Colour Connection and Diquark Fragmentation in 
$e^+e^- \rightarrow c\bar{c}q\bar{q} \rightarrow h'$s Process

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Abstract

The hadronization effects induced by different colour connections of $c\bar{c}q\bar{q}$ system in $e^+e^-$ annihilation are investigated by a toy model where diquark fragmentation is employed based on Pythia. It is found that the correlations between the charm baryons and charm antibaryons produced via diquark pair fragmentation are much stronger, and their momentum spectra are harder than those from the standard colour connection in Pythia.

keywords: Colour Connection, Diquark, Hadronization

The hadronization for partons fragmenting into hadrons is very important, and can only be treated by hadronization models up to now. The colour connection plays a crucial rôle to set the “surface” between the Perturbative Quantum Chromodynamics (PQCD) phase and the hadronization one, while the topic related to the colour connection is beyond the approach of PQCD. It is argued that some clues can be drawn from analyzing the decomposition of the colour space of the final partons produced in PQCD phase [1–3]. For the colour space of the parton system, there are many decomposition ways corresponding to various colour connections, respectively (see, e.g., [4, 5]). Hence, it is instructive to study the special properties of the final hadrons, which could give information for the evidence of specific colour connections. Such kinds of investigation have been made for various parton systems [6–8]. One interesting and important example is the $(q_1\bar{q}_2q_3\bar{q}_4)$ system produced via hard collisions. This is the simplest system where many phenomena/mechanisms related to QCD properties could be studied, e.g., (re)combination of quarks in producing special hadrons, influence on reconstruction of intermediate particles (like $W^\pm$) by soft interaction, etc., most of which more or less relate with the colour connections among the four (anti)quarks. In this letter, the possible colour connections of this system are briefly reviewed. It is pointed out that the hadronization effects of one kind of the colour connections have never been modeled yet. Its special case (diquark pair fragmentation) in $e^+e^-$ annihilation is investigated in detail.

For $q_1\bar{q}_2q_3\bar{q}_4$ system, two of the decomposition ways of its colour space are given as follows:

$$(3_1 \otimes 3_2^* \otimes (3_3 \otimes 3_4^*) = (1_{12} \oplus 8_{12}) \otimes (1_{34} \oplus 8_{34}) = (1_{12} \otimes 1_{34}) \oplus (8_{12} \otimes 8_{34}) \oplus \cdots, \quad (1)$$

$$(3_1 \otimes 3_4^*) \otimes (3_3 \otimes 3_2^*) = (1_{14} \oplus 8_{14}) \otimes (1_{32} \oplus 8_{32}) = (1_{14} \otimes 1_{32}) \oplus (8_{14} \otimes 8_{32}) \oplus \cdots, \quad (2)$$

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where 3, 3*, 1, 8 respectively denote the representations triplet, anti-triplet, singlet and octet of the Group $SU_c(3)$, and the subscripts correspond to the relevant (anti)quarks. In these two colour decompositions, quark and antiquark form a cluster/string which fragments into hadrons independently. This picture is adopted in the popular hadronization models (for detail, see [9–12]). The difference between these two decompositions leads to the colour reconnection phenomena as discussed in the processes $e^+e^- \to W^+W^-/Z^0Z^0 \to q_1\bar{q}_2q_3\bar{q}_4 \to 4$ jets at LEP II [2, 8, 13–16], etc. One might also notice, in the $e^+e^- \to q_1\bar{q}_1 + g^* \to q_1\bar{q}_1q_2\bar{q}_2$ process, $(q_1\bar{q}_1)$ and $(q_2\bar{q}_2)$ cannot be in colour-singlets, while $(q_1\bar{q}_2)$ and $(q_2\bar{q}_1)$ are usually treated as colour-singlets and hadronize independently. This corresponds to the term $1_{14} \otimes 1_{32}$ in eq. (2) [17].

