Diffractive production of vector mesons in high-energy photon-photon collisions

L. Maharana,* S. P. Misra, and A. R. Panda
Institute of Physics, Bhubaneswar-751007, India
(Received 8 April 1981; revised manuscript received 3 June 1981)

We examine here the energy dependence of the production of vector mesons in photon-photon collisions based on a model applied earlier to the calculation of diffractive photoproduction cross sections with a derived form of the vector-dominance model. We observe here that production of *heavy* vector mesons is considerably suppressed.

I. INTRODUCTION

At present many experiments are performed to study photon-photon collisions.[1] Such collisions are expected to reveal some clean features of quantum-choromodynamic calculations,[2] as well as to give some insight into the dynamics of the photon, i.e., its hadronic nature or otherwise[3] in the context of vector dominance,[4] deep-inelastic collisions,[5] or photon-gluon-fusion models.[6] Besides Ref. 6, a derived form of vector dominance[7] also yields an energy dependence for diffractive photoproduction of heavy vector mesons in agreement with experiments. In the present analysis we use this model to calculate the cross sections for the *diffractive* processes $\gamma\gamma\rightarrow V_1V_2$, where an energy dependence for heavy vector mesons is predicted.

II. CALCULATIONS

The interaction Hamiltonian in *quark* space for the process $\gamma\gamma\rightarrow V_1V_2$ is taken as[7]

$$\mathscr{H}_I(x)=eJ^{\mu}_{\rm EM}(x)A_\mu(x)+\mathscr{V}(x)\ , \tag{2.1}$$

where $J^{\mu}_{\rm EM}(x)$ is the electromagnetic current,[8] and the effective interaction $\mathscr{V}(x)$ in quark space was introduced to yield diffraction scattering and diffractive dissociation processes.[9] $\mathscr{V}(x)$ had the form[9]

$$\mathscr{V}(x)=f_{QQ'}J^{\mu}_{Q}(x)J_{Q'\mu}(x)\ . \tag{2.2}$$

With the Hamiltonian (2.1) we now consider the matrix element through the perturbation steps[7] such as $\gamma\gamma\rightarrow V_1\gamma\rightarrow V_1V_2\rightarrow V_1'V_2'$, where V_1 and V_2 are intermediate vector mesons, and the corresponding diagram with an obvious notation for the spins and the four-momenta of the initial and final particles, as well as for the two intermediate states, have been drawn in Fig. 1. Considering all such contributions, we obtain the matrix element for $\gamma\gamma\rightarrow V_1'V_2'$ as[7]

$$\begin{aligned}M_{fi}=&-ie^2(2\pi)^{10}\times2\times2f_{QQ'}(k_1^0-k^0_{V_1})^{-1}(2k_2^0-2k^0_{V_2})^{-1}\\&\times\langle k'_{V_1}\lambda_1'\,|\,J^{\mu}_{Q}(0)\,|\,k_{V_1}\lambda_1\rangle\langle k'_{V_2}\lambda_2'\,|\,J_{Q'\mu}(0)\,|\,k_{V_2}\lambda_2\rangle\\&\times\langle k_{V_1}\lambda_1\,|\,J^{\alpha}_{\rm EM}(0)A_\alpha(0)\,|\,k_1i_1\rangle\langle k_{V_2}\lambda_2\,|\,J^{\beta}_{\rm EM}(0)A_\beta(0)\,|\,k_2i_2\rangle\ .\end{aligned} \tag{2.3}$$

