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NARROW HEAVY RESONANCE PRODUCTION BY GLUONS

B. Humpert*),**)
Institut de Physique Nucléaire
Université de Lausanne

ABSTRACT

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.

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**) Also at Artificial Intelligence Group, HASLER Research Laboratories, CH-3000 BERN, Switzerland.

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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 signification 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: $g + g \rightarrow {}^3P_J + g$. 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 the 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 $gg \rightarrow {}^3P_{J+g}$ is shown in Fig. 1. Assuming unbound Q_1Q_2-quarks the amplitude reads: $A = v_2\, O(k)\, u_1$. The Dirac-operator $O(k)$ depends on the initial 4-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 $O^\mu \equiv \frac{\partial}{\partial k_\mu} O \;{}_{k=0}$ the amplitudes for the ${}^3P_J$-states read

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

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

$$A({}^3P_2) = \frac{a}{\sqrt{2}}\, \mathrm{Tr}\left[\hat{O}^\mu \gamma^\nu \left(\frac{M+\not{P}}{2}\right)\right]\cdot \epsilon_{\mu\nu} \tag{3}$$

ϵ_μ, $\epsilon_{\mu\nu}$ are the polarization vector and tensor for the $J=1,2$ states and $(a,b,c,d) = \mathrm{Det}\,(a,b,c,d)$ is the anti symmetric $\epsilon^{\alpha\beta\gamma\delta}$-tensor in 4 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: $\Sigma\epsilon^\mu\epsilon^{*\nu} \equiv \mathbb{P}^{\mu\nu} = [-g^{\mu\nu} + 2/s\,(q_1^\mu q_2^\nu + q_1^\nu q_2^\mu)]$ [5] 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 SCHOONSHIP [6] and partially also REDUCE [7], we similarly have evaluated the traces which required considerable amounts of computer-time.

The parton cross-sections read

$$\frac{d\sigma}{dt}(^3P_0) = \xi\left(\frac{1}{stu}\right)\frac{s^{14}\left\{\sum_{n=0}^{6}\left(\frac{tu}{s^2}\right)^n C_n(v)\right\}}{\left[(M^2-s)(M^2-t)(M^2-u)\right]^4} \tag{4}$$

$$\frac{d\sigma}{dt}(^3P_1) = 3\cdot\xi\cdot\frac{s^{11}\left\{\sum_{n=0}^{5}\left(\frac{tu}{s^2}\right)^n C_n(v)\right\}}{\left[(M^2-s)(M^2-t)(M^2-u)\right]^4} \tag{5}$$

$$\frac{d\sigma}{dt}(^3P_2) = \xi\cdot\left(\frac{1}{stu}\right)\cdot\frac{s^{14}\left\{\sum_{n=0}^{6}\left(\frac{tu}{s^2}\right)^n C_n(v)\right\}}{\left[(M^2-s)(M^2-t)(M^2-u)\right]^4} \tag{6}$$

where s,t,u are the parton-invariants and $\xi \equiv \left(\frac{\pi\alpha_s^3}{16}\right)\left(\frac{M\Gamma_e\, r}{\alpha^2 e_Q^2 s^2}\right)$.

The bound state wave function at the origin is related to the decay width $\Gamma_e \equiv \Gamma(^3S_1 \to e^+e^-)$ as $R(o)^2 = \Gamma_e M^2/(2\alpha e_Q)^2$. M is the mass of the narrow QQ-resonance with the constituents's charge fraction e_Q, and $r \equiv (2R'(0)/MR(0)) \simeq 0.074$. The coefficients C_n are linear combinations of $v \equiv (M^2/s)$ and read

$^3P_0$:

```
CN(0) = 9.*V**2*(V**8-6.*V**7+17.*V**6-30.*V**5+36.*V**4
          -30.*V**3+17.*V**2-6.*V+1.)
CN(1) = 6.*V*(6.*V**8-35.*V**7+98.*V**6-168.*V**5+187.*V**4
          -135.*V**3+60.*V**2-14.*V+1.)
CN(2) = (54.*V**8-324.*V**7+920.*V**6-1506.*V**5+1476.*V**4
          -850.*V**3+263.*V**2-34.*V+1.)
CN(3) = 2.*(18.*V**7-126.*V**6+377.*V**5-571.*V**4+456.*V**3
          -187.*V**2+35.*V-2.)
CN(4) = (9.*V**6-102.*V**5+344.*V**4-454.*V**3+269.*V**2
          -68.*V+6.)
CN(5) = 2.*(-9.*V**4+42.*V**3-43.*V**2+16.*V-2.)
CN(6) = (9.*V**2-6.*V+1.)
```

$^3P_1$:

```
CN(0) = V*(V**6-8.*V**5+26.*V**4-44.*V**3+41.*V**2-20.*V+4.)
CN(1) = 2.*(V**6-9.*V**5+31.*V**4-51.*V**3+41.*V**2-14.*V+1.)
CN(2) = (2.*V**5-18.*V**4+59.*V**3-84.*V**2+49.*V-8.)
CN(3) = 2.*(V**4-7.*V**3+16.*V**2-17.*V+6.)
CN(4) = (V**3-10.*V**2+13.*V-8.)
CN(5) = 2.*(-2.*V+1.)
```

