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Role of photoproduction in exotic meson searches

Adam P. Szczepaniak, Maciej Swat

Physics Department and Nuclear Theory Center, Indiana University, Bloomington, IN 47405, USA

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Abstract

We discuss two production mechanisms of the $J^{\mathrm{PC}} = 1^{-+}$ exotic meson, hadroproduction, using pion beams and photoproduction. We show that the ratio of exotic to nonexotic, in particular the a_2, meson-production cross sections is expected to be by a factor of 5 to 10 larger, in photoproduction then in hadroproduction. Furthermore we show that the low-t photoproduction of exotic meson is enhanced as compared to hadronic production. This findings support the simple quark picture in which exotic meson production is predicted to be enhanced when the beam is a virtual $Q\overline{Q}$ pair with a spin-1 (photon) rather then with a spin-0 (pion). © 2001 Published by Elsevier Science B.V.

1. Introduction

Present understanding of confinement is still mostly qualitative. Even though in recent years significant progress has been made in lattice gauge studies of QCD, the dynamics of confinement, especially in association with light quarks, remains mysterious. Similarly, it remains to be verified whether soft gluonic excitations responsible for confinement are present in the low energy resonance spectrum.

In the past few years, a number of strong candidates for states lying outside the valence quark model spectrum have been reported. Examination of the scalar–isoscalar mesons produced in $p\bar{p}$ annihilation [1], central production and J/ψ [2] radiative decays [3] indicates that in the 1–2 GeV mass range there is an overpopulation of states as compared to predictions of the valence quark model. Furthermore analysis of the decay patterns seems to indicate that some of these states may have a significant non-$Q\overline{Q}$ component. Since these states can mix with the regular $Q\overline{Q}$ mesons the non-$Q\overline{Q}$ components cannot be disentangled in a model independent way. A much cleaner signatures for non-$Q\overline{Q}$ and/or gluonic excitations could come from exotic states. By definition, these are states which have combinations of spin, parity and charge conjugation quantum numbers that cannot be attributed to the valence quark degrees of freedom, e.g., $J^{\mathrm{PC}} = 0^{--}, 0^{+-}, 1^{-+}, \ldots$. Recently, the E852 BNL Collaboration has reported an exotic, resonant signal with $J^{\mathrm{PC}} = 1^{-+}$ in the reaction $\pi^- p \to Xp$ at 18 GeV in two decay channels, $X \to \rho\pi$ [4] and $\eta'\pi$ [5] corresponding to the resonance mass of $M_X \approx 1.6$ GeV and width of $\Gamma \approx 170$ MeV and $\Gamma \approx 340$ MeV in the two channels, respectively. The existence of the $J^{\mathrm{PC}} = 1^{-+}$ exotic meson below 2 GeV has been reported elsewhere [6]. Furthermore, lattice and model calculations indicate that the lightest exotic meson indeed should have $J^{\mathrm{PC}} = 1^{-+}$ and mass below 2 GeV [7–9].

The exotic resonance measured by the E852 Collaboration is observed to be produced predominantly via natural parity exchange, and so is the nearby $a_2(1320)$

E-mail address: aszczepa@indiana.edu (A.P. Szczepaniak).

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resonance. The later is a well established regular $Q\overline{Q}$ state. Furthermore, in the $\rho\pi$ decay channel the exotic wave is observed to be roughly 5% of the a_2 wave. In the $\eta'\pi$ channel the exotic signal seems to be much stronger but it is also much broader.

It has been argued that real photons may be a better source of exotic mesons in high-s, low-t reactions [10]. The argument is based on a simple quark picture. At high energies, photon couples to the $Q\overline{Q}$ pair in total helicity-1 state, corresponding (in the $Q\overline{Q}$ rest frame) to the quark–antiquark pair being in the spin-1 configuration. The majority of models dealing with soft gluons predict that the low lying gluonic excitations are in the TE mode, i.e., with $J_g^{\rm PC} = 1^{+-}$ [9,11]. This is also supported by the recent lattice calculations of the excited adiabatic potentials for heavy quarkonia [8]. As a consequence, the 1^{-+} ground state has the $Q\overline{Q}$ pair in $S = 1$, so that $J^{\rm PC}_{Q\overline{Q}} \times J_g^{\rm PC} = 1^{--} \times 1^{+-} = 1^{-+}$. Thus, according to this simple quark picture one would expect exotic mesons production to be enhanced in reactions with real photon ($Q\overline{Q}$ in spin-1) as compared to reactions with pseudoscalar (π, K) meson beams.

In this Letter we show that this microscopic picture is supported by the standard, Regge phenomenology of high-s, low-t peripheral production. In particular we show that exotic meson production is expected to be comparable to production of other, nonexotic resonances in particular the a_2 meson, and to be enhanced at low-t as compared to hadronic production with pion beams.

