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Exclusive $\Omega_{ccc}^{++}\bar{\Omega}_{ccc}^{--}$ Production from Z^0/γ^* Decays *

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Based on the quark model the cross section for the $e^+e^- \to Z^0/\gamma^* \to \Omega_{ccc}^{++}\bar{\Omega}_{ccc}^{--}$ exclusive process is investigated at the tree level. Compared with the $Z^0 \to \Omega^-\bar{\Omega}^+$ decay, our result shows that the Z^0 boson favors decaying into charmed baryon pairs. The results are also compared with the calculation of inclusively charmed baryon production.

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In the quark model, charmed baryons belong to the $SU(4)$ multiplets made of light quarks, strange quarks and charmed quarks. Searches for the charmed baryon have been a topic in particle physics in the existent high-energy experiments. Nowadays, there are 17 candidate baryons of singly charmed quarks established in experiment,[1] such as Λ_c, Σ_c, Ξ_c and Ω_c baryons. However, few of the decay properties and spin parity quantum numbers are measured in experiments. The LHC and Belle Ⅱ experiments will provide us with an ideal laboratory to search for charmed baryons. Very recently, two narrow baryon states with charmed quarks, Ω_c^0 and Ξ_{cc}^{++},[2,3] were discovered in the LHCb experiments.

The triply charmed baryon Ω_{ccc}^{++} is the charmed quark version of the Ω^- baryon with replacement of three strange quarks by charmed quarks in the quark model. Due to the totally symmetric configuration of charmed quarks, the Ω_{ccc}^{++} baryon is assumed as an interesting bound state to study the three-body static potential. However, no information from experiments is available. Its mass, lifetime and other properties were studied over past years.[4–7] The cross section for the Ω_{ccc}^{++} inclusive production from gluon fusions was predicted for the LHC experiment,[7] and the prospects to search for the Ω_{ccc}^{++} baryon produced via quark coalescence mechanism in the high-energy nuclear collisions were discussed in Refs. [4,8].

Another mechanism for the Ω_{ccc}^{++} production is from the weak decays of Z^0 boson. The abundant production of Z^0 boson in the LHC or super Z-factory[9] will provide us with another laboratory to search for the charmed baryons. The Ω_{ccc}^{++} inclusive production from Z^0 decays has been investigated based on the assumption that a $c\bar{c}$ quark pair is produced from Z^0 weak decays, and then a charmed quark evolves into a Ω_{ccc}^{++} baryon by emitting gluons and fragmentation into the triply charmed baryon. In this ansatz, the total cross section for the $e^+e^- \to Z^0 \to \Omega_{ccc}^{++}(\bar{c}\bar{c}\bar{c})$ process was calculated to be 0.04 fb.[10]