The colour space of $q_1\bar{q}_2q_3\bar{q}_4$ system can also be decomposed as follows:

$$(3_1 \otimes 3_3) \otimes (3_2 \otimes 3_4^*) = (3_{13}^* \otimes 6_{13}) \otimes (3_{24} \oplus 6_{24}^*) = (3_{13}^* \otimes 3_{24}) \oplus (6_{13} \otimes 6_{24}^*) \oplus \cdots , \quad (3)$$

where $6_{13}$ ($6_{24}^*$) denotes the representation sextet (anti-sextet) of the Group $SU_c(3)$. A special case is that two quarks in colour state 3* attract each other and form a “diquark” when their invariant mass is small enough, and similarly two antiquarks form an antidiquark. For this decomposition, only the whole four (anti)quarks system can form a colour singlet, hence they must hadronize altogether. This hadronization picture is quite different from that adopted in the popular hadronization models. Unfortunately, this picture has not been taken into account though it is crucial and exists indeed in many processes. One example is the exclusive $B^- \to \pi^- + D^0$ decay as shown in fig. (1) where $b \to c + W^{- \to} c + d + \bar{u}_1$. In this process, the quark-antiquark pairs $d\bar{u}_1$ and $c\bar{u}$ are in colour-singlet, and naturally form two mesons $\pi^-$ and $D_0$ (fig. (1)(a)). Here the combination for $d\bar{u}$ and $c\bar{u}_1$ is also possible. These two combinations correspond to the colour connections shown in eqs. (1) and (2), respectively. The branching ratio of $B^- \to \pi^- D^0$ has been measured to be $(4.98 \pm 0.29) \times 10^{-3}$ [18]. In the meantime, it is very interesting to notice that another kind of colour connection corresponding to eq. (3) exists, i.e., the $cd$ and $\bar{u}\bar{u}_1$ are in colour state 3* and 3, and combine with a $d$ or $\bar{d}$ from vacuum to form two baryons $\Sigma^0_c$ and $\bar{p}$, respectively. This is a 'signal channel' for diquark-antidiquark pair fragmentation, and its branching ratio is $(0.45^{+0.26}_{-0.19} \pm 0.007 \pm 0.12) \times 10^{-4}$ [19]. Additionally, the three body baryonic decay processes such as $B^- \to \Lambda_c \bar{p}\pi^-$ ($Br = (2.1 \pm 0.7) \times 10^{-4}$ [18]) can also be regarded to be induced by diquark fragmentation. Another example is the doubly-heavy baryon production in high energy collisions [20, 21]. Recently, SELEX Collaboration observed the hadronic production of $\Xi_{cc}^+$ at
Fermilab [22]. This is dominated by the production of $cc$ pair in PQCD process, and can also give an unambiguous confirmation of the existence of the diquark fragmentation.

The aim of this letter is to investigate the diquark fragmentation in $e^+e^- \rightarrow q_1\bar{q}_1 q_2\bar{q}_2 \rightarrow h's$ process. The accumulated/accumulating data in various $e^+e^-$ colliders can provide sufficient statistics to study the hadronization of the four quark states. In order to specify different colour connections of the four quark system via measuring the corresponding hadron(s), we focus on the $e^+e^- \rightarrow c\bar{c}q\bar{q} \rightarrow h's$ process, where $q$ represents $u$, $d$, or $s$ quark. The ensemble properties related to a class of hadrons (e.g., charm baryons) are investigated, so that we can search for the quantities which could be measured in experiments. The statistics can also be enhanced by studying a group of hadrons.

As mentioned above, the hadronization of the colour connection displayed in eq. (3) has not been considered in popular hadronization models. However, one can employ the event generator Pythia [10] based on Lund model [9], to describe the hadronization of the special case that both $cq$ (in $3^*$) and $\bar{c}\bar{q}$ (in $3$) have small invariant masses so that they can be regarded as diquark and antidiquark, respectively. For this specific case, there are strong constrains on both colour state and phase space. Therefore it is important to investigate the fraction of this specific case, and relevant properties, at parton level.

**Parton level analysis** At leading order QCD, the differential cross section for $e^+e^- \rightarrow c\bar{c}q\bar{q}$ process (fig. 2) can be written as

$$d\sigma = \frac{1}{2s} d L_{ips4} |M|^2;$$

(4)

where $s$ is the total energy square, $L_{ips4}$ represents the 4-particle phase space and $|M|^2$ is the spin averaged-summed invariant amplitude square. At the energy of B factories (e.g., $\sqrt{s} = 10.52 GeV$), we calculate the joint distribution $d^2N/(dm_1dm_2)$ where $m_1$ and $m_2$ respectively represent the invariant mass of $cq$ and $\bar{c}\bar{q}$. In our calculation, we take $q = u$ as an example, and set the precise structure constant to be $1/137$, the strong coupling constant $\alpha_s = 0.2$, the quark masses $m_c = 1.5 GeV/c^2$ and $m_u,d = 0.3 GeV/c^2$. The corresponding results are shown in fig. 3. It is important to notice that the production probability is not quite small when $m_1$ and $m_2$ are close to the diquark mass $^5$.

