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PHOTOPRODUCTION OF RESONANCES FROM COMPACT AND SPATIALLY EXTENDED SOURCES*

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We discuss the photoproduction of resonances observed in the $\pi^+\pi^-$ system. For the $\gamma p \to \pi^+\pi^- p$ reaction, we consider two production mechanisms: the one-pion exchange known in the literature as the Deck mechanism and collective contribution of all other short-range exchanges which we parametrize in terms of a smooth function of $s_{\pi\pi}$. We have found a very good agreement of the model with experimental mass distributions for partial waves S, P and D. Our calculations are in line with the expectation that while the P- and D-wave resonances $\rho(770)$ and $f_2(1270)$ are conventional $q\bar{q}$ states, the S-wave $f_0(980)$ resonance is rather a more loosely bound $qq\bar{q}\bar{q}$ state.

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1. Introduction

Proper description of the spectrum of resonances as well as the mechanisms of their production is fundamental for understanding the long-range properties of QCD, particularly the confinement phenomenon. Photoproduction of meson resonances is of particular interest since, as shown in [1], it is the reaction with high probability of producing exotic states. Studies on reliable photoproduction models are timely and opportune due to abundant photoproduction data to be expected in the near future from experiments in JLab, ELSA, MAMI, BESIII and SPring-8. In this study, we focus on the $\gamma p \to \pi^+\pi^- p$ reaction, as for the time being, it is the only reaction where the scalar meson $f_0(980)$ has been observed in the photoproduction [2].

2. Model description

The relation between invariant amplitude and the S-matrix for the reaction $\gamma\,(q,\lambda) + p(p_1,\lambda_1) \to p(p_2,\lambda_2) + \pi^+\,(k_1) + \pi^-\,(k_2)$ reads

$$S_{\rm fi} = \delta_{\rm fi} + i(2\pi)^4\,\delta^4(p_2 + k_1 + k_2 - p_1 - q)\,\mathcal{T}_{\rm fi}\,, \tag{1}$$

where λs denote particle helicities. The invariant double-differential cross section expressed in terms of $\pi\pi$ partial wave cross sections is given by

$$\frac{{\rm d}^2\sigma}{{\rm d}|t|\,{\rm d}\sqrt{s_{\pi\pi}}} = \frac{1}{64(2\pi)^4}\frac{|\boldsymbol{k}|}{(s-m^2)^2}\sum_{lm}\sum_{\lambda_2\lambda\lambda_1}\left|\mathcal{T}^{lm}\right|^2\,, \tag{2}$$

where $|\boldsymbol{k}| = \sqrt{s_{\pi\pi}/4 - m_\pi^2}$ is the magnitude of pion momenta in the $\pi\pi$ rest frame. The partial wave expansion is defined in the $\pi\pi$ center-of-mass frame where the direction of the recoil proton defines the negative z axis, and y axis is perpendicular to the di-pion production plane. The q, p_1, p_2, k_1 and k_2 denote, respectively, the 4-momenta of photon, initial proton, final proton, positive pion and negative pion. The partial wave expansion of the production amplitude $\mathcal{T}$ reads

$$\mathcal{T}^{lm} = \int {\rm d}\Omega\; Y^*_{lm}(\Omega)\;\mathcal{T}\,(p_2\lambda_2\,k_1k_2, q\lambda\,p_1\lambda_1)\;, \tag{3}$$

where ${\rm d}\Omega = {\rm d}\cos\theta\,{\rm d}\phi$ and the angles θ and ϕ define the direction of π^+ in the $\pi^+\pi^-$ center-of-mass system. The formal amplitude expansion given by Eq. (3) includes long- (spatially extended source) and short-range (compact source) $\pi^+\pi^-$ production amplitudes which play the role of Born terms as well as the final-state $\pi\pi$ rescattering term. The long-range part known as the Deck amplitude includes pion pole modification (third term in Eq. (4)), so that gauge invariance is properly imposed [3]

$$M_{\lambda_2\lambda\lambda_1} = e\left[\frac{\epsilon_\lambda\, k_2}{q\, k_2} T^-_{\lambda_1\lambda_2} - \frac{\epsilon_\lambda\, k_1}{q\, k_1} T^+_{\lambda_1\lambda_2} + \frac{\epsilon_\lambda\,(p_1+p_2)}{q\,(p_1+p_2)}\left(T^+_{\lambda_1\lambda_2} - T^-_{\lambda_1\lambda_2}\right)\right] , \quad (4)$$

where e is the electric charge, ϵ_λ is the photon helicity polarization vector and $T^+_{\lambda_1\lambda_2}$ and $T^-_{\lambda_1\lambda_2}$ are $\pi^\pm N$ scattering amplitudes. The partial wave expansion of the long-range contribution is obtained using the formula analogous to Eq. (3). The $\pi^+\pi^-$ pair photoproduced through the pion exchange undergoes the final-state rescattering (we call it "Deck+FSI" in what follows) described by the partial wave amplitudes of the form of

$$t^I_l = \frac{1}{2i\rho}\left(\eta^I_l\, \mathrm{e}^{2i\delta^I_l} - 1\right) . \quad (5)$$