$^3P_2$:

```
CN(0) = 12.*V**2*(-V**8+6.*V**7-17.*V**6+30.*V**5-36.*V**4
          +30.*V**3-17.*V**2+6.*V-1.)
CN(1) = 3.*V*(-16.*V**8+96.*V**7-257.*V**6+408.*V**5
          -434.*V**4+324.*V**3-161.*V**2+44.*V-4.)
CN(2) = 2.*(-36.*V**8+228.*V**7-557.*V**6+747.*V**5
          -663.*V**4+421.*V**3-173.*V**2+34.*V-1.)
CN(3) = (-48.*V**7+360.*V**6-782.*V**5+814.*V**4-513.*V**3
          +244.*V**2-83.*V+8.)
CN(4) = 2.*(-6.*V**6+72.*V**5-149.*V**4+109.*V**3-32.*V**2
          +11.*V-6.)
CN(5) = (24.*V**4-75.*V**3+46.*V**2-7.*V+8.)
CN(6) = 2.*(-6.*V**2+6.*V-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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References

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[6] SCHOONSHIP-created by M. Veltman; M. Strubbe, Comp. Phys. Communic. 8, (1974) 1.

[7] REDUCE-created by A. Hearn, Rand Corporation, Santa Monica, USA.

Figure Caption

Fig. 1 : Lowest order QCD-graphs contributing to the process:

$$g + g \to {}^3P_J + g .$$

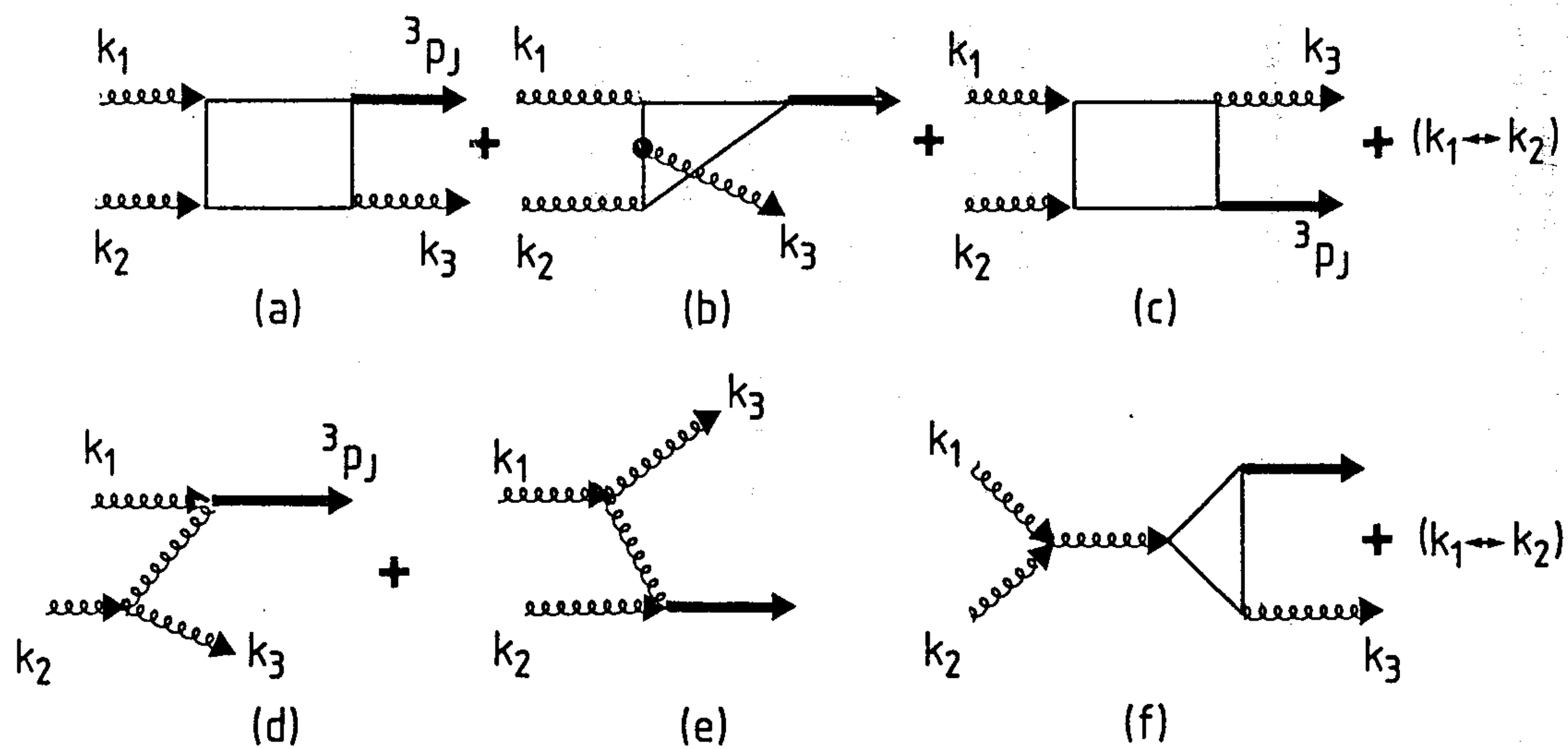

Fig. 1