In this equation we have used the "old-fashioned" perturbation technique as in Ref. 7, with, e.g., the two energy denominators as in (2.3) for the two intermediate states. We shall also use here[7,10]

$$\langle k_V\lambda\,|\,J^{\alpha}_{\rm EM}(0)|\ \text{vac}\ \rangle=\frac{{m_V}^2}{f_V}(2\pi)^{-3/2}(2k_V^0)^{-1/2}\epsilon^{\alpha}(k_V,\lambda)\ , \tag{2.4}$$

where f_V is experimentally known from the coupling of the vector mesons to the e^+e^- channel. Other hadronic matrix elements in (2.3) can be related to the form factors, which are parametrized as[7,9] $G_{V_1}(t_1')=\exp(B_{V_1}t_1'/2)$ and $G_{V_2}(t_2')=\exp(B_{V_2}t_2'/2)$ with $t_1'=(k_{V_1}-k'_{V_1})^2$ and $t_2'=(k_{V_2}-k'_{V_2})^2$. We take the c.m. frame of reference for the evaluation of (2.3) and, after a straightforward but lengthy calculation involving spin summations, we finally obtain[7]

$$\frac{d\sigma}{dt}(\gamma\gamma\rightarrow V_1'V_2')=\frac{16{f_{QQ'}}^2}{\pi}\left[\frac{4\pi\alpha}{{f_{V_1}}^2}\frac{4\pi\alpha}{{f_{V_2}}^2}\right]\frac{{m_{V_1}}^6{m_{V_2}}^6}{4s^2{k^0_{V_1}}^2{k^0_{V_2}}^2(k_1^0-k^0_{V_1})^2(k_2^0-k^0_{V_2})^2}\exp(B_{V_1}t_1'+B_{V_2}t_2')\times f(\theta). \tag{2.5}$$

In the above the kinematics is as in Fig. 1, and we remember that in "old-fashioned" perturbation theory, momentum is conserved.[7] We have also substituted $\vec{k}_1\cdot\vec{k}'_{V_1}=\vec{k}_2\cdot\vec{k}'_{V_2}=\kappa_i\kappa_f\cos\theta$ with κ_i and κ_f as the magnitudes of the initial and final momenta. In (2.5) the t dependence is mainly given by the form factors. $f(\theta)$ is an extremely complicated expression, which for $\theta=0$ is given as

$$f(0)=(64m_{V_1}{}^2m_{V_2}{}^2)^{-1}\left[4[(k'^0_{V_1}+k^0_{V_1})(k'^0_{V_2}+k^0_{V_2})+(\kappa_i-\kappa_f)^2] +2\left[-m_{V_1}{}^2+\frac{(k^0_{V_1}k'^0_{V_1}-\kappa_i\kappa_f)^2}{m_{V_1}{}^2}\right]\left[-m_{V_2}{}^2+\frac{(k^0_{V_2}k'^0_{V_2}-\kappa_i\kappa_f)^2}{m_{V_2}{}^2}\right]\right] . \tag{2.6}$$

Equations (2.5) and (2.6) qualitatively demonstrate the energy dependence which will be present. In the asymptotic high-energy limit we obtain from (2.5) that

$$\frac{d\sigma}{dt}=\frac{16f_{QQ'}{}^2}{\pi}\left[\frac{4\pi\alpha}{f_{V_1}{}^2}\frac{4\pi\alpha}{f_{V_2}{}^2}\right]\exp[(B_{V_1}+B_{V_2})t] . \tag{2.7}$$

This is the same as for the conventional vector dominance model when we remember that for diffraction scattering[9]

$$\frac{d\sigma}{dt}(V_1V_2\to V'_1V'_2)=\frac{16f_{QQ'}{}^2}{\pi}\exp[(B_{V_1}+B_{V_2})t] . \tag{2.8}$$

In the next section we shall numerically integrate (2.5) to obtain the total cross sections for the processes $\gamma\gamma\to V'_1V'_2$, which includes the advertised energy dependence.

