental inputs there should be no difficulty in satisfying Eqs. (19) and (20) by varying the quark numbers.

However, in our approach the quark numbers must fit into our scheme of quark enhancement via gluon conversion. Moreover, there is the issue of precisely what the central region is at which the experimental numbers of the hadron ratios are measured. Clearly, the valence to sea quark ratio depends on the region of small x considered. The experiments do not have a common and unique definition of the central rapidity region. From the theoretical side there is also the ambiguity of how best to treat the soft processes at low p_T in the parton model. For hard processes at high p_T the use of the parton model has become a routine practice with little controversy. However, in extending the consideration to $p_T < 2$ GeV/c phenomenological models are often used without strict adherence to the notion of partons. In this paper we shall stay as closely as possible to the parton model and use the CTEQ4LQ parton distributions [14] at $Q^2 = 1$ (GeV/c)^2, low enough to be sensible and relevant, but not lower, since the reliability of the distribution functions becomes questionable. Besides, analytical formulas for the distribution functions at $Q^2 = 1$ (GeV/c)^2 have been developed in Ref. [22] for easy application.

It is important to be clear that our concerns in this paper are quark numbers, which are denoted by the symbols used in Eq. (5), e.g., u and d, whereas the distribution functions given in Ref. [14] are densities, e.g., $u(x)$ and $d(x)$, distinguished from u and d by the explicit display of their dependencies on x as a notational compromise for brevity. We assume that the central region in which the data are used above corresponds to $x < x_1$ for a particular value of x_1 at a given energy $\sqrt{S}$. Then the quark numbers used in the quark counting are given by

$$u = \int_0^{x_1} dx u(x), \quad d = \int_0^{x_1} dx d(x), \tag{24}$$

and so on. We now simplify our calculation by making a linear approximation of the distribution functions (in x, not $\log x$) in the region $0 < x < x_1$ so that Eq. (24) may be approximated by

$$u = x_1 u(x_0), \quad d = x_1 d(x_0), \tag{25}$$

where $x_0 = x_1/2$. We shall never be concerned with the absolute values of the quark numbers, but only with their ratios, such as u/d, in which case the x_1 factor cancels so that

$$u/d = u(x_0)/d(x_0). \tag{26}$$

Thus x_0 becomes a parameter that determines the quark-number ratios from the quark distributions, and we shall use this procedure even if the distribution functions at small x are not exactly linear. We believe that this procedure is simple and transparent and gives reasonable values of the quark-number ratios for our calculations without making significant errors that would seriously affect our results.

In reality we shall not distinguish u and d quarks, since we shall assume isosymmetry in the AA collisions so that the initial numbers of p and n are the same. The total number of light quarks is $q = u + d$. In considering strangeness enhancement we shall use as a baseline the parton numbers (before enhancement) determined from CTEQ4LQ at $Q^2 = 1$ (GeV/c)^2 and $x = x_0$, and denote them by q_0, s_0, and g_0 for light quarks, strange quarks, and gluons, and identify them with $2x_0[u(x_0) + d(x_0)], 2x_0 s(x_0)$, and $2x_0 g(x_0)$, respectively.

III. GLUON CONVERSION

Before gluon conversion we have q_v valence quarks, $2\bar{q}_0$ nonstrange sea quarks, and $s_0 + \bar{s}_0$ strange quarks. In the case of hadronic collisions, it has been shown that the inclusive distributions of produced hadrons can be reproduced without any free parameters, if the gluons are completely converted to nonstrange sea quarks before hadronization through recombination [15]. Now, in the case of AA collisions we must consider the conversion of gluons to strange quarks in addition to the nonstrange quarks because of Pauli blocking in the light sector. We use γ to denote the fraction in the strange sector. That is, the number of converted strange and nonstrange quarks, labeled with the subscript c, are

$$s_c = \gamma\ g_0, \quad q_c = (1-\gamma) g_0, \tag{27}$$

with the corresponding antiquarks $\bar{s}_c$ and $\bar{q}_c$ being equal in number, respectively. Thus after conversion we have

$$q = q_v + \bar{q}_0 + q_c, \tag{28}$$

$$s = s_0 + s_c. \tag{29}$$

The quark and gluon distributions at x_0 can be either obtained from the graphs posted by CTEQ4LQ [14], or determined numerically from the analytic formulas given in Ref. [22]. We use the latter to fix $q_v, \bar{q}_0, s_0$, and g_0 for every x_0, while q_c and s_c depend on γ. Hence, we have two free parameters, x_0 and γ, to fit the data through the use of Eqs. (19)–(23).

