NARROW HEAVY RESONANCE PRODUCTION BY GLUONS

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We give explicit formulae for the parton cross sections for the gluonic production of heavy narrow $Q\bar{Q}$ resonances in the $^3P_0$, $^3P_1$ and $^3P_2$ states.

The hadronic production of hidden charm (and beauty) states allows for fruitful tests of the present-day strong interaction concept. In the framework of perturbative QCD several theoretical models [1,2] have been proposed permitting order-of-magnitude estimates on the rates. Reliable determination of the production rate for B mesons which, to a significant fraction, decay into hidden charm states, requires determination of their "direct" cc production rates [3].

We therefore give in this paper the parton cross sections for $g+g\to{}^3P_J+g$. The authors of ref. [1] have earlier numerically evaluated these processes by using non-publishable long expressions for their parton cross sections. In this paper we give short and concise formulas which may be useful to experimentalists and theorists.

In order to determine the parton cross section for heavy resonance production in the non-relativistic bound state approximation we follow ref. [4]. The lowest order (gauge invariant) set of QCD graphs for $gg\to{}^3P_J+g$ is shown in fig. 1. Assuming unbound Q_1Q_2 quarks the amplitude reads: $A=v_2O(k)u_1$. The Dirac operator $O(k)$ depends on the initial four-momentum k via the quark momenta $p_1=P/2-k$, $p_2=P/2+k$. P is the momentum of the ^3P_J state. Defining $O^\mu\equiv\partial o/\partial k_\mu|_{k=0}$ the amplitudes for the ^3P_J states read

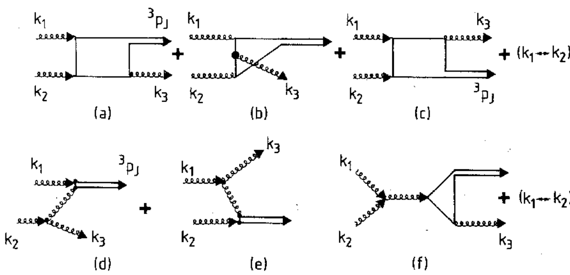

Fig. 1. Lowest order QCD graphs contributing to the process $g+g\to{}^3P_J+g$.

$$A(^3P_0)=(a/\sqrt{6})\ \mathrm{Tr}\{3O_0 + (g^{\mu\nu}-P^\mu P^\nu/M^2)\gamma^\nu\hat{O}^\mu\tfrac{1}{2}[M-\not{P})/2]\}\,, \quad (1)$$

$$A(^3P_1)=(a/2)\ \mathrm{Tr}\{2O_0\not{\epsilon}\gamma_5 - \mathrm{i}(P,\hat{O},\gamma,\epsilon)[(M+\not{P})/2M]\}\,, \quad (2)$$

$$A(^3P_2)=(a/\sqrt{2})\ \mathrm{Tr}\{\hat{O}^\mu\gamma^\nu[(M+\not{P})/2]\}\,\epsilon_{\mu\nu}. \quad (3)$$

ϵ_μ, $\epsilon_{\mu\nu}$ are the polarization vectors and tensors for the $J=1$, 2 states and $(a,b,c,d)=\mathrm{Det}(a,b,c,d)$ is the antisymmetric $\epsilon^{\alpha\beta\gamma\delta}$-tensor in four dimensions. The Dirac operators O and O^μ still contain the polarization vectors of the gluons. Whilst calculating the parton cross section the sum over the gluon polarization vectors must be carried out. Since we are dealing with graphs containing triple-gluon vertices the longitudinal components must be eliminated. This is achieved either by using the transverse projector [5]:

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$$\Sigma\epsilon^{\mu}\epsilon^{*\nu}\equiv P^{\mu\nu}$$

$$=[-g^{\mu\nu}+(2/s)(q_1^{\mu}q_2^{\nu}+q_1^{\nu}q_2^{\mu})]\ ,$$

or, since we are dealing with a set of graphs containing couplings with three gluons at most, by modifying the triple-gluon vertex using the Lorentz conditions of the gluon wave functions. This latter elegant method has been suggested in ref. [4]. We have analytically certified that both methods indeed lead to the same result.