III. RESULTS

We now apply the above for $\gamma\gamma\to V'_1V'_2$ for different vector mesons. The slope parameters B_V for form factors have been determined earlier while considering diffractive photoproduction of vector mesons and diffraction scattering,[7,9] where they were regarded as free parameters so that the observed slopes and the energy dependence were obtained.[11] In a crude manner, they are also consistent with the "size" of the vector mesons, and thus link spectroscopy with high-energy diffractive scattering.[8,9] We next come to flavor symmetry breaking in strong interactions needed to estimate $f_{QQ'}$ in (2.2). The factorization of total hadronic cross sections will, e.g., imply that $\sigma_{V_1V_2}{}^2=\sigma_{V_1V_1}\sigma_{V_2V_2}$, which, with Eq. (2.8), yields *for the quark space* the relation

$$f_{q_1q_2}{}^2=f_{q_1q_1}f_{q_2q_2} . \tag{3.1}$$

For diffraction scattering and for the production of vector mesons, earlier[7,9] f_{qq}, $f_{q\lambda}$, f_{qc}, and f_{qb}

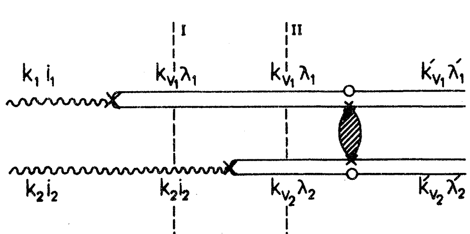

FIG. 1. The perturbation diagram for the matrix element for the process $\gamma\gamma\to V'_1V'_2$ which corresponds to $\gamma\gamma\to V_1\gamma\to V_1V_2\to V'_1V'_2$ as in Ref. 7.

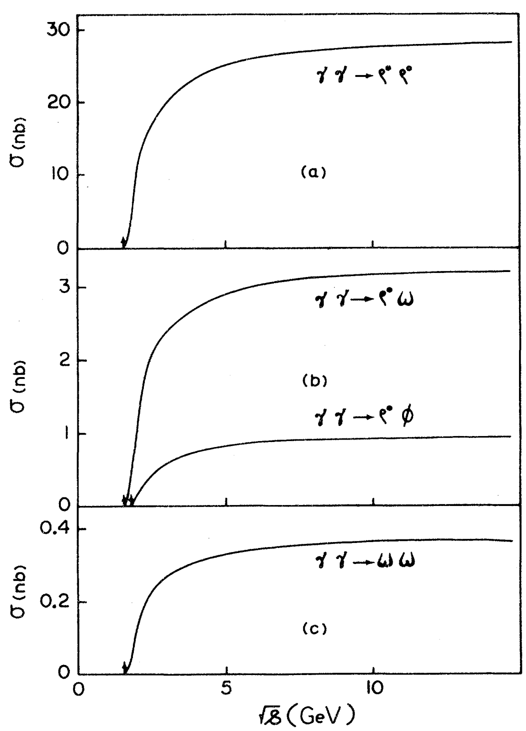

FIG. 2. Cross sections (a) $\sigma(\gamma\gamma\to\rho^0\rho^0)$, (b) $\sigma(\gamma\gamma\to\rho^0\omega)$ and $\sigma(\gamma\gamma\to\rho^0\phi)$, and (c) $\sigma(\gamma\gamma\to\omega\omega)$ are plotted against c.m. energy $\sqrt{s}$.

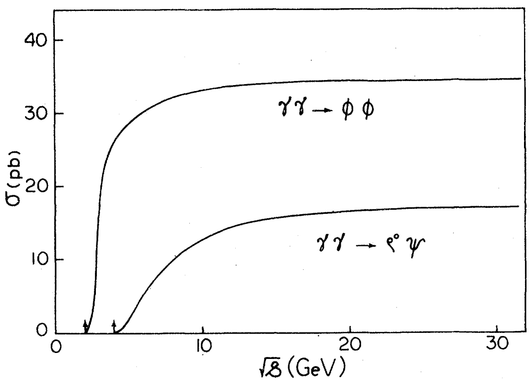

FIG. 3. $\sigma(\gamma\gamma\to\phi\phi)$ and $\sigma(\gamma\gamma\to\rho^0\psi)$ are plotted against c.m. energy $\sqrt{s}$.

