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Sea quark flavor asymmetry of hadrons in statistical balance model

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We suggested a Monte Carlo approach to simulate a kinetic equilibrium ensemble, and proved the equivalence to the linear equations method on equilibrium. With the convenience of the numerical method, we introduced variable splitting rates representing the details of the dynamics as model parameters which were not considered in previous works. The dependence on model parameters was studied, and it was found that the sea quark flavor asymmetry weakly depends on model parameters. It reflects the statistics principle, contributes the dominant part of the asymmetry, and the effect caused by details of the dynamics is small. We also applied the Monte Carlo approach of the statistical model to predict the theoretical sea quark asymmetries in kaons, octet baryons Σ, Ξ, and Δ baryons, even in exotic pentaquark states.

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I. SEA QUARK FLAVOR ASYMMETRY FROM STATISTICAL BALANCE MODEL

Although the proton is the simplest system in which the three colors of QCD neutralize into a colorless bound state, we still do not know how to describe the proton in terms of its fundamental quark and gluon degrees of freedom from basic principles. The structure of the proton is rather complicated due to the nonperturbative and relativistic nature of the quark and gluon in the protons. The complication also comes from the presence of sea quarks in the proton. The sea flavor symmetry naively assumed in the Gottfried sum rule [1], which is a symmetry between the light flavor u and d sea quarks inside the proton, was disproved by experiments of both deep inelastic scattering and Drell-Yan processes [2–7].

Many theoretical attempts have been made to describe the origin of the nucleon sea and its antiquark asymmetry [7–21]. It is assumed that the primary mechanism to generate the sea is gluon splitting into $u\bar{u}$ and $d\bar{d}$ pairs. Field and Feynman [22] suggested that the extra valence u quark in the proton could lead to a suppression of $g \to u\bar{u}$ relative to $g \to d\bar{d}$ via Pauli blocking. But a subsequent calculation [23] found that the effects of Pauli blocking are very small, and this result has been confirmed by another calculation [24]. Thus, it is believed that there must be a nonperturbative origin. For example, the meson cloud inside the nucleon can account for such asymmetry [7–15] and chiral quark models [16–19]. Also the large-N_c approach [20] can explain the flavor asymmetry of the antiquark distribution.

Another attempt to understand the sea flavor asymmetry of the proton is from a pure statistical consideration in a kinetic equilibrium model [21] or “statistical balance model” as called in previous papers. The idea is rather simple and perspicuous: while the sea quark-antiquark $u\bar{u}$ and $d\bar{d}$ pairs can be produced by gluon splitting with equal probabilities, the time-reversal invariant processes of the annihilation of the antiquarks with their quark partners into gluons are not flavor symmetric due to the net excess of u quarks over d quarks. As a consequence, the $\bar{u}$ quarks have a larger probability to annihilate with the u quarks than that of the $\bar{d}$ quarks, and this brings an excess of $\bar{d}$ over $\bar{u}$ inside the proton. Taking the proton as an ensemble of a complete set of quark-gluon Fock states (and assuming that the probability of “arriving in” one state from others equals the probability of “leaving” it), one can obtain the probabilities of finding every Fock state (state density) in the proton. Thus one can calculate the quark and gluon content of the nucleon from a pure statistical consideration. It is interesting that the model gives a sea flavor $\bar{u}$ and $\bar{d}$ asymmetry as $[\bar{d} - \bar{u}] \sim 0.132$, which agrees with the experimental data

The diagram in Fig. 1 can describe the “state shifting” between states.

Assuming kinetic equilibrium, we have these kinetic equilibrium equations

$$\sum_{j\neq i}^{n} c_{ij}\rho_i = \sum_{j\neq i}^{n} c_{ji}\rho_j, \tag{1}$$

where ρ_i is $|i\rangle$ state density, c_{ij} is the non-normalized state-shift probability (NSSP) of $|i\rangle \to |j\rangle$, and n is the total state number. Also there is the normalization condition

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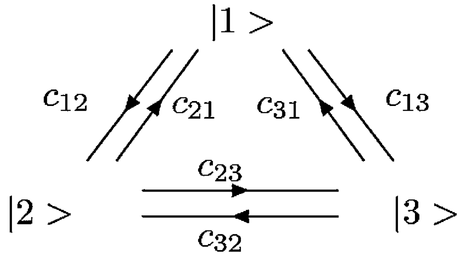