From Eq. (19) one gets $q_v/s = 3.86$. Using that in Eq. (20) yields $\bar{q}/s = 7.53$, whereupon one obtains

$$\frac{\bar{q}}{q} = \frac{1}{1 + q_v/\bar{q}} = 0.66. \tag{30}$$

From Eqs. (27) and (29) we have

$$s = s_0 + \gamma g_0 = q_v/3.86, \tag{31}$$

$$\bar{q}_0 + (1-\gamma) g_0 = 7.53 s; \tag{32}$$

together they give

$$\bar{q}_0 + s_0 + g_0 = 2.21 q_v. \tag{33}$$

This is an equation that depends on CTEQ4LQ distributions only, so we can solve for the value of x_0. The determination of x_0 is facilitated by the analytic formulas for the distributions given in Ref. [22]. The result then determines also the values of q_v, s_0, and g_0, which, when used in Eq. (31), fix γ. The process yields

$$x_0 = 0.135, \tag{34}$$

$$\gamma = 0.08. \tag{35}$$

These values are obtained for the SPS energy only at $\sqrt{S} = 17$ GeV. The value of x_0 is reasonable, but the value of γ seems surprisingly low, since 8% conversion from the gluons seems insufficient to justify the notion of SE.

IV. STRANGENESS ENHANCEMENT

To appreciate the value of γ found above, let us examine the parton numbers before gluon conversion. Our solution of Eq. (33) gives

$$q_v = 0.924, \quad \overline{q}_0 = 0.236,$$

$$s_0 = 0.104, \quad g_0 = 1.7. \tag{36}$$

These values are for each nucleon, so the parton numbers for AA collisions are much larger. From Eq. (27) we have $s_c = 0.136$. Comparing s_c with s_0, we see that the strangeness enhancement factor E_s at the quark level is

$$E_s = \frac{s}{s_0} = 1 + \frac{s_c}{s_0} = 2.3. \tag{37}$$

This indicates quite an appreciable amount of increase of the strange quarks, qualitatively consistent with the hyperon enhancement. The point is that there are so many gluons that an 8% conversion significantly enhances the strangeness content. The remaining 92% conversion to q_c should be compared to 100% conversion in the case of hadronic collisions [15]. Let us call the light quark population in the sea after 100% conversion $\overline{q}_1$, i.e.,

$$\overline{q}_1 = \overline{q}_0 + g_0. \tag{38}$$

Then the change in the sea from pp to AA collisions can be characterized by the ratio B:

$$B = \frac{\overline{q}}{\overline{q}_1} = \frac{\overline{q}_0 + (1-\gamma) g_0}{\overline{q}_0 + g_0} = 0.94. \tag{39}$$

This may be regarded as a numerical factor quantifying Pauli blocking in the light quark sector. Note that it is less than one by only a small amount, but enough to boost E_s from one by more than a factor of 2.

The extension of this consideration to RHIC energies is straightforward. For the energy dependence of x_0 we use the relation

$$x_0 = (S_0/S)^{1/2} \tag{40}$$

to extrapolate to higher energies, since the momentum fraction is scaled by $\sqrt{S}$. From the value of x_0 at SPS where $\sqrt{S} = 17$ GeV, we obtain $\sqrt{S_0} = 2.3$ GeV. Now, holding S_0 fixed, we have the corresponding x_0 value (call it x_0') at $\sqrt{S} = 130$ GeV to be

$$x_0' = 0.0177. \tag{41}$$

The values of q_v, $\overline{q}_0$, s_0, and g_0 at x_0' are (from CTEQ4LQ)

$$q_v' = 0.298, \quad \overline{q}_0' = 0.368,$$

$$s_0' = 0.178, \quad g_0' = 2.458. \tag{42}$$

Note that even before gluon conversion we have $\overline{q}_0'/(q_v' + \overline{q}_0') = 0.55$, which is much larger than $\overline{q}_0/(q_v + \overline{q}_0) = 0.2$. Thus we expect that after gluon conversion the antiparticle/particle ratios will be much closer to one at the higher energy.