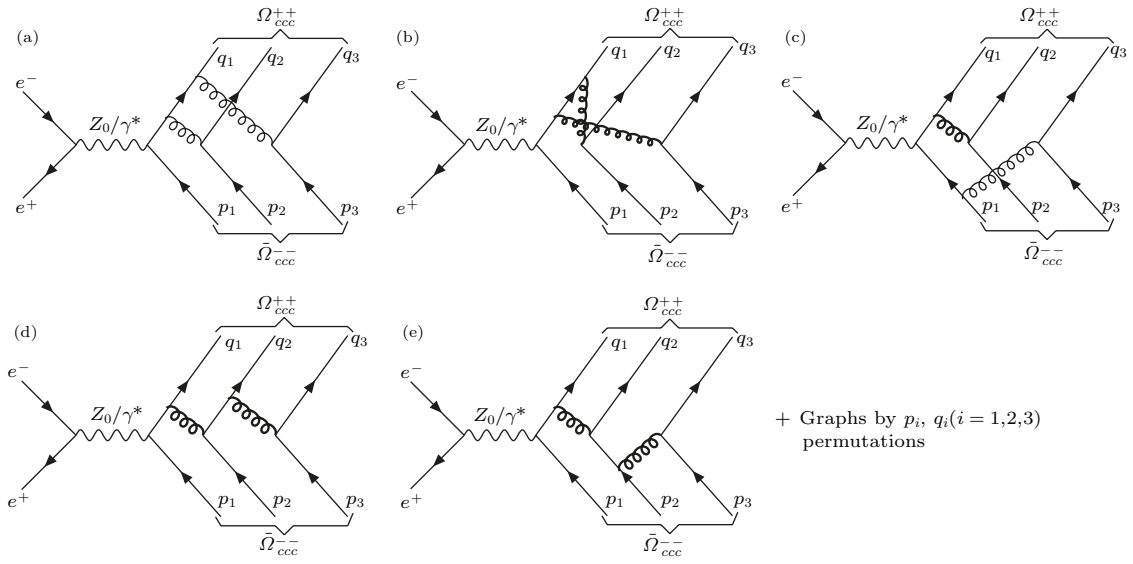


Fig. 1. Feynman diagrams for the process $e^+e^- \to Z^0/\gamma^* \to \Omega_{ccc}^{++}\bar{\Omega}_{ccc}^{--}$. The cross diagrams for the interchanging $ccc \leftrightarrow \bar{c}\bar{c}\bar{c}$ are implied.

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In this work, we investigate the production of charmed baryons from the $e^+e^- \to Z^0/\gamma^* \to \Omega_{ccc}^{++}\bar{\Omega}_{ccc}^{--}$ process. Compared with the situation of inclusive production, the exclusive production of baryons make the calculation comparable with the experimental results unambiguously. Since it is well known that the baryon number is conserved in the strong and weak interaction, the number of baryons and antibaryons produced from the Z^0 decays should be the same. However, this requirement is impossible to implement in the calculation of inclusive production, and thus it overestimates the baryon production rate.

We consider the $\Omega_{ccc}^{++}\bar{\Omega}_{ccc}^{--}$ pair produced from the e^+e^- annihilation via the electromagnetic and weak processes, i.e., $e^+e^- \to Z^0/\gamma^* \to c\bar{c}$. Then the $c\bar{c}$ quark pair is further fragmented into $3(c\bar{c})$ by assumption of the gluon emission mechanism $g \to c\bar{c}$. At tree level, the $c\bar{c}$ quark fragmentation is described by the processes shown in Fig. 1, together with the diagrams for $ccc \leftrightarrow \bar{c}\bar{c}\bar{c}$ interchanges, which are implied throughout this work. The final stage is the transition of three charmed/anti-charmed quarks into the charmed $\Omega/\bar{\Omega}$ baryons. There are a total of 360 graphs considered in the calculation either for the Z^0 or virtual photon processes. The cross section for the process $e^+e^- \to 3(c\bar{c})$ will be calculated in the framework of perturbative QCD (pQCD). However, the quark–hadron transition is a nonperturbative process, and we use the baryon wave function to parameterize this process.

Firstly, let us consider the neutral weak current contribution, and the Lagrangian takes the form as

$$\frac{g}{2\cos\theta}\sum_i \bar{\psi}_i\gamma^\mu(g_{\rm V}^i - g_{\rm A}^i\gamma^5)\psi_i Z_\mu, \tag{1}$$

where $g_{\rm V}^e = -\frac{1}{2} + \sin^2\theta$, $g_{\rm A}^e = -\frac{1}{2}$, and $g_{\rm V}^c = -\frac{1}{2} - \frac{4}{3}\sin^2\theta$, $g_{\rm A}^c = \frac{1}{2}$, and θ is the weak angle.

For the decay $Z^0 \to e^-(p,s)e^+(q,\bar{s})$, the decay amplitude reads

$$\bar{M}_{s\bar{s}} = \frac{g_z}{2}\bar{v}(q,\bar{s})\not{\epsilon}(g_{\rm V}^e - g_{\rm A}^e\gamma^5)u(p,s), \tag{2}$$

where s and $\bar{s}$ denote spins, p and q denote momenta, and the free Dirac spinors are normalized as $u^+u = v^+v = 2E$. Then one has the decay width

$$\begin{aligned}\Gamma_{e^+e^-} &= \frac{1}{8\pi}\sum_{s\bar{s}}|\bar{M}_{s\bar{s}}|^2\frac{|\boldsymbol{p}|}{M_Z^2}\\ &= \frac{\sqrt{2}G_{\rm F}}{12\pi}M_Z^3({g_{\rm V}^e}^2 + {g_{\rm A}^e}^2),\end{aligned} \tag{3}$$

where $|\boldsymbol{p}| = \frac{M_z}{2}$, M_Z is the mass of Z^0 boson, and $G_{\rm F}$ is the Fermi coupling constant.