The t^I_l amplitudes are defined in terms of the phase shifts δ^I_l and inelasticity parameters η^I_l for individual isospins I and angular momenta l, where $\rho = 2|\boldsymbol{k}|/\sqrt{s_{\pi\pi}}$. For this study, we have used the partial wave amplitudes where crossing symmetry and once subtracted dispersion relations were imposed [4]. The short-range contribution for each partial wave can be expressed by

$$(A_l + B_l\, s_{\pi\pi})\, \mathrm{e}^{i\delta^I_l}\, \sin\delta^I_l , \quad (6)$$

where the term in the parentheses effectively parametrizes the smooth $s_{\pi\pi}$ dependence related to exchanges of heavy particles and quark/gluon processes. This term is modified by elastic final-state $\pi\pi$ interactions. Other channels are neglected due to limited energy range covered by data.

Elastic amplitudes of the π^+ and π^- scattering off protons used in Eq. (4) can be expressed in terms of the isospin amplitudes

$$T^+_{\lambda_1\lambda_2} = T^{\frac{3}{2}}_{\lambda_1\lambda_2} , \qquad T^-_{\lambda_1\lambda_2} = \frac{1}{3}\left(T^{\frac{3}{2}}_{\lambda_1\lambda_2} + 2T^{\frac{1}{2}}_{\lambda_1\lambda_2}\right) . \quad (7)$$

These in turn can be expressed in terms of the standard Lorentz invariant isospin amplitudes [5]

$$T^I_{\lambda_1\lambda_2} = \overline{u}\,(p_2,\lambda_2)\left(A^I + \gamma\, Q B^I\right) u\,(p_1,\lambda_1) , \quad (8)$$

with $Q = \frac{1}{2}(q \mp k_1 \pm k_2)$, for π^- and π^+ scattering, respectively. We have expressed the isospin amplitudes A^I and B^I in Eq. (8) in terms of the SAID πN partial wave parametrization [6].

3. Numerical results

In order to compare our model with the mass distributions for low partial waves determined by the CLAS Collaboration [2], we fitted the short-range part of the partial wave amplitudes to these data. We stress that relevant parameters A and B used in Eq. (6) are the only free parameters of the model, while the long-range contribution is basically parameter free. The full model containing both the short-range and the long-range contributions along with the $\pi\pi$ final-state interactions is called "Deck+FSI+short range" in what follows. In Fig. 1, we show the prediction for the S-wave mass distribution and compare it with the CLAS fit [2]. It is clear that the model which includes the long-range (Deck) and short-range contribution (with parameters $A_0 = -14.5 \pm 0.6$ GeV^{-1} and $B_0 = 2.7 \pm 0.6$ GeV^{-3}) together with final-state interactions fairly reproduces the mass distribution behavior both in resonance region and outside. The model's behavior slightly differs from CLAS data above 1 GeV. This can be attributed to the absence of the $K\bar{K}$ channel in the model.

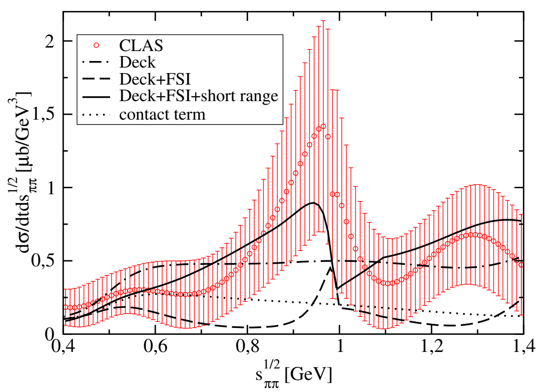

Fig. 1. (Color online) S-wave double differential cross section at $E_\gamma = 3.3$ GeV and $-t = 0.55$ GeV^2. Dash-dotted line — pure Deck model; dashed line — Deck model with final-state $\pi\pi$ interactions; solid line — Deck model with FSI and the short-range term; dotted line — contribution of the contact term; gray/red points — CLAS fit to the experimental data. The error band shows the total uncertainty that combines the systematic and statistical uncertainties.

