Universal form factor for exclusive production of pairs of heavy mesons in photon–photon interactions

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Equations which relate the form factors for the production of vector and pseudoscalar states at intermediate energies are derived. The derivation is carried out in the leading approximation in the reciprocal mass of the heavy quark. These equations are independent of the flavor of the heavy quark. © *1995 American Institute of Physics.*

Photon–photon interactions open up some interesting new possibilities for studying the properties of fundamental interactions at both high and intermediate energies. In the latter case, studies of these collisions are feasible even today, at the LEP, in processes with equivalent photons.[1] In addition, feasibility studies for developing photon–photon colliders are being discussed.

In this letter we examine the exclusive production of pairs of heavy mesons (pseudoscalar and vector states), $\gamma\gamma\to H_Q H_{\bar Q}$, in the limit of an infinitely heavy quark, $m_Q \gg \Lambda_{\rm QCD}$, where $\Lambda_{\rm QCD}$ determines the energy scale of the confinement. Since in this limit the effective action of the heavy quarks has a spin–flavor symmetry,[2] a heavy quark moving at a velocity v can be replaced by another heavy quark moving at the same velocity v and having any flavor and any spin orientation.

Using covariant notation for the pseudoscalar (P) and vector (V) states of the ($Q\bar q$) system,[3] we can write the following expressions for the t-channel amplitudes for the exclusive production of pairs of heavy mesons in photon–photon collisions, in the leading order in $\alpha_s\,(m_Q)$:

$$M_{PP}(t)=2m_Q \mathrm{Tr}\left\{\gamma_5\frac{1-\hat v}{2}\,\hat\epsilon_1 S(k-q)\hat\epsilon_2\frac{1+\hat v'}{2}\,\gamma_5\right\}\bar\omega(y)4\pi\alpha_{em}e_Q^2,$$

$$M_{PV}(t)=2m_Q \mathrm{Tr}\left\{\gamma_5\frac{1-\hat v}{2}\,\hat\epsilon_1 S(k-q)\hat\epsilon_2\frac{1+\hat v'}{2}\,\hat\epsilon_V\right\}\bar\omega(y)4\pi\alpha_{em}e_Q^2, \qquad (1)$$

$$M_{VV}(t)=2m_Q \mathrm{Tr}\left\{\hat\epsilon_V\frac{1-\hat v}{2}\,\hat\epsilon_1 S(k-q)\hat\epsilon_2\frac{1+\hat v'}{2}\,\hat\epsilon_{V'}\right\}\bar\omega(y)4\pi\alpha_{em}e_Q^2.$$

The factor $(\sqrt{2m_Q})^2$ arises from the normalization of the meson fields, and e_Q is the charge of the heavy quark. The meson momenta p and p', directed toward the meson–photon vertex, are determined by the four-velocities of the heavy quarks, v and v':

$$p_\mu=m_Q\cdot v_\mu,\quad p'_\mu=m_Q\cdot v'_\mu.$$

Here $\epsilon_{1,2}$ and $\epsilon_{V,V'}$ are the polarization vectors of the photons and the vector mesons, respectively;

$$k=\frac{1}{2}(p_1-p_2),\quad q=\frac{m_Q}{2}(v-v'),$$

where $p_{1,2}$ are the momenta of the photons directed away from the vertex; and $S(p)$ is the propagator of the heavy quark in the case of a large virtuality, $|p^2-m_Q^2|\gg m_Q^2$. In this order in the hard corrections to QCD, $S(p)$ is given by the expression for a free quark:

$$S(p)=\frac{\hat{p}+m_Q}{p^2-m_Q^2}.$$

In the leading approximation in the reciprocal mass of the heavy quark, the scalar form factor $\bar{\omega}(y=v\cdot v')$ is universal, i.e., independent of the flavor of the heavy quark and independent of the orientation of the spin.

The u-channel amplitudes can be found from the t-channel expressions by making the replacement $k\to -k$ and the interchange $\epsilon_1\Leftrightarrow\epsilon_2$.

As was mentioned in Ref. 4, expressions of this sort for the amplitudes for the production of heavy quarks are valid in the region of the soft production of a pair of light quarks which are parts of mesons. One finds substantial corrections in the limit $s\to\infty$, in which an additional parameter $\sqrt{s}\Lambda_{\rm QCD}/m_Q^2$ arises and becomes comparable to unity. Expressions (1) are thus valid at intermediate energies (at $\sqrt{s}<50$ GeV for the case of $P\bar{P}$-pair production).

In addition, we easily find

$$t=(k-q)^2=-m_Q^2(y+\sqrt{y^2-1}\cos\theta),$$

where θ is the angle between the photon momentum p_1 and the meson velocity v. We then have

$$S(k-q)=\frac{1}{2m_Q}\frac{\hat{n}-\hat{v}+\hat{v}'+2}{1+y+\sqrt{y^2-1}\cos\theta},$$

where $n=2k/m_Q$ and $n^2=-2(y+1)$.