The cross section for the $e^+e^- \to Z^0 \to \Omega_{ccc}^{++}\bar{\Omega}_{ccc}^{--}$ process reads

$$\sigma = \frac{4\pi(2J+1)}{2\cdot 2M_Z^2}\frac{\Gamma_{e^+e^-}\Gamma_{\Omega_{ccc}^{++}\bar{\Omega}_{ccc}^{--}}}{(E-M_Z)^2 + \frac{1}{4}\Gamma^2}, \tag{4}$$

where Γ is the full width of the Z^0 boson, the factor $2\cdot 2$ accounts for the average over e^+e^- spins, and J is the spin of Z^0 boson. Here $\Gamma_{\Omega_{ccc}^{++}\bar{\Omega}_{ccc}^{--}}$ is the decay width for the $Z^0(S_Z) \to \Omega_{ccc}^{++}(Q,S)\bar{\Omega}_{ccc}^{--}(P,\bar{S})$ decay, and is estimated with the decay amplitude

$$\begin{aligned}M_{S\bar{S}S_z} &= \langle\psi_B(Q,S)\psi_{\bar{B}}(P,\bar{S})|\mathcal{M}|Z^0(S_z)\rangle\\ &= \int\prod_{i,j=1}^{3}\left[\frac{d^3p_i}{2p_i^0}\right]\left[\frac{d^3q_j}{2q_j^0}\right]\\ &\quad\times\langle\psi_B(Q,S)\psi_{\bar{B}}(P,\bar{S})|\prod p_i\bar{s}_iq_j\bar{s}_j\rangle\\ &\quad\times\langle\prod p_i\bar{s}_iq_j\bar{s}_j|\mathcal{M}|Z^0\rangle\\ &\quad\times\delta^3(\boldsymbol{p}_1+\boldsymbol{p}_2+\boldsymbol{p}_3-\boldsymbol{P})\\ &\quad\times\delta^3(\boldsymbol{q}_1+\boldsymbol{q}_2+\boldsymbol{q}_3-\boldsymbol{Q}),\end{aligned} \tag{5}$$

where $\psi_B(Q,S)$ and $\psi_{\bar{B}}(P,\bar{S})$ are the wave functions for Ω_{ccc}^{++} and $\bar{\Omega}_{ccc}^{--}$ with momenta Q, P and total spin S and $\bar{S}$, respectively. By inserting the free quark states p_i and s_i for charm quarks and q_i, $\bar{s}_i$ for anti-charm quarks, into the amplitude matrix element, the baryonic wave functions are expanded in the flavor-spin and momentum space. The delta functions ensure the momentum conservation for quarks transition into baryons.

If the mass of the Ω_{ccc}^{++} baryon is taken as 4.8476 GeV, predicted in the quark model,[11] the outgoing charmed baryon carries momentum $p = 45.3$ GeV. Hence, the transverse momenta for bounded charm/anti-charm quark are negligible compared with the longitudinal momenta, and the baryonic wave functions are approximated in collinear direction. The amplitude is calculated in the helicity frame, and the outgoing directions for baryon and anti-baryon are chosen as the z and $-z$ axis directions, respectively. One has

$$\begin{aligned}M_{S\bar{S}S_z} &= \int\prod\left[\frac{p_i dx_i}{2p_i^0}\right]\left[\frac{q_j dy_j}{2p_i^0}\right]\\ &\quad\times\langle\psi_B^{\parallel}(Q,S)\psi_{\bar{B}}^{\parallel}(P,\bar{S})|\prod p_i\bar{s}_iq_j\bar{s}_j\rangle\\ &\quad\times\langle\prod p_i\bar{s}_iq_j\bar{s}_j|\mathcal{M}|Z^0\rangle\\ &\quad\times\delta(x_1+x_2+x_3-1)\\ &\quad\times\delta(y_1+y_2+y_3-1),\end{aligned} \tag{6}$$

where x_i and $y_i (i = 1,2,3)$ are the fraction of momentum carried by charm and anti-charm quarks, respectively.