Especially, when the luminosity is large, the absolute event number with diquark pair production could be large enough to be measured. Employing the KEK B factory integrated luminosity ($525.828 fb^{-1}$ until Dec. 23, 2005) we obtain the number of the events with $m_1, m_2 \leq 2.5 GeV/c^2$ to be around $3 \times 10^4$. The number of events for $q = d$ or $q = s$ is at the same order.

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$^5$The diquark mass is around $2 GeV/c^2$ set by Pythia.
It is well known that in the $e^+e^- \rightarrow \gamma^* \rightarrow f\bar{f}$ process, the polar angle distribution of the massless spin $1/2$ fermion ($f\bar{f}$) is predicted to be $1 + \cos^2\theta$. For the 2-jet events initialized by $e^+e^- \rightarrow q\bar{q}$ at energies much smaller than $M_Z/2$, this will be approximately reproduced for the local parton hadron duality. For the two clusters $cq$ and $\bar{c}\bar{q}$ fragmentation, the event shape is very close to 2-jet event. If the polar angle distribution in this case is much different from the lowest order one, it can be expected as a possible signal to identify diquark pair fragmentation at B factory energy. The corresponding distributions with $m_1, m_2 \leq 2.5 GeV$ are shown in fig. 4. Obviously the distribution is quite different from $1 + \cos^2\theta$, where $\theta$ refers to the angle between the cluster $cq$ momentum and the $e^-$ momentum.

Before investigating the hadronization effects induced by different colour connections, we discuss the theoretical uncertainties caused by quark mass, parton shower, etc. For charm quark mass, it is general to take the value between $1.2 GeV/c^2$ to $1.8 GeV/c^2$, and for light quark mass, the same value as that in Pythia is adopted. For $e^+e^- \rightarrow c\bar{c}q\bar{q}$ ($q = u, d$) process, we calculate its cross section $\sigma(m_q)$ with respect to light quark mass $m_q$. At the same time, we investigate the production cross section $\sigma(m_c)$ of $e^+e^- \rightarrow c\bar{c}c\bar{c}$. The ratios for $\sigma(m_i)/\sigma(m_0)(i = q, c)$ with $m_{q0} = 0.33 GeV/c^2$ and $m_{c0} = 1.5 GeV/c^2$ are shown in fig. 5(a). One can find that the cross section for $e^+e^- \rightarrow c\bar{c}q\bar{q}$ process is not quite sensitive to the light quark mass with charm mass fixed. This implies that the small light quark mass does not introduce any more dangerous singularities. The differential distributions $1/\sigma d\sigma/dM_{cq/cc}$ are displayed in fig. 5(b). It is easy to find that the shape of the distributions for $e^+e^- \rightarrow c\bar{c}q\bar{q}$ and that for $e^+e^- \rightarrow c\bar{c}c\bar{c}$ (fig. 5(b)) are quite similar, and a similar study on doubly charm diquark fragmentation for four charm process might also be plausible. We also compare our results for the cross section of $e^+e^- \rightarrow c\bar{c}c\bar{c}$ with those given in [23], and find completely agreement. The cross section for four quark production in $e^+e^-$ annihilation at high energies (eg., LEPI and LEP2) may be affected by the gluon radiation, which is simulated by parton shower process in Pythia. Fortunately, at B factory energies, $\sqrt{s} \sim 10 GeV$, the largest energy of each quark is about $5 GeV$. If it could radiate gluons further, its virtuality will quickly
reach the lower limit that perturbative QCD can be applied safely. As a result, the parton shower process at B factory energies would not play an important rôle as that at LEP energies. When one investigates physics for the $e^+e^- \rightarrow h's$ process at LEP or even higher energies, the parton shower process must be taken into account. Unfortunately, till now, it is still unclear how to describe the gluon radiation from diquark pair in $e^+e^-$ annihilation. As the first step of the investigation, we concentrate on the physics at the B factory energy, where the influence of gluon radiation seems to be small and could be neglected.