The analytic checking of the gluon gauge-invariance has been carried out. Using the symbolic formula manipulation system SCHOONSCHIP [6] and partially also REDUCE [7], we similarly have evaluated the traces which required considerable amounts of computer time.

The parton cross sections read

$$\frac{d\sigma}{dt}(^3P_0)=\xi\left(\frac{4}{stu}\right)\times\frac{s^{14}[\sum_{m=0}^{6}(tu/s^2)^n\,C_n(V)]}{[(M^2-s)(M^2-t)(M^2-u)]^4}\ , \tag{4}$$

$$\frac{d\sigma}{dt}(^3P_1)=12\xi\times\frac{s^{11}[\sum_{n=0}^{5}(tu/s^2)^n\,C_n(V)]}{[(M^2-s)(M^2-t)(M^2-u)]^4}\ , \tag{5}$$

$$\frac{d\sigma}{dt}(^3P_2)=\xi\left(\frac{-4}{stu}\right)\times\frac{s^{14}[\sum_{n=0}^{6}(tu/s^2)^n\,C_n(V)]}{[(M^2-s)(M^2-t)(M^2-u)]^4}\ , \tag{6}$$

where s, t, u are the parton-invariants and

$$\xi\equiv(\pi\alpha_s^3/16)(M\Gamma_e r/\alpha^2 e_Q^2 s^2)\ .$$

The bound state wave function at the origin is related to the decay width $\Gamma_e\equiv\Gamma(^3S_1\to e^+e^-)$ as $R(0)^2=\Gamma_e M^2/(2\alpha e_Q)^2$. M is the mass of the narrow QQ resonance with the constituents' charge fraction e_Q, and $r\equiv[2R'(0)/MR(0)]\simeq0.074$. The coefficients C_n are linear combinations of $v\equiv(M^2/s)$ and read

$^3P_0$:

$$C_0=9V^2(V^8-6V^7+17V^6-30V^5+36V^4-30V^3+17V^2-6V+1)\ ,$$

$$C_1=6V(6V^8-35V^7+98V^6-168V^5+187V^4-135V^3+60V^2-14V+1)\ ,$$

$$C_2=54V^8-324V^7+920V^6-1506V^5+1476V^4-850V^3+263V^2-34V+1\ ,$$

$$C_3=2(18V^7-126V^6+377V^5-571V^4+456V^3-187V^2+35V-2)\ ,$$

$$C_4=9V^6-102V^5+344V^4-454V^3+269V^2-68V+6\ ,$$

$$C_5=2(-9V^4+42V^3-43V^2+16V-2)\ ,$$

$$C_6=9V^2-6V+1\ .$$

$^3P_1$:

$$C_0=V(V^6-8V^5+26V^4-44V^3+41V^2-20V+4)\ ,$$

$$C_1=2(V^6-9V^5+31V^4-51V^3+41V^2-14V+1)\ ,$$

$$C_2=2V^5-18V^4+59V^3-84V^2+49V-8\ ,$$

$$C_3=2(V^4-7V^3+16V^2-17V+6)\ ,$$

$$C_4=V^3-10V^2+13V-8\ ,$$

$$C_5=2(-2V+1)\ .$$

$^3P_2$:

$$C_0=12V^2(-V^8+6V^7-17V^6+30V^5 -36V^4+30V^3-17V^2+6V-1),$$

$$C_1=3V(-16V^8+96V^7-257V^6+408V^5 -434V^4+324V^3-161V^2+44V-4)\ ,$$

$$C_2=2(-36V^8+228V^7-557V^6+747V^5 -663V^4+421V^3-173V^2+34V-1)\ ,$$

$$C_3=-48V^7+360V^6-782V^5 +814V^4-513V^3 +244V^2-83V+8\ ,$$

$$C_4=2(-6V^6+72V^5-149V^4+109V^3-32V^2 +11V-6)\ ,$$

$$C_5=24V^4-75V^3+46V^2-7V+8\ ,$$

$$C_6=2(-6V^2+6V-1)\ .$$

The cross sections are t–u symmetric. The production of the $^3P_0$ and $^3P_2$ states reveals the t (and u) infrared singularities whereas these poles are absent in the production of the $^3P_1$ state. These characteristics can already be observed in the processes $gq\to{}^3P_J+q$.

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