The matrix elements for the $Z^0 \to 3(c\bar{c})$ transition are calculated by

$$\mathcal{M} = \langle\prod_{i,j} p_i\bar{s}_iq_j s_j|\sum_k \mathcal{M}^{(k)}|Z^0\rangle, \tag{7}$$

where matrix elements $\mathcal{M}^{(k)}$ are calculated using the standard Feynman rule according to all diagrams as shown in Fig. 1. For example, the amplitude for

Fig. 1(a) reads

$$\begin{aligned}\mathcal{M}^{(a)} =& \frac{g_z}{2}\mathcal{C}\bar{u}(q_1,s_1)\gamma_\mu \frac{\not{q}_1 - \not{q}_3 - \not{p}_3 + m}{(q_1-q_3-p_3)^2-m^2}\gamma_\nu \\ &\times \frac{\not{q}_1 - \not{p}_2 - \not{p}_3 - \not{q}_2 - \not{q}_3 + m}{(q_1-q_2-q_3-p_2-p_3)^2-m^2}\not{\epsilon} \\ &\times (g_{\rm V}^c - g_{\rm A}^c\gamma_5)v(p_1,\bar{s}_1)\bar{u}(q_2,s_2)\gamma^\nu \\ &\times v(p_2,\bar{s}_2)\frac{\bar{u}(q_3,s_3)\gamma^\mu v(q_3,\bar{s}_3)}{(q_2+p_2)^2(p_3+q_3)^2}, \end{aligned} \tag{8}$$

where $\mathcal{C}=\frac{4}{9}$ is the color factor, $u(q_i,s_i)$ and $v(p_j,\bar{s}_j)$ are the Dirac spinors for free charmed quarks. The graphs for the $p_i\bar{s}_i \leftrightarrow q_i s_i$ interchanges are implied for the $ccc \leftrightarrow \bar{c}\bar{c}\bar{c}$ cross diagrams. The decay width for the $Z^0 \to \Omega_{ccc}^{++}\bar{\Omega}_{ccc}^{--}$ decay is calculated by

$$\Gamma_{\Omega_{ccc}^{++}\bar{\Omega}_{ccc}^{--}} = \frac{1}{16\pi}\frac{\sum|M_{S\bar{S}S_Z}|^2}{M_Z}\frac{8\pi^2}{3}, \tag{9}$$

where the factor $1/3$ accounts for the average over the Z^0 spins, and 8π factor comes from the integration over the Wigner-D function in the helicity amplitude.

Finally, let us consider the contributions from the electromagnetic process $e^+e^- \to \gamma^* \to c\bar{c}$. The diagrams are the same as that for the neutral current process, but only differ in the coupling constants. The amplitudes are calculated by making a replacement of coupling constant in Eq. (1) with

$$g_{\rm V}^i = Q^i,\ g_{\rm A}^i = 0,\ \frac{g}{\cos\theta} = ie, \tag{10}$$

where Q^i is the charge for the ith quark.