FIG. 1. Diagram describing the shifting between states.

$$\sum_i^n \rho_i = 1. \tag{2}$$

If we know c_{ij}, we can derive state densities ρ_is by solving a system of n linear algebraic equations when n is a finite number. If n is infinite, we can get ρ_i by the asymptotic approach in some cases, if ρ_i converges as $n \to \infty$. Actually, if we change c_{ij} to c_{ij}/C_0, where C_0 is a arbitrary constant, the result would be the same. It means we only need the ratios of NSSP's c_{ij}s.

If only considering the particle numbers of quark, antiquark, and gluon, the proton state can be described as an ensemble of Fock states

$$|uud\rangle, |uudg\rangle, |uudu\bar{u}\rangle, |uudd\bar{d}\rangle, |uudd\bar{d}\rangle, \ldots, \\ \times |N_u, N_d, N_{\bar u}, N_{\bar d}, N_g\rangle, \ldots$$

Because the u quark number $N_u \equiv N_{\bar u} + 2$, and $N_d \equiv N_{\bar d} + 1$, all Fock states can be denoted with just three numbers as $|N_{\bar u}, N_{\bar d}, N_g\rangle$.

In order to derive the state density $\rho_{|N_{\bar u},N_{\bar d},N_g\rangle}$ we should know the probability of states shifting. We introduce the rate $f_{q\to qg}$ as a quark splitting ability factor; there are $2N_{\bar u} + 2N_{\bar d} + 3$ quarks (including antiquarks) in the initial state, so the NSSP of $|N_{\bar u}, N_{\bar d}, N_g\rangle \to |N_{\bar u}, N_{\bar d}, N_g + 1\rangle$ is

$$(2N_{\bar u} + 2N_{\bar d} + 3)f_{q\to qg}. \tag{3}$$

We also introduce a splitting rate $f_{g\to q\bar q}$ and $f_{g\to gg}$, so the NSSP of $|N_{\bar u}, N_{\bar d}, N_g\rangle \to |N_{\bar u}, N_{\bar d} + 1, N_g - 1\rangle$ and $|N_{\bar u}, N_{\bar d}, N_g\rangle \to |N_{\bar u} + 1, N_{\bar d}, N_g - 1\rangle$ is

$$N_g f_{g\to q\bar q}, \tag{4}$$

and the NSSP of $|N_{\bar u}, N_{\bar d}, N_g\rangle \to |N_{\bar u}, N_{\bar d}, N_g + 1\rangle$ is

$$N_g f_{g\to gg}. \tag{5}$$

Now, we consider the time-reversal process and assume those fusion rates

$$f_{qg\to q} = f_{q\to qg}, \qquad f_{q\bar q\to g} = f_{g\to q\bar q}, \qquad f_{gg\to g} = f_{g\to gg}$$

for time-reversal invariance.

Hence, the NSSP of $|N_{\bar u}, N_{\bar d}, N_g\rangle \to |N_{\bar u}, N_{\bar d}, N_g - 1\rangle$ is

$$(2N_{\bar u} + 2N_{\bar d} + 3)N_g f_{qg\to q} + \frac{N_g(N_g - 1)}{2} f_{gg\to g}, \tag{6}$$

the NSSP of $|N_{\bar u}, N_{\bar d}, N_g\rangle \to |N_{\bar u} - 1, N_{\bar d}, N_g + 1\rangle$ is

$$(N_{\bar u} + 2)N_{\bar u} f_{q\bar q\to g}, \tag{7}$$

and the NSSP of $|N_{\bar u}, N_{\bar d}, N_g\rangle \to |N_{\bar u}, N_{\bar d} - 1, N_g + 1\rangle$ is

$$(N_{\bar d} + 1)N_{\bar d} f_{q\bar q\to g}. \tag{8}$$

We can see that the probability of $u\bar u$ annihilation is larger than $d\bar d$ annihilation in all of the proton states because of valence quark asymmetry. This is the origin of the sea quark flavor asymmetry.