For the P-wave mass distribution, the overall agreement of data with the full model (Deck+FSI+ short range), especially in the resonance region, is good, as shown in Fig. 2. The agreement is mainly due to the short-range production because the values of parameters $A_1 = 48.9 \pm 1.6$ GeV^{-1} and $B_1 = -24.3 \pm 2.0$ GeV^{-3} are considerably larger than for the S-wave. This implies, as expected, that the P-wave resonance $\rho(770)$ is the standard $q\bar{q}$ state.

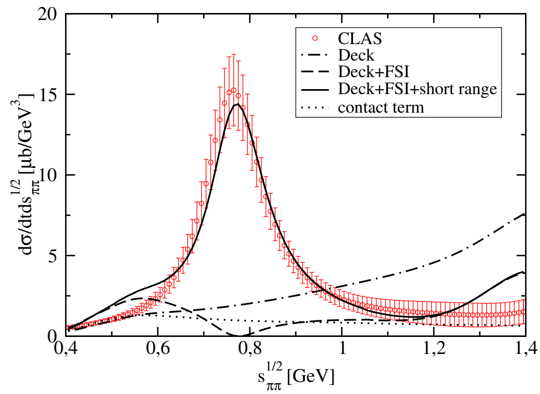

Fig. 2. (Color online) P-wave double differential cross section at $E_\gamma = 3.3$ GeV and $-t = 0.55$ GeV^2. Dash-dotted line — pure Deck model; dashed line — Deck model with final-state $\pi\pi$ interactions; solid line — Deck model with FSI and the short-range term; dotted line — contribution of the contact term; gray/red points — CLAS fit to the experimental data. The band shows the total uncertainty of the fit.

Figure 3 shows that inclusion of the final-state interactions in the Deck D-wave amplitude, similarly as in the P-wave, results in developing the minimum rather than the maximum for the invariant masses around the $f_2(1270)$. The minimum in the D-wave is due to the $\pi\pi$ phase shift passing

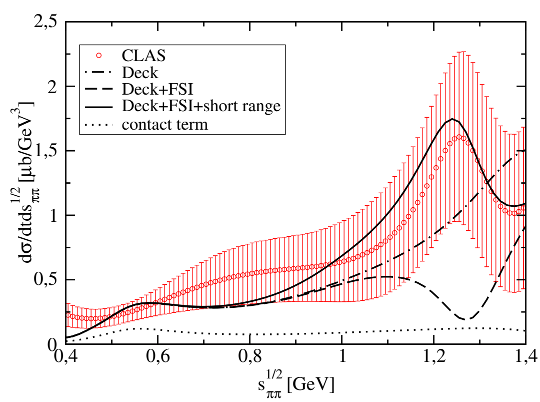

Fig. 3. (Color online) D-wave double differential cross section at $E_\gamma = 3.3$ GeV and $-t = 0.55$ GeV^2 with $M \leq 1$. Dash-dotted line — pure Deck model; dashed line — Deck model with final-state $\pi\pi$ interactions; solid line — Deck model with FSI and the short-range term; dotted line — contribution of the contact term; gray/red points — CLAS fit to the experimental data. The band shows the total uncertainty of the fit.

$\pi/2$ at about 1.25 GeV. This observation is compatible with previous analyses [7]. The model develops the maximum in the D-wave if the short-range component with parameters $A_2 = -24 \pm 11$ GeV^{-1} and $B_2 = 10 \pm 7$ GeV^{-3} is included. The contribution of the contact term has little effect in the P- and D-waves and is more pronounced in the S-wave. However, in all considered waves, it results in producing a tiny bump below 0.6 GeV. More detailed discussion of the mass distribution properties and definitions of partial wave amplitudes can be found in [8].

4. Summary

We have shown that photoproduction mechanism of the $\pi^+\pi^-$ resonances in low partial waves can be treated as a superposition of two production modes. The diffuse source (long range) mode can be attributed to pion exchange and is dominated by the singularity which is closest to the physical region. The compact source (short range) mode collectively includes exchanges of heavier particles together with quark/gluon processes. Our approach turns out to be successful in description of mass distributions in S-, P- and D-waves and properly reproduces the fact that they are dominated by $f_0(980)$, $\rho(770)$ and $f_2(1270)$ resonances, respectively. Moreover, the large relative magnitude of the short-range components of P and D partial wave amplitudes confirms the expectation that resonances in these waves are conventional $q\bar{q}$ states. On the other hand, the compact source component of the $f_0(980)$ photoproduction amplitude is smaller which implies that this resonance is rather a weakly bound tetraquark state.

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