At fixed meson velocities, the amplitudes for the production of heavy-meson pairs are thus independent of the flavor of the heavy quark, being determined by the universal form factor $\bar{\omega}(y)$. In the axial gauge, $\epsilon_{1,2}\cdot n=0$, the amplitudes are

$$M_{PP}(t)=-4\pi\alpha_{em}e_Q^2\frac{2\bar{\omega}(y)}{1+y+\sqrt{y^2-1}\cos\theta}[4(\epsilon_1\cdot v)(\epsilon_2\cdot v)$$
$$-(\epsilon_1\cdot\epsilon_2)\sqrt{y^2-1}\cos\theta],$$

$$M_{PV}(t)=4\pi\alpha_{em}e_Q^2\frac{\bar{\omega}(y)}{1+y+\sqrt{y^2-1}\cos\theta}\epsilon_{\mu\nu\alpha\beta}[\epsilon_1^\mu\epsilon_2^\nu\epsilon_V^\alpha(v'(y-\sqrt{y^2-1})-v-n)^\beta$$
$$+(\epsilon_1\cdot v)\epsilon_2^\mu\epsilon_V^\nu v'^\alpha(n-3v)^\beta+(\epsilon_2\cdot v)\epsilon_1^\mu\epsilon_V^\nu v^\alpha(n+v')^\beta$$
$$+(\epsilon_2\cdot\epsilon_V)v^\mu v'^\nu n^\alpha\epsilon_1^\beta],$$

$$M_{VV}(t)=-4\pi\alpha_{em}e_Q^2\frac{\bar{\omega}(y)}{1+y+\sqrt{y^2-1}\cos\theta}[8(\epsilon_1\cdot v)(\epsilon_2\cdot v)(\epsilon_V\cdot\epsilon_{V'})+2(\epsilon_1\cdot v)\{(\epsilon_2$$
$$\cdot\epsilon_V)(\epsilon_{V'}\cdot(n-v))+(\epsilon_2\cdot\epsilon_{V'})(\epsilon_V\cdot(v'-n))\}+2(\epsilon_2\cdot v)$$
$$\times\{-(\epsilon_1\cdot\varepsilon_V)(\epsilon_{V'}\cdot(n+v))+(\epsilon_1\cdot\epsilon_{V'})(\epsilon_V\cdot(v'+n))\}+(\epsilon_1\cdot\epsilon_2)$$
$$\times\{(\epsilon_V\cdot v')(\epsilon_{V'}\cdot n)-(\epsilon_V\cdot n)(\epsilon_{V'}\cdot v)\}+2\sqrt{y^2-1}\cos\theta\{(\epsilon_1\cdot\epsilon_{V'})(\epsilon_2\cdot\epsilon_V)$$
$$-(\epsilon_1\cdot\epsilon_V)(\epsilon_2\cdot\epsilon_{V'})-(\epsilon_1\cdot\epsilon_2)(\epsilon_V\cdot\epsilon_{V'})\}. \qquad (2)$$

Strictly speaking, Eqs. (2) establish the relationship between the cross sections for the production of various spin states. The corresponding explicit expressions are quite cumbersome, and we will not discuss them here. For the ratios of the total cross sections for the production of meson pairs with different heavy quarks we find

$$\frac{\sigma_{PP}(s_1)}{\sigma_{PP}(s_2)}=\frac{\sigma_{PV}(s_1)}{\sigma_{PV}(s_2)}=\frac{\sigma_{VV}(s_1)}{\sigma_{VV}(s_2)}=\frac{m_{Q_2}^2}{m_{Q_1}^2} \qquad (3)$$

for $s_{1,2}=2m_{Q_{1,2}}^2(1+y)$, $y>1$.

Finally, examining the exclusive production of pairs of heavy mesons in the leading order of QCD perturbation theory, we find that of the 20 diagrams for the $\gamma\gamma\rightarrow H_Q H_{\bar{Q}}$ process in the limit $\Lambda_{\rm QCD}/m_Q\rightarrow 0$, at a fixed s, the leading contribution comes from two t-channel diagrams and two u-channel diagrams with soft gluons.

The latter are radiated by heavy quarks which are parts of mesons, and the universal form factor is

$$\bar{\omega}(y)=\frac{2\pi\alpha_s}{9}\frac{1}{(y+1)^2}\frac{f^2M}{m_q^3}, \qquad (4)$$

where α_s is determined by the leading value at the scale $\mu^2=sm_q^2/m_Q^2$. In the limit $m_Q\rightarrow\infty$ we have the following scaling law[2] for the lepton constants of heavy mesons:

$$f^2\cdot M=\text{const}.$$

In addition, the effective mass of the light quark, m_q, is independent of the flavor of the heavy quark.

In summary, we have shown that in the leading approximation in the reciprocal mass of the heavy quark the amplitudes for the exclusive production of pairs of heavy mesons are determined by a single universal form factor $\bar{\omega}(y)$, which is independent of the flavor of the heavy quark. In QCD perturbation theory, this form factor is given by expression (4).

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