It is assumed that all the splitting and fusion rates are the same in the previous papers [21]. If we get all the non-normalized state-shift probabilities c_{ij}, the state densities can be derived out if the particle numbers $N_{\bar u,\bar d,g}$ are finite. We set an artificial limit $N_{\bar u,\bar d,g} \le N_{\max}$ and solve the finite linear equations. The numeric state densities are then derived. The sea quark flavor asymmetry can be written as

$$[\bar d - \bar u] = \sum_{\bar u,\bar d,g} (N_{\bar d} - N_{\bar u})\rho_{|N_{\bar u},N_{\bar d},N_g\rangle}. \tag{9}$$

The sea quark flavor asymmetry converges to 0.133 when $N_{\max}$ increases. The result is consistent with experiment data [2–6]. Some subsequent works [25,26] followed the kinetic equilibrium principle to study the spin of nucleons and the parton distributions in the proton and pion, and obtained quite good results, agreeing with the corresponding experimental values.

However, in the previous works, we assumed that all the splitting rates are the same as $f_{q\to qg} = f_{g\to q\bar q} = f_{g\to g\bar g} \equiv 1$ and we did not estimate the "error bound" caused by the assumption. As we can imagine, if the splitting rates vary in different orders of magnitude, the convergence of flavor asymmetry will be bad. It is necessary to solve large $N_{\max}$ linear equations. So we need a convenient numerical method to explore the effects of different splitting rates and to study more complex hadronic states.

II. MONTE CARLO SIMULATION APPROACH OF A KINETIC EQUILIBRIUM ENSEMBLE

Monte Carlo simulation also can give the numeric state densities instead of solving algebraic equations, even when the number of states is infinite. Here, we want to explain some details about the Monte Carlo evolution on kinetic equilibrium and prove the equivalence between the Monte Carlo evolution approach and solving algebraic equations. Let us start with an arbitrary initial state $|i\rangle$, and then let it make a possible shift during each unit step. The probability of the state $|i\rangle$ shifting to $|j\rangle$ is c_{ij}/C_0. Here, C_0 is an arbitrary large constant we introduced to ensure that the total shifting probability for each prior state is less than 1. It is required that $C_0 > \sum_{j\neq i} c_{ij}$ for all prior states $|i\rangle$, so the probability of staying in the prior state $|i\rangle$ is

$$1 - \sum_{j\neq i} c_{ij}/C_0. \tag{10}$$

The state evolves step-by-step as random walk, and we record the number of iteration steps as T_i while the state $|i\rangle$ is emerging. And after a large number of iteration steps T, the normalized $|i\rangle$ emerging probability is T_i/T. For each step while the state is $|i\rangle$, the next step has the probability c_{ij}/C_0 to be $|j\rangle$. So there are the times $T_i c_{ij}/C_0$ of state shifting $|i\rangle \longrightarrow |j\rangle$. Of course, other states also can shift to $|j\rangle$; meanwhile $|j\rangle$ has chance to stay at $|j\rangle$. That means the number of those steps $|j\rangle$ emerging should be

$$T_j = \sum_{i\neq j} c_{ij}/C_0 T_i + \Big(1 - \sum_{i\neq j} c_{ji}/C_0\Big) T_j. \tag{11}$$

The equation can be reduced to

$$\sum_{i\neq j} c_{ij} T_i = \sum_{i\neq j} c_{ji} T_j. \tag{12}$$

The equation is independent of the constant C_0. The value of C_0 only determines the number of iteration steps needed to arrive at the equilibrium state after starting from an arbitrary initial state. We can find the above equation is just the kinetic equilibrium equation (1), if we consider that the normalized $|i\rangle$ emerging probability T_i/T is equivalent to the state density as

$$T_i/T = \rho_i. \tag{13}$$

And we also have the sum condition

$$\sum_i T_i = T, \tag{14}$$

which is equal to the normalization condition Eq. (2). Hence, we proved the equivalence of the Monte Carlo simulation approach and solving algebraic equations.

The Monte Carlo simulation approach provides a powerful method for solving kinetic equilibrium ensemble problems. This method is error-controllable and very useful especially on complex multistate systems, such as the applications to other hadrons in the following sections. We gain the same value of the sea quark flavor asymmetry 0.132 ± 0.02 in the proton as expected. Here, the error bar ± 0.02 is the standard deviation of results with different random number series, and the deviation will decrease when computing time increases.