**Hadronization** For the $e^+e^- \rightarrow c\bar{c}q\bar{q}$ process, when $m_1$ and $m_2$ near the mass threshold of diquark, we employ Pythia to investigate the differences in final hadron states corresponding to two kinds of colour connections. One is that $cq$ and $\bar{c}\bar{q}$ form diquark-antidiquark pair, and hadronize altogether. In the picture of Lund model, diquark and antidiquark are in $3^*$ and 3 colour state, respectively. As a result, one colour string will be stretched between them, and the string will fragment into hadrons at the end. The other case is that $c\bar{q}$ and $\bar{c}q$ form two colour singlet clusters (strings). These two strings will fragment into hadrons independently. This hadronization picture is widely adopted in the popular event generators, and hereafter we denote it as '2-string fragmentation’. The hadronization of these two cases can be treated by the corresponding subroutines in Pythia. For simplicity, we fix the invariant masses of the (anti-)quark pair $cq$ ($\bar{c}\bar{q}$) to be the (anti)diquark mass used in Pythia. The results obtained under this simplification can be considered as a good approximation of the average over a reasonable (hence small) range of $cq/\bar{c}\bar{q}$ cluster mass. It is straightforward to adopt that the quantities we calculate in this section is not sensitive to the cluster mass in a small range around the diquark mass set by Pythia. By a similar argument, we also assume the inner orbital angular momentum of the $cq$ ($\bar{c}\bar{q}$) cluster to be 0. However, for treating the second kind of colour connection, the inner relative movements between $c$ ($\bar{c}$) and $q$ ($\bar{q}$) are still not fixed and generated with the relative weight given by the differential cross section at parton level discussed above.

![Figure 4: Normalized polar angle distribution of diquark $cq$ (solid histogram). The dashed curve is for the normalized $1 + \cos^2\theta$ distribution.](image)
Figure 5: (a) The dependence of cross section on quark mass for $e^+e^- \to c\bar{c}q\bar{q}$ process (solid line) and $e^+e^- \to c\bar{c}c\bar{c}$ process (dashed line). (b) The normalized distribution $1/\sigma \, d\sigma/dM$ for $e^+e^- \to c\bar{c}q\bar{q}$ process (solid line) and $e^+e^- \to c\bar{c}c\bar{c}$ process (dashed line).

Figure 6: (a) $X_p \,(= \frac{p}{p_{max}})$, with $p_{max} = \sqrt{\frac{s}{4} - m^2}$) spectra of $\Lambda_c$ at $\sqrt{s} = 10.52 GeV$, from diquark fragmentation (solid line), 2-string fragmentation (dashed line) and $e^+e^- \to c\bar{c} \to \Lambda_c + X$ (dotted line). (b) Comparing with data [24]. The histograms correspond to three different baryon production scenarios in Pythia: solid line for 'diquark', dotted line for 'simple popcorn', dashed line for 'advanced popcorn'.
In the diquark pair fragmentation process, it is straightforward that diquark tends to fragment into baryon, which is in general the leading particle. If the charm baryons from the diquark fragmentation are detected, their momentum spectra should be harder than those from the 2-string fragmentation, or those from the general $e^+e^- \rightarrow c\bar{c} \rightarrow h's$ process. This feature can be displayed by the momentum (fraction) spectra of $\Lambda_c$ at $\sqrt{s} = 10.52\text{GeV}$ (fig. 5(a)). Recently, the momentum spectra of various charm hadrons have been measured by BELLE Collaboration [24]. To make full use of the available data and to identify whether the diquark fragmentation events exist or not, we must make clear to what extent Pythia can reproduce the data. For charm meson production, we find that the predictions of Pythia agree to the available data quite well (also see [25]). For our aim, we concentrate on the investigation of charm baryon (eg., $\Lambda_c$) production. In Pythia, there are three scenarios to describe baryon production, i.e., diquark, simple popcorn and advanced popcorn. Their predictions can be consistent with each other provided that the relevant parameters are tuned (fig. 6(b), the parameters all take default values except $\text{PARJ}(1) = 0.2, \text{PARJ}(18) = 0.19$ and $\text{PARF}(192) = 0$ for advanced popcorn). From fig. 5(b), one can find that the distributions of $\Lambda_c$ predicted by standard Pythia are slightly softer than the data, while the momentum spectrum obtained by diquark fragmentation is slightly harder. It is also interesting to notice that for the diquark fragmentation process, the small momentum region is slightly enhanced for the mass effect (fig. 5(a)). This phenomenon is also indicated by the data shown in fig. 6(b), though the statistical error is too large to give a definite conclusion. Because of the phase space limit, the probability of diquark pair production may not be large. As a result, the predictions for $\Lambda_c$ production including the diquark pair production will not conflict with the available data, and a portion of diquark fragmentation events is favoured.