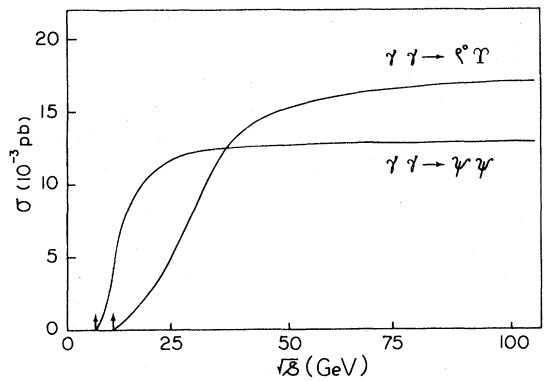

FIG. 4. $\sigma(\gamma\gamma\to\rho^0\Upsilon)$ and $\sigma(\gamma\gamma\to\psi\psi)$ are plotted against c.m. energy $\sqrt{s}$.

had been estimated.[12] We may recall that this symmetry breaking is already observed in diffractive photoproduction processes $\gamma p\to\rho p$ and $\gamma p\to\omega p$ as compared with[7] $\gamma p\to\phi p$ and $\gamma p\to\psi p$. In quark space we now use (3.1) to calculate $f_{\lambda\lambda}$, f_{cc}, and f_{bb}.[12]

We now calculate the respective "elastic" cross sections $\sigma(\gamma\gamma\to V_1'V_2')$ by numerically integrating (2.5). For the different pairs of vector mesons, these have been plotted against $\gamma\gamma$ c.m. energy in Figs. 2, 3, and 4. The energy dependence near threshold is seen to be appreciable even for $\gamma\gamma\to\rho^0\rho^0$ in Fig. 2(a). In the other diagrams it may further be seen to be extremely relevant for heavy vector mesons, similar to what was earlier seen for $\gamma p\to\psi p$, both theoretically and experimentally.[7] We feel that it will be desirable to look for diffractive ϕ or ψ production along with a ρ^0 in $\gamma\gamma$ collisions, as noted in Fig. 2(b) and Fig. 3, or for the diffractive process $\gamma\gamma\to\phi\phi$ as in Fig. 3, since ϕ and ψ signals, being relatively sharp, may be easier to detect against background.

We next calculate the asymptotic values of the total cross sections which, in decreasing order of magnitude, are given as $\sigma(\gamma\gamma\to\rho^0\rho^0)=26.6$ nb, $\sigma(\gamma\gamma\to\rho^0\omega)=3.1$ nb, $\sigma(\gamma\gamma\to\rho^0\phi)=0.91$ nb, $\sigma(\gamma\gamma\to\omega\omega)=353$ pb, $\sigma(\gamma\gamma\to\phi\phi)=33.5$ pb, $\sigma(\gamma\gamma\to\rho^0\psi)=16.9$ pb, $\sigma(\gamma\gamma\to\rho^0\Upsilon)=0.017$ pb, $\sigma(\gamma\gamma\to\psi\psi)=0.014$ pb, and $\sigma(\gamma\gamma\to\Upsilon\Upsilon)=0.24\times10^{-7}$ pb. We may further note that with the scattering amplitude as pure imaginary, as is true for diffractive processes, we have $(d\sigma/dt)(V_1V_2\to V_1'V_2')\,|_{t=0}=\sigma_t^2(V_1V_2)/(16\pi)$, such that from (2.8) we get $\sigma_t(V_1V_2)=16f_{QQ'}$. This yields the total cross section for photon-photon collisions as

$$\sigma_t(\gamma\gamma)=\sum_{V_1,V_2}\left[\frac{4\pi\alpha}{f_{V_1}{}^2}\right]\left[\frac{4\pi\alpha}{f_{V_2}{}^2}\right]\sigma_t(V_1V_2)\ , \quad (3.2)$$