III. DYNAMICS-NONSENSITIVE SEA QUARK FLAVOR ASYMMETRY IN THE PROTON

The fusion rate should be the same as the splitting rates for a time-reversal process. In other words, the evolution in the proton should be time-reversal invariant. But there is no principle that requires that the quark and gluon splitting evolution abilities of $g \longrightarrow q\bar{q}(gg)$ and $q \longrightarrow qg$ are equal. Therefore we should introduce three splitting rates $f_{q\to qg}$, $f_{g\to q\bar{q}}$, and $f_{g\to gg}$, to represent the quark and gluon splitting evolution abilities which are determined by the dynamics of quarks and gluons. Each rate enhances the corresponding splitting or fusion evolution probability. In previous works, we assumed that all the splitting rates are the same, to be $f_{q\to qg} = f_{g\to q\bar{q}} = f_{g\to g\bar{g}} \equiv 1$ and we did not estimate an "error band" caused by the assumption. In the present work, we introduced a numerical Monte Carlo approach. This new method is easy to apply to complex systems, and it is easy to put the variable splitting rates in evolutions and calculate the deviation caused by them.

In the above section, we can see that the state densities or results are independent of the constant C_0. The numerical value of $f_{g\to q\bar{q}}$, for example, is input as $f_{g\to q\bar{q}}/C_0$. Therefore the result does not depend on the absolute value of $f_{g\to q\bar{q}}$. It means that the sea quark asymmetry does not depend on the absolute values of those splitting rates. Only two ratios between three splitting rates will affect the state densities and the value of sea quark flavor asymmetry. So, we can fix the rate $f_{q\to qg} \equiv 1$, and vary the other two ratios $f_{g\to q\bar{q}}/f_{q\to qg}$ and $f_{g\to gg}/f_{q\to qg}$ as two parameters in the model.

In Table I, the values of sea quark asymmetry for different ratios of splitting rates are listed. The previous result 0.132 ± 0.02 is reproduced when $f_{g\to q\bar{q}}/f_{q\to qg} = f_{g\to gg}/f_{q\to qg} = 1$.

From Table I, we can see that the asymmetry value $[\bar{d} - \bar{u}]$ is not sensitive to the model parameter $f_{g\to q\bar{q}}/f_{q\to qg}$; it is almost fixed when $f_{g\to q\bar{q}}/f_{q\to qg}$ varies in a very large range over five order of magnitudes. We also can find that the values of asymmetry are always larger than 0.123, whatever the splitting rates vary even over an arbitrary

TABLE I. The values of sea quark asymmetry for different ratios of splitting rates.

$[\bar{d} - \bar{u}] \times 100$ $f_{g\to gg}/f_{q\to qg}$	$f_{g\to q\bar{q}}/f_{q\to qg}$ 100	10	1	0.1	0.01	0.001
0	123 ± 2	124 ± 2	124 ± 2	124 ± 3	125 ± 3	126 ± 6
1	131 ± 2	132 ± 2	132 ± 2	134 ± 3	135 ± 3	136 ± 6
2	137 ± 2	138 ± 3	140 ± 3	140 ± 4	141 ± 3	141 ± 6
5	150 ± 2	152 ± 3	153 ± 3	154 ± 3	156 ± 4	156 ± 7
10	161 ± 3	163 ± 3	164 ± 4	164 ± 3	165 ± 5	166 ± 8
100	179 ± 4	180 ± 4	180 ± 4	180 ± 3	181 ± 5	182 ± 9

large range. This reflects the principle of statistics and contributes the dominant part of sea quark flavor asymmetry. The asymmetry only has a variation $[\bar{d} - \bar{u}] = (0.12\text{–}0.16)$ which is within 30% when $f_{g\to gg}/f_{q\to qg}$ varies in the range $0 \le f_{g\to gg}/f_{q\to qg} \le 10$, and still a small variation $[\bar{d} - \bar{u}] = (0.12\text{–}0.18)$ even when $f_{g\to gg}/f_{q\to qg}$ varies in a larger magnitude range $0 \le f_{g\to gg}/f_{q\to qg} \le 100$. So the effect brought from details of the dynamics is small and within the bound of the experiments' uncertainty.