For further investigation, we calculate thrust distribution $1/N dN/dT$ for the diquark fragmentation, 2-string fragmentation and $e^+e^- \rightarrow c\bar{c} \rightarrow h's$ process (fig. 7(a)). One can find that the thrust distribution of the diquark fragmentation is much 'thinner' than those of the other cases (fig. 7(a)). Aware that the diquark fragmentation events are mostly 2-jet like, we compare the thrust distributions of the diquark fragmentation is much 'thinner' than those of the other cases (fig. 7(a)). We use the JADE algorithm with $y_{cut} = 0.12$. In this case, around 90% diquark fragmentation events are 2-jet. The properties are similar to those without jet constraint (fig. 7(b)). According to these discussions, further experimental investigation of the colour connections shown in eq. (3) can be done by selecting 2-jet charm events at the B factory, and choosing those with large thrust (say, larger than 0.85).

It is natural that in the fragmentation of diquark-antidiquark pair, a baryon is produced together with an antibaryon. That means, the correlation between charm and anti-charm baryons in the diquark pair fragmentation is much stronger than that in the single charm quark fragmentation (either the 2-string fragmentation or the general $e^+e^- \rightarrow c\bar{c} \rightarrow h's$). We know that, in the latter two cases, the production probability for charm meson is much larger than that for charm baryon. This phenomenon can be illustrated by the baryon ($B$) antibaryon ($\bar{B}$) correlation, defined as,

\[ A(B\bar{B}) = \frac{2N(B\bar{B})}{N(B) + N(\bar{B})}, \]

where $N(B\bar{B})$, $N_B$ and $N_{\bar{B}}$ respectively denote the probability for finding $B\bar{B}$ pair, $B$ and $\bar{B}$. We take the correlation of $\Lambda_c$ and $\bar{\Lambda}_c$ as an example in Table 1. One can notice that the correlation in the diquark pair fragmentation process is stronger than the other cases by about 10 times. This correlation is not sensitive to the gluon radiation of the diquark pair so we also give the results at $Z^0$ pole. This quantity could be a good probe for the diquark pair fragmentation. The results for other charm baryons, such as $\Sigma_c$, $\Xi_c$ and the corresponding spin-3/2 particles are similar.

To summarize, we investigate the hadronization effects induced by different colour connections of four quark system (eg., $c\bar{c}q\bar{q}$) in $e^+e^-$ annihilation. It is interesting to point out that besides the normal colour structure with two colour singlets $c\bar{q}$ and $q\bar{c}$ which fragment into hadrons independently in the popular models, there exists another kind of colour structure, as shown in eq. (3).
Figure 7: Thrust distributions of three cases at $\sqrt{s} = 10.52\, GeV$. (a) Diquark fragmentation (solid line), 2-string fragmentation (dashed line) and $e^+e^- \to c\bar{c} \to h's$ (dotted line). (b) Same as (a) except that we select 2-jet events, with JADE Algorithm and $y_{cut} = 0.12$.

| $\sqrt{s}$  | $e^+e^- \to c\bar{c} \to h's$ | Diquark Fragmentation | 2-string |
|------------|-----------------------------|-----------------------|----------|
| 10.52GeV   | 0.057                       | 0.76                  | 0.044    |
| 91.19GeV   | 0.081                       | 0.72                  | 0.081    |

Table 1: $\Lambda_c\bar{\Lambda}_c$ flavor correlations.
which has to be taken into account in some cases. For that colour connection, needless to say, the hadronization of these four quarks should be treated as a whole system, i.e., they interact among each other during the hadronization process. In this letter, considering an extreme limit case that $cq$ and $c\bar{q}$ form diquark-antidiquark pair, we propose a toy model based on Pythia to describe the hadronization of them. It is found that the results originated from diquark fragmentation are significantly different from those of the ordinary colour connections. However because of the phase space limit, the hadronization effect from diquark pair fragmentation is not very large. To understand the hadronization mechanism induced by different colour connections of final partons produced perturbatively, further theoretical and experimental investigations are still necessary.

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