which on direct evaluation gives[11,12] $\sigma_t(\gamma\gamma)=253.4$ nb. This may be compared with the measured asymptotic values[13] of $\sigma_t(\gamma\gamma)=233\pm38$ nb of PLUTO and $\sigma_t(\gamma\gamma)=380$ nb of TASSO. Clearly, more careful experimental analysis seems to be needed. With the TASSO data being preliminary,[13] the predictions appear to be reasonable. We may also note here an anomalous situation regarding the above total cross section: this cross section appears to *rise* quite sharply at low energies[13] around 2–3 GeV. We believe that at such energies the vector-dominance model as in Fig. 1 (or otherwise) is inadequate, and other processes which are *not* diffractive are present.[14,15]

We may conclude this paper with the following remarks. Firstly, the present form of the vector-dominance model through Ref. 7 has clear predictions regarding the *diffractive* production of vector mesons in case of photon-photon collisions, just as for diffractive photoproduction,[7] and without fresh parameters. The energy dependence arises here from the matrix element of Fig. 1 through the kinematic factors, and will be observed when this dependence is not swamped by nondiffractive dynamics. This may arise as in Ref. 14 or from the diagrams of quantum chromodynamics[15] at low energies. In fact, it is quite possible that different dynamical approaches may be equivalent.[6] What is done here to isolate *one* source of energy dependence, so that other effects, complementary or supplementary, may also be separately considered. Similar to the case of diffractive photoproduction of vector mesons, we expect that for *light* vector mesons near threshold, nondiffractive processes will dominate, whereas for heavy vector mesons, the present calculations will be useful.[7]

We share the common belief that we should ultimately be able to explain everything in terms of quantum chromodynamics. However, with our incomplete understanding of the same at low energies, where it is not clear which diagrams will come into picture,[15] we feel rather helpless regarding even order-of-magnitude estimates.[16] In this context it is useful to separately consider individual effects, which has been the motivation of the present paper. We expect that the present calculations will be particularly relevant for the production of *heavy* vector mesons in $\gamma\gamma$ collisions.[7]

ACKNOWLEDGMENTS

The authors would like to thank K. Biswal and B. K. Parida for discussions. Two of us (L. M. and A. R. P.) are grateful to the University Grants Commission for financial assistance.

---

*Present address: Post-graduate Department of Physics, Ravenshaw College, Cuttack-753003, India.

[1]H. J. Besch *et al.*, Phys. Lett. 81B, 79 (1979); Ch. Berger *et al.* (PLUTO Collaboration), *ibid.* 89B, 120 (1979); G. S. Abrams *et al.*, Phys. Rev. Lett. 43, 477 (1979); W. Frazer, in *High Energy Physics—1980,* proceedings of the XX International Conference, Madison, Wisconsin, edited by L. Durand and L. G. Pondrom (AIP, New York, 1981).

[2]E. Witten, Nucl. Phys. B120, 189 (1977); S. J. Brodsky, T. A. DeGrand, J. F. Gunion, and J. H. Weis, Phys. Rev. Lett. 41, 672 (1978); W. R. Frazer and J. F. Gunion, Phys. Rev. D 20, 147 (1978); T. A. DeGrand, Phys. Lett. 84B, 478 (1979).

[3]For a review, see, e.g., T. H. Bauer, R. D. Spital, D. R. Yennie, and F. M. Pipkin, Rev. Mod. Phys. 50, 261 (1980); See also M. Fontannaz, A. Mantrach, D. Schiff, and B. Pire, Z. Phys. C 6, 241 (1980).

[4]J. J. Sakurai, Ann. Phys. (N.Y.) 11, 1 (1980); M. Gell-Mann and F. Zachariasen, Phys. Rev. 124, 953 (1961); H. Fritzsch and K. H. Streng, Phys. Lett. 72B, 385 (1978).

[5]S. P. Misra, Phys. Rev. D 21, 1231 (1980). See also M. Fontannaz *et al.*, Ref. 3.