The inclusion of the baryonic wave function is essential in our model to account for the transition of free quarks into hadrons. However, little information about baryon structures from the perturbative QCD theory is known, since the hadron lies out of the asymptotic region. Phenomenologically, the properties of charmed baryons are described with the bound-state wave functions in the naive quark model. The flavor-spin wave function of the charmed baryon is symmetric and constructed in the representation of the $SU(4)\otimes SU(2)$ group

$$\Psi_{\rm FS} = \Psi_{\rm F}^B\chi(S), \tag{11}$$

where the flavor $\Psi_{\rm F}^B$ and spin wave function $\chi(S)$ are explicitly expressed by

$$\begin{aligned}\Psi_{\rm F}^B =& |ccc\rangle,\ \Psi_{\rm F}^{\bar{B}} = |\bar{c}\bar{c}\bar{c}\rangle, \\ \chi\Big(\frac{3}{2}\Big) =& |\uparrow\uparrow\uparrow\rangle, \\ \chi\Big(\frac{1}{2}\Big) =& \frac{1}{\sqrt{3}}(|\uparrow\uparrow\downarrow\rangle + |\uparrow\downarrow\uparrow\rangle + |\downarrow\uparrow\uparrow\rangle), \\ \chi\Big(-\frac{1}{2}\Big) =& \frac{1}{\sqrt{3}}(|\downarrow\downarrow\uparrow\rangle + |\downarrow\uparrow\downarrow\rangle + |\uparrow\downarrow\downarrow\rangle), \\ \chi\Big(-\frac{3}{2}\Big) =& |\downarrow\downarrow\downarrow\rangle. \end{aligned}$$

We assume that the spatial distribution for charmed quarks in a baryon can be described by a simple harmonic-oscillator eigenfunction in their center-of-mass (c.m.) system, i.e.,

$$\Psi(\boldsymbol{k}_{12},\boldsymbol{k}_{23}) = \frac{1}{(\pi^2\alpha_{12}\alpha_{23})^{3/4}}\exp\Big(\frac{-\boldsymbol{k}_{12}^2}{2\alpha_{12}} - \frac{\boldsymbol{k}_{23}^2}{2\alpha_{23}}\Big), \tag{12}$$

where $\boldsymbol{k}_{ij} = \boldsymbol{k}_i - \boldsymbol{k}_j$ is the momentum difference between quarks i and j, and α_{ij} is the harmonic oscillator parameter. The quark masses and α_{ij} can be obtained from global fitting to the baryon spectroscopy. We quote the results obtained with the Hamiltonian[11]

$$H = \sum(m_l^2 + \boldsymbol{p}_l^2)^{1/2} + \sum_{l<m}\frac{1}{2}K\boldsymbol{r}_{lm}^2 + \sum_{l<m}U_{lm} + H_0, \tag{13}$$

where K is the spring constant, and U_{lm} is the Breit–Fermi term. The global fit yields masses of doubly charmed baryon with the expected accuracy of $\pm 10\,$MeV. Then the mass of Ω_{ccc}^{++} baryon is calculated to be $4847.6\,$MeV with the fitted parameters: $m_{\rm c} = 1952.97\,$MeV, $\alpha_{12} = \alpha_{23} = 0.189\,{\rm GeV}^2$. Here the charm quark mass is model dependent, and it is different from the value $m_{\rm c} = 1275.0\,$MeV in the PDG.[1]

In the e^+e^- c.m. system, the outgoing baryon carries large momentum. To boost the baryonic wave function from its c.m. system to the e^+e^- c.m. system will bring about significant Lorentz contraction. In general, the Lorentz transformation includes two aspects. One is the Lorentz boost of the spatial wave functions from the charmed baryon rest frame to the e^+e^- c.m. system; the other is the Melosh rotation of quark spinors. For simplicity, the free Dirac quark spinors have been factored out and calculated in the e^+e^- c.m. system. We only perform the Lorentz transformation for the spatial wave function as

$$\Psi(\boldsymbol{p}_{12},\boldsymbol{p}_{23}) = \Big|\frac{\partial(\boldsymbol{k}_{12},\boldsymbol{k}_{23})}{\partial(\boldsymbol{p}_{12},\boldsymbol{p}_{23})}\Big|^{1/2}\Psi(\boldsymbol{k}_{12},\boldsymbol{k}_{23}), \tag{14}$$

where $\boldsymbol{p}_{ij}$ is the momentum difference between i,j-quark in the laboratory system, and the collinear wave function is obtained by integrating the transverse momentum of the bound quarks. One has

$$\Psi^{\parallel}(\boldsymbol{p}_{12},\boldsymbol{p}_{23}) = \int d\boldsymbol{p}_{12}^{\perp}d\boldsymbol{p}_{23}^{\perp}\Psi(\boldsymbol{p}_{12},\boldsymbol{p}_{23}). \tag{15}$$