By now, we do not consider the probability of $g \to ggg$ splitting and $ggg \to g$ recombination, because the probability is suppressed by a coupling constant and "three-body" splitting kinematics. $g \to ggg$ can be regarded as two successive $g \to gg$, and its effect is the same as the effect of increasing $f_{g\to gg}$, as we can see from Table II. However, the rate of three-body splitting $g \to ggg$ must be much smaller than two-body splitting $g \to gg$ or $q \to qg$, because the three-body phase space in perturbative QCD is suppressed by the factor of 2–3 orders of magnitudes compared with the two-body splitting. Though the parton splitting in hadrons is a strong-coupling nonperturbative process, we believe that we still can safely assume $f_{g\to ggg}/f_{q\to qg} \ll 0.1$ which only causes a very small enhancement as shown in Table II. The effect of the splitting $g \to ggg$ is thus negligible.

Because the effect of the splitting $g \to ggg$ and recombination $ggg \to g$ is negligible and the asymmetry value of $[\bar{d} - \bar{u}]$ is almost independent of the parameter $f_{g\to q\bar{q}}/f_{q\to qg}$, there is only one parameter $f_{g\to gg}/f_{q\to qg}$ that can vary the asymmetry. This parameter is QCD relevant and it is the only input from dynamics. If the parameter could be fixed by analysis of QCD, the deviation on sea quark asymmetry caused by the details of dynamics could be determined and the sea quark flavor asymmetry in proton is predictable.

These two splitting vertices are QCD vertices and have the same coupling constant. The splitting kinematics of $g \to gg$ and $q \to qg$ are also similar. So, the splitting rates of $g \to gg$ and $q \to qg$ should be in the same order of magnitude. The assumption can be supported by the integrations of Altarelli-Parisi (AP) splitting functions. Though these equations are valid in the perturbative region and the parton splitting in hadrons is a nonperturbative process, the ratio of the total splitting rates is still inspirational. The ratio parameter $f_{g\to gg}/f_{q\to qg}$ can be heuristically "derived" from Altarelli-Parisi splitting functions [27].

TABLE II. The values of sea quark asymmetry $[\bar{d} - \bar{u}] \times 100$ for different value of $f_{g\to ggg}/f_{q\to qg}$, for $f_{g\to qg} = 1$, $f_{q\to gg} = 1$, $f_{g\to q\bar{q}} = 1$, and $f_{g\to ggg} = f_{ggg\to g}$.

$f_{g\to ggg}/f_{q\to qg}$						
0	0.1	0.2	0.4	0.6	0.8	1.0
132 ± 2	135 ± 2	137 ± 2	142 ± 3	145 ± 3	148 ± 3	150 ± 4

The AP splitting functions are

$$P(q \to q(z)g) = C_F \frac{1 + z^2}{1 - z},$$

$$P(g \to g(z)g) = C_A\left[\frac{1 - z}{z} + \frac{z}{1 - z} + z(1 - z)\right],$$

$$P(g \to q(z)\bar{q}) = T_R[z^2 + (1 - z)^2],$$

where the color factors $C_F = 4/3$, $C_A = 3$, and $T_R = 1/2$.

The integrations of AP splitting functions are assumed to be the total probabilities of quarks and gluons splitting. So the splitting rates directly are

$$f_{q\to qg} = \int_0^{1-z_{\min}} P(q \to q(z)g)dz,$$

$$f_{g\to gg} = \int_{z_{\min}}^{1-z_{\min}} P(g \to g(z)g)dz,$$

$$f_{g\to q\bar{q}} = \int_0^1 P(g \to q(z)\bar{q})dz.$$

The rates $f_{q\to qg}$ and $f_{g\to gg}$ are logarithmic divergent when the integration limit $z_{\min} \to 0$, but fortunately the ratio between the two rates is not divergent, and thus we have the model parameter

$$\frac{f_{g\to gg}}{f_{q\to qg}} = \frac{\int_{z_{\min}}^{1-z_{\min}} P(g \to g(z)g)dz}{\int_0^{1-z_{\min}} P(q \to q(z)g)dz} \to \frac{C_A}{C_F} = \frac{9}{4},$$