As before, we need the experimental inputs at RHIC's. From Refs. [23–25] we have at $\sqrt{S} = 130$ GeV,

$$r = 1.136, \quad R = 0.77, \quad \rho = 0.64. \tag{43}$$

So we get from Eq. (13)

$$\kappa = 0.628, \quad \overline{\kappa} = 0.713. \tag{44}$$

Assuming that γ remains constant, we now can calculate the quark ratios

$$\frac{q_v'}{s'} = 0.8, \quad \frac{\overline{q}'}{s'} = 7.06, \tag{45}$$

which, when used in Eqs. (19) and (20), enable us to calculate the hadron ratios. As a consequence, we obtain

$$\frac{p}{K^+} = 0.71, \quad \frac{K^+}{\pi^+} = 0.18. \tag{46}$$

The latter, compared to the value, 0.21, at SPS, is a 14% decrease and agrees well with the data at RHIC [26], which shows $K^+/\pi^+ = 0.176 \pm 0.004$. For the former we find indirect confirmation from the following ratios reported by STAR [23,27] for $\sqrt{S} = 130$ GeV:

$$\frac{\overline{p}}{p} = 0.65 \pm 0.07, \quad \frac{\overline{p}}{\pi^-} = 0.08 \pm 0.01,$$

$$\frac{K^-}{\pi^-} = 0.149 \pm 0.02, \quad \frac{K^-}{K^+} = 0.88 \pm 0.05.$$

These numbers can be used to imply

$$\frac{p}{K^+} = 0.73 \pm 0.1, \tag{47}$$

which agrees well with the calculated number in Eq.(46). These results give support to our assumption that γ is constant when the energy is increased and to our procedure of treating the energy dependence.

The SE factor becomes at RHIC ($\sqrt{S}=130$ GeV)

$$E_s=\frac{s'}{s'_0}=1+\frac{s'_c}{s'_0}=2.1. \tag{48}$$

Although the gluon density increases by 45% as x_0 decreases to x'_0, the s quark density in the quiescent sea increases by even more, so the net enhacement factor E_s decreases slightly. This small decrease is in agreement with that of the statistical model [28], although the physics is totally different. The Pauli blocking factor becomes

$$B=0.93, \tag{49}$$

which is essentially unchanged from Eq. (39).

V. CONCLUSION

Since we have left out the multistrange hyperons from our consideration, we cannot expect the numbers calculated to be accurate. Moreover, the necessity to use such experimental inputs as r,R, and ρ to determine κ and γ renders the approach highly phenomenological, far from first principles. However, the basic attributes of this line of study are to use the parton model (and the distributions of CTEQ4LQ) as the basis for the investigation of particle ratios in nuclear collisions at the quark level, and to use simple linear relations, Eqs. (6)–(9), based on quark counting as the only constraints among the strange and nonstrange hadrons. We have found consistency within this simple approach, and can successfully describe the energy dependence. We have not assumed thermal equilibrium, nor relied on the statistical model. We have also deliberately avoided treating mesons and baryons as products of quark densities, as has been attempted in Refs. [5,6], since they lead to either $s\neq\bar{s}$ or undetermined constants.

As we have stated at the outset, it is not our aim to predict particle ratios. We have used the experimental values of the ratios to lead us to the determination of the SE factor, E_s, and the Pauli blocking factor, B, defined at the quark level. In so doing we have gained some insight into how the enhancement mechanism works through the process of gluon conversion. We have further learned that a slight suppression of the conversion into the nonstrange sector gives rise to a substantial increase in the strange sector. Such a small change from hadronic to nuclear collisions makes strangeness enhancement an unreliable signature for the formation of quark-gluon plasma.

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