[6]L. M. Jones and H. W. Wyld, Phys. Rev. D 17, 759 (1978); M. Glück and E. Reya, Phys. Lett. 79B, 453 (1978); 83B, 98 (1979); 94B, 84 (1980); J. P. Leveille and T. Weiler, Nucl. Phys. B147, 147 (1979); V. Barger, W. Y. Keung, and R. J. N. Phillips, Phys. Lett. 91B, 253 (1980); T. Weiler, Phys. Rev. Lett. 44, 304 (1980).

[7]S. P. Misra and L. Maharana, Phys. Rev. D 18, 4018 (1978); S. P. Misra, L. Maharana, and A. R. Panda, Phys. Rev. D 22, 2744 (1980); K. Biswal and S. P. Misra, Phys. Rev. D 24, 106 (1981). For timelike photons, threshold dependence is also discussed in S. P. Misra, K. Biswal, and B. K. Parida, Phys. Rev. D 21, 2029 (1980) regarding $D\bar{D}$ production.

[8]S. P. Misra, Phys. Rev. D 18, 1661 (1978); 18, 1673 (1978). The model has also been applied to incoherent processes as in S. P. Misra and A. R. Panda, Phys. Rev. D 21, 3094 (1980).

[9]S. P. Misra and L. Maharana, Phys. Rev. D 18, 4103 (1978); S. P. Misra, A. R. Panda, and B. K. Parida, *ibid.* D 22, 1574 (1980), which has been applied in S. P. Misra, L. Maharana, and A. R. Panda, Ref. 7. This involves an extrapolation of the idea contained in F. Ravndal, Phys. Rev. D 8, 847 (1973).

[10]Although the equation has the *form* of field-current identity, only Lorentz-boosted states are used as in Ref. 7 and the identity is in the context of quark model only, as in Ref. 8.

[11]We take $f_\rho{}^2/4\pi=2.11$, $f_\omega{}^2/4\pi=18.3$, $f_\phi{}^2/4\pi=13.5$, $f_\psi{}^2/4\pi=11.45$, $f_\Upsilon{}^2/4\pi\simeq130$, and $B_\rho=B_\omega=3.5$ GeV^{-2}, $B_\phi=2$ GeV^{-2}, $B_\psi=1.2$ GeV^{-2}, and $B_\Upsilon=0.5$ GeV^{-2} as in Ref. 7.

[12]We take $f_{qq}=2.8$ GeV^{-2}, $f_{q\lambda}=1.16$ GeV^{-2}, $f_{qc}=0.135$ GeV^{-2}, and $f_{qb}=0.0132$ GeV^{-2} as in Ref. 7. We then have $f_{\lambda\lambda}=0.4806$ GeV^{-2}, $f_{cc}=0.00651$ GeV^{-2}, and $f_{bb}=0.000062$ GeV^{-2}.

[13]B. H. Wiik, in *Gauge Theories and Experiments at High Energies,* proceedings of the 21st Scottish Universities Summer School, 1980, edited by K. C. Bowler and D. Sutherland (SUSSP, Edinburgh, 1981), p. 101.

[14]This may be mainly due to resonance productions. Another type of coherent effect present at low energies is discussed in K. Biswal and S. P. Misra, Phys. Rev. D (to be published). The present model as a variant of the vector-dominance model as in Ref. 7, *does not* imply that the photon always behaves like a vector meson, (Refs. 6, 7, and 8).

[15]Such diagrams have been also considered for *exclusive* processes $\gamma\gamma\to MM$ for large momentum transfers by S. J. Brodsky and G. P. Lepage [work presented at the XX International Conference in High Energy Physics, Madison, Wisconsin, 1980, Report No. SLAC-PUB-2587, 1980 (unpublished)]. It is very likely that such contributions will also be relevant for small momentum transfers, but here it becomes difficult to estimate the corresponding effects.

[16]See, however, some estimates of Brodsky and Lepage (Ref. 15), emphasizing the effect of nondiffractive dynamics, and Ref. 14.