when $z_{\min} \to 0$. The ratio parameter is not sensitive to the integration limit $z_{\min}$. For example, when $z_{\min} = 0.1$, the ratio is 2.01 which is close to 9/4. Such a small deviation change on parameter $f_{g\to gg}/f_{q\to qg}$ does not have an effect on sea quark asymmetry. Considering that the integration limit is relative to Q^2 scale, then the model parameter $f_{g\to gg}/f_{q\to qg}$ and sea quark asymmetry are not sensitive to the Q^2 scale. We estimated the ratio parameter by the perturbative AP splitting functions and it is just the ratio of color factors. We assume the parameter value is still similar in the nonperturbative region.

The nonsensitive parameter $f_{g\to q\bar{q}}/f_{q\to qg}$ also can be derived by the above method. But it is relevant to the integration limit or Q^2 scale. The dependence can be extracted as $\frac{-0.075T_R}{C_F \log z_{\min}}$ when $z_{\min}$ is small on the order of magnitude and becomes zero when $z_{\min} \to 0$. For example, the value of parameter $f_{g\to q\bar{q}}/f_{q\to qg} = 0.005$ when $z_{\min} = 10^{-6}$, and the value is not sensitive to the magnitude of $z_{\min}$ or Q^2 scale because of its $\log z_{\min}$ dependence. We can see from Table. I, the sea quark asymmetry is not sensitive to this parameter even though it is so small.

As discussed above, the ratio $f_{g\to gg}/f_{q\to qg}$ is almost fixed to a ratio of color factors as 9/4 and the asymmetry is independent of other details except the parameter $f_{g\to gg}/f_{q\to qg}$. Therefore we arrived at the following

TABLE III. $\int[\bar{d}(x) - \bar{u}(x)]dx$ as determined by three experiments. The range of the measurement is shown along with the value of the integral over all x ($Q^2 = 54\ \mathrm{GeV}^2/c^2$).

Experiment	x range	$\int_0^1[\bar{d}(x) - \bar{u}(x)]dx$
E866	$0.015 < x < 0.35$	0.118 ± 0.012
NMC	$0.004 < x < 0.80$	0.148 ± 0.039
HERMES	$0.020 < x < 0.30$	0.16 ± 0.03

conclusion: after considering the detail of QCD, especially the color factors, we can predict the sea quark flavor asymmetry in the proton is 0.142 ± 0.03. It is enhanced a little compared to the value given in the previous papers. More precise measurement of $[\bar{d} - \bar{u}]$ is needed to examine the statistical balance model.

The x-dependent $[\bar{d}(x) - \bar{u}(x)]$ can be derived from deep inelastic scattering and Drell-Yan processes, and $\int_0^1[\bar{d}(x) - \bar{u}(x)]dx$ is given by extrapolating $[\bar{d}(x) - \bar{u}(x)]$ to $x \longrightarrow 0$ and $x \longrightarrow 1$. The sea quark asymmetry values from three collaborations are listed in Table. III—they are all consistent with the sea quark asymmetry value predicted above. The value of E866 seems a little bit smaller compared to the prediction value, but the x range of the E866 measurement is narrow and the uncertainty brought by extrapolating to small x is out of control. So, more precise measurements are needed to test the prediction.

IV. SEA QUARK FLAVOR ASYMMETRY IN MESONS

Because the sea quark asymmetry value is not sensitive to details of dynamics and only depends on the parameter $f_{g\to gg}/f_{q\to qg}$ which is almost fixed as 9/4, then it should not only work for the proton, but also for the mesons and other baryons. We suppose the statistical model also has validity on predicting sea quark asymmetry in other hadrons. M. Alberg, E. M. Henley [26], and C.-B. Yang [28] derived the parton distributions of pions according the statistical model, but the sea quark asymmetry is zero because of the same valence quark number in pions. While the valence quark numbers of the u and d quarks are different for the kaons, for example, $K^+(u\bar{s})$ has one u valence quark and no d valence quark. The statistical balance model predicts the sea quark asymmetry value $\bar{d} - \bar{u} = 0.284$ in K^+, when $f_{g\to gg}/f_{q\to qg} = 9/4$. In the same way, the sea quark asymmetry value $[\bar{d} - \bar{u}] = -0.275$ in $K^0(d\bar{s})$ and $[d - u] = -0.275$ in $\bar{K}^0(\bar{d}s)$, $d - u = 0.275$ in $K^-(\bar{u}s)$. These sea quark asymmetry values are also not sensitive to dynamics as shown in Table IV.