The strong running constant $\alpha_{\rm s}(Q^2)$ up to next-to-leading-log is written as

$$\alpha_{\rm s}(Q^2) = \pi\Big[\frac{1}{\beta_1 L} - \frac{\beta_2}{\beta_1}\frac{\ln L}{(\beta_1 L)^2}\Big], \tag{16}$$

with $L = \ln(Q^2/\Lambda_{\rm QCD}^2)$, $\beta_1 = (33-2n_f)/12$, $\beta_2 = (153-19n_f)/24$, $n_f = 4$, and $\Lambda_{\rm QCD} = 0.25\,$GeV.

With these parameters, the partial decay width for $Z^0 \to e^+e^-$ is calculated to be $8.34\times10^{-2}\,$GeV, which is comparable with the measurement $(8.39\pm0.01)\times10^{-2}\,$GeV.[1] At the Z^0 peak, the cross section from virtual photon process is suppressed by a factor of 2.7×10^{-3} respective to the Z^0 contribution,

and is negligible. Before we present the numerical results, it is worthwhile to examine the amplitudes by counting the α_s power multiplied by the gluon propagators. Two $c\bar{c}$ quark pairs are created and accompanied by two gluon propagators $1/(p_i+q_i)^2$. Hence the amplitude squared is suppressed by a factor of $\alpha_s^4/(p_i+q_i)^8 \sim \alpha_s^4/(M_z/3)^8$. Considering the branching fraction $Br(Z^0 \to c\bar{c}) = 12.03\%$,[1] the branching fraction for $Br(Z^0 \to \Omega_{ccc}^{++}\bar{\Omega}_{ccc}^{--})$ is suppressed by a factor of 6.4×10^{-17}. If one incorporates the contributions from the baryon wavefunctions to count for the triply charmed quark distribution, the branching fraction becomes even smaller. To cancel uncertainties associated with the parameters, we normalize the cross section with the decay $Z^0 \to \Omega^-\bar{\Omega}^+$ with the strange quark mass taken as $m_s = 0.538\,\text{GeV}$, and the ratio is determined to be

$$\frac{\sigma(e^+e^- \to Z^0 \to \Omega_{ccc}^{++}\bar{\Omega}_{ccc}^{--})}{\sigma(e^+e^- \to Z^0 \to \Omega^-\bar{\Omega}^+)} = 1.81 \times 10^2.$$

The result indicates that though the Lorentz contraction effect for baryon wave function is non-negligible, the quark mass dominates the amplitude of quark propagator. The branching fraction for the $Z^0 \to \Omega_{ccc}^{++}\bar{\Omega}_{ccc}^{--}$ decay is enhanced by a factor of 181 relative to the $Z^0 \to \Omega^-\bar{\Omega}^+$ decay.

In summary, the cross section for the $e^+e^- \to Z^0/\gamma^* \to \Omega_{ccc}^{++}\bar{\Omega}_{ccc}^{--}$ exclusive process is investigated based on the quark model at the tree level. The cross section is extremely suppressed compared with the calculation of Ω_{ccc}^{++} inclusive production. This can be understood from the factor that the calculation of exclusive production of charmed baryons introduces a probability to describe the charmed/anti-charmed quarks distribution in space, hence it significantly suppresses the exclusively charmed baryon production. This indicates that to search for $\Omega_{ccc}^{++}\bar{\Omega}_{ccc}^{--}$ baryon pairs in the Z-Factory needs a huge integrated luminosity of data set, while in the LHC experiments, the $\Omega_{ccc}^{++}\bar{\Omega}_{ccc}^{--}$ baryon production is dominated by the gluon–gluon fusion process[7] relative to the Z^0 decays. Compared with the $Z^0 \to \Omega^-\bar{\Omega}^+$ decay, the Z^0 boson favors decaying into charmed baryon pairs.

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