We can see from Table IV that the asymmetry $[\bar{d} - \bar{u}]$ is independent of $f_{g\to q\bar{q}}/f_{q\to qg}$ and varies in a small range 0.263–0.31 as $f_{g\to gg}/f_{q\to qg}$ varies in a large range 0–10.

TABLE IV. The values of sea quark asymmetry $\bar{d} - \bar{u}$ in K^+ for different split factors.

$[\bar{d} - \bar{u}]$	$f_{g\to q\bar{q}}/f_{q\to qg}$				
$f_{g\to gg}/f_{q\to qg}$	100	10	1	0.1	0.01
0	0.263	0.264	0.264	0.264	0.265
0.1	0.264	0.265	0.265	0.266	0.266
1	0.272	0.274	0.275	0.277	0.278
5	0.296	0.300	0.303	0.304	0.305
10	0.311	0.312	0.312	0.312	0.313

V. SEA QUARK FLAVOR ASYMMETRY IN BARYONS

We also use our statistical model to predict sea quark asymmetry for baryons. In a previous paper [29], L. Shao *et al.* derived the octet baryons' sea quark asymmetry values by the method of solving linear equations. They give $[\bar{d} - \bar{u}] = 0.41$ in $\Sigma^+(uus)$ and $[\bar{d} - \bar{u}] = 0.276$ in $\Xi^+(uss)$. In this paper, we get the same number by the Monte Carlo approach. We can find that the sea quark asymmetry value in $\Xi^+(uss)$ is almost the same as the meson $K^+(u\bar{s})$ because their u and d valence quark numbers are the same. So, in the statistical model, the s valence quark number in the hadron has a negligible effect on the $[\bar{d} - \bar{u}]$ sea quark asymmetry. We also find the sea quark asymmetry values in the octet baryons are not sensitive to details of dynamics—they just depend on the valence quark numbers in those baryons. The asymmetries $[\bar{d} - \bar{u}]$ in $\Sigma^+(uus)$ and $\Xi^+(uss)$ are enhanced a little to be 0.42 and 0.285 when $f_{g\to gg}/f_{q\to qg} = 9/4$.

Besides octet baryons, we also derived Δ baryons' sea quark asymmetry value as

$$\bar{d} - \bar{u} = 0.50 \quad \text{for } \Delta^+(uuu),$$

$$\bar{d} - \bar{u} = 0.14 \quad \text{for } \Delta^+(uud),$$

$$\bar{d} - \bar{u} = -0.14 \quad \text{for } \Delta^0(udd),$$

$$\bar{d} - \bar{u} = -0.50 \quad \text{for } \Delta^-(ddd),$$

where $f_{g\to gg}/f_{q\to qg} = 9/4$. The sea quark asymmetry in $\Delta^+(uud)$ is the same as in the proton because of their same u and d valence quark numbers. Of course, the asymmetry in $\Delta^0(udd)$ is the same as in the neutron.

We also derived exotic baryons' (pentaquark states) sea quark asymmetry values as:

$$\bar{d} - u = -0.14 \quad \text{for } \Phi^{--}(ssdd\bar{u}),$$

$$d - \bar{u} = 0.14 \quad \text{for } \Phi^-(ssuu\bar{d}),$$

where the sea quark asymmetry values are the same as in the proton because of their same $u(\bar{u})$ and $d(\bar{d})$ valence quark numbers.

If there is such a pentaquark state $X^{++}(uuud\bar{s})$, then its sea quark asymmetry value would be $[\bar{d} - \bar{u}] = 0.21$ derived by the statistical model.

TABLE V. The sea quark asymmetry values for different u, d valence quark numbers $f_{g\to gg}/f_{q\to qg} = 9/4$.

Asymmetry values d valence quark number	u valence quark number 0	 1	 2	 3
0	0	$0.284(K^+, \Xi^0)$	$0.42(\Sigma^+)$	$0.50(\Delta^{++})$
1	$-0.284(K^0, \Xi^-)$	$0(\Lambda^0, \Sigma^0)$	$0.14(P, \Delta^+, \Phi^-)$	$0.21(uuud\bar{s})$
2	$-0.42(\Sigma^-)$	$-0.14(N, \Delta^0, \Phi^{--})$	$0(\Theta^+, \Theta_c)$	$0.07(uuudd\bar{s}\,\bar{s})$
3	$-0.50(\Delta^-)$	$-0.21(dddu\bar{s})$	$-0.07(uuddd\bar{s}\,\bar{s})$	0

VI. CONCLUSIONS

In the previous works in the statistical balance model, the sea quark flavor asymmetry $[\bar{d} - \bar{u}] \equiv \int dx(\bar{d}(x) - \bar{u}(x))$ in the proton was computed using the "linear equations method." Because of the difficulty and limit of the linear equations method, it is hard to apply the method to more complex systems. It is also assumed that all the splitting rates are the same, $f_{q\to qg} = f_{g\to q\bar{q}} = f_{g\to g\bar{g}} \equiv 1$ in the previous works, and the "error band" caused by the assumption was not estimated. In the present work, we introduced a numerical Monte Carlo approach. This new method is easy to apply to complex systems, such as other mesons and baryons. We also introduced the variable splitting rates representing details of the dynamics and we studied the dependence on them. We find the sea quark flavor asymmetry in the proton is always larger than 0.123 whatever the splitting rates vary even over an arbitrary large range. It reflects that the statistics principle contributes the dominant part of the asymmetry. The asymmetry is almost independent of the model parameter $f_{g\to q\bar{q}}/f_{q\to qg}$ and only changes within 30% when $f_{g\to gg}/f_{q\to qg}$ varies in the range 0–10. So the effect caused by details of the dynamics is small and within the bound of the experiments' uncertainty. However, these two splitting vertices are QCD vertices and have the same coupling constant. The splitting kinematics of $g \to gg$ and $q \to qg$ are also similar. So the splitting rates of $g \to gg$ and $q \to qg$ should be in the same order of magnitude. The assumption can be supported by the integrations of Altarelli-Parisi splitting functions. Though these equations are valid in the perturbative region, one may heuristically assume that the ratio of the total splitting rates obtained from them holds approximately also in the nonperturbative regime. The parameter $f_{g\to gg}/f_{q\to qg}$ can be fixed to the ratio of color factors as $9/4$ by integrations of Altarelli-Parisi splitting functions. According to the above reasons, we can conclude that the prediction only from a statistics principle has an accuracy $<30\%$. Or, in other words, the details of the dynamics only bring less than 30% effect. After considering the details of QCD, especially the color factors, the sea quark flavor asymmetry in proton is enhanced to 0.142 ± 0.03 which is consistent with present experimental measurements and can be tested by more precise measurements.

The sea quark asymmetries are not sensitively dependent on the details of dynamics. The sea quark flavor asymmetry derived only from statistics principle contributes the dominant part of the asymmetry. It strongly implies that the origin of the sea quark flavor asymmetry of hadrons is the asymmetry of valence quarks. We also applied this Monte Carlo approach of statistical model to predict the sea quark asymmetries in kaons, octet baryons Σ, Ξ, and Δ baryons, even in exotic pentaquark states. All these asymmetries only depend on the valence quarks number in those hadrons. The sea quark asymmetries for different u and d valence quark numbers are listed in Table V. These values can confirm the mechanism we proposed to explain the sea quark asymmetry in the proton. It can be observed from Table V that the sea quark asymmetries are enhanced by the difference of corresponding valence quark numbers and suppressed by the sum of valence quark numbers. When the valence quark numbers $[u_v] > [d_v]$, the sea quarks $\bar{u}$ are easier to annihilate because of the existence of more u valence quarks and it leads the sea quark asymmetry. On the other hand, the larger total number of valence quark $[u_v + d_v]$ suppresses the relative difference of valence quarks and weakens the sea quark asymmetries even if $[u_v - d_v]$ remains the same. These sea quark asymmetries for hadrons, except the proton, are listed purely for theoretical interest, as it is not known presently how to access this information in experiment.

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