2. Peripheral meson production

We begin with the analysis of the reaction $\pi N \to XN \to M_1 \dots M_n N$ at high-s and low-t. In particular, a good candidate decay channel for exotic meson searches is $M_1 \dots M_n = (3\pi)^{\pm}$. The charged 3π system has $I = 1$ and $G = -1$, thus assuming isospin invariance a resonating 3π P-wave belongs to the exotic 1^{-+} isovector multiplet (a neutral 3π system will overlap with the isospin-0, i.e., nonexotic, 1^{--}, ω-like resonance). The E852 data corresponds to $\pi^- p \to \pi^+\pi^-\pi^- p$ at the lab energy $p_L = 18$ GeV [4]. The 3π mass spectrum is dominated by the $a_2(1320)$ $J^{\rm PC} = 2^{++}$ resonance and at higher mass, the $\pi_2(1600)$ with $J^{\rm PC} = 2^{-+}$ is seen together with a small $\pi_1(1600)$, $J^{\rm PC} = 1^{-+}$ exotic signal. Both the a_2 and the exotic, π_1 resonances are observed to be produced via natural parity exchange and appear in the $D_+ = 1/\sqrt{2}(D_{M=1} + D_{M=-1})$ and P_+ waves, respectively. Here D_M, P_M, etc. refer to the t-channel (Gottfried–Jackson) amplitudes corresponding to the spin quantization axis along the direction of the beam in the resonance rest frame. In the following we will make a simplifying assumption that the natural parity exchange can be saturated by the ρ-trajectory. This is certainly a good assumption for the case of a charge exchange reaction, e.g., $\pi^- p \to \pi^+\pi^-\pi^0 n$ [12]. In the neutral case ρ-exchange should be supplemented by the f_0 and/or Pomeron exchange contributions [13]. In the later case, which, corresponds to the E852 measurement, the estimates for the exotic meson natural exchange amplitude should be considered as an upper bound. The ρ and scalar meson exchange contribute mainly to the nucleon helicity-flip and -nonflip, respectively, i.e., are essentially noninterfering. The E852 data lacks absolute normalization therefore we can only use it to establish the relative strength of the exotic to a_2 production yields. We will compare our predictions for the charge exchange a_2 production with the data from Ref. [12].

The t-channel amplitude for the reaction $\pi^- p \to X^0 n$ producing a natural parity, $J^{\rm PC}$ resonance via ρ-exchange can be written as $A = A(s, t, \lambda' N, \lambda_N, \lambda)$ (neglecting the pion mass),

$$A_\pi = g_{X\rho\pi} \sqrt{\frac{2J+1}{4\pi}} \sqrt{\frac{-t'}{4m_N^2}}\, R_\rho(t,s)\, e^{b_\rho t/2} \times \left(\frac{m_X^2 - t}{2m_X^2}\right)^{J-1} \left[G_V I + \sqrt{\frac{-t'}{4m_N^2}} G_T i\sigma_2\right]_{\lambda'_N, \lambda_N}, \tag{1}$$

where λ'_N, λ_N are the recoil and target nucleon helicities, G_V and G_T are the vector and tensor (helicity nonflip, and flip) ρNN couplings and $R(t,s)$ is the ρ meson, Regge propagator:

$$R(s,t) = \frac{1}{2}\left(1 - e^{i\pi\alpha_\rho(t)}\right) \Gamma\left(1 - \alpha_\rho(t)\right) (\alpha' s)^{\alpha_\rho(t)}, \tag{2}$$

with $\alpha_\rho(t) = 1 + \alpha'(t - m_\rho^2)$ and $\alpha' = 0.9\ {\rm GeV}^{-2}$.

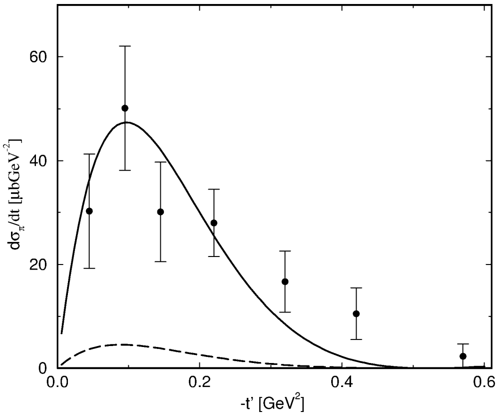

Fig. 1. Comparison of the $a_2(1320)$-regular meson (solid) and $\pi_1(1600)$-exotic meson (dashed) production cross sections in reaction $\pi^- p \to X\pi^+\pi^-\pi^0 n$ at $p_\pi = 18$ GeV. The data correspond to a_2 production at 15 GeV.

The $g_{X\rho\pi}$ coupling is normalized so that the partial $\rho\pi$ width of the natural parity resonance is given by

$$\Gamma_{X\to\rho\pi} = m_X \frac{g^2_{X\rho\pi}}{32\pi^2}\left(\frac{q}{m_X}\right)^{2J+1}, \tag{3}$$

with q being the on-shell breakup momentum, $q = \lambda(M_X, m_\pi, m_\rho)$. Finally, the differential cross section is then given by

$$\frac{d\sigma}{dt} = \frac{389\,\mu\text{b}\,\text{GeV}^2}{64\pi m_N^2 p_L^2}\frac{1}{2}\sum_{\lambda'_N,\lambda_N,\lambda_X}|A|^2. \tag{4}$$

For the a_2, the $\rho\pi$ partial width is known [14], $\Gamma_{a2\rho\pi} = 0.7 \times 110$ MeV. Since we are primarily interested in comparing the a_2 and the π_1, exotic meson we will consider the production at $p_L = 18$ GeV corresponding to the E852 data. Prediction for the differential cross section for the a_2 following from Eq. (1) is shown by the solid line in Fig. 1. This can be compared with the $p_L = 15$ GeV charge exchange data from Ref. [12]. The vector and tensor ρNN couplings used are somewhat larger, $G_V = 5.9$, $G_T = 27.7$ then the “standard” parameters ($G_V = 2.3$, $G_T = 18.4$) and come from what is referred to as the “theoretical” parameterization in Ref. [15]. One should note however, that even the “standard” parameters which come from the non-Regge ρ propagator after changing to the Regge propagators should be renormalized which enhances their values [16]. The characteristic dip at $t \sim -0.5\ \text{GeV}^2$ may be washed out by absorption (Regge + Pomeron) rescattering corrections. Finally the low value of slope parameter $b_\rho = 2$–$3\ \text{GeV}^{-2}$ in the residue function is typical to the ρ-exchange.

The E852 result indicates that the π_1 exotic wave found in the $\rho\pi$ channel has the total width of $\Gamma_{\pi_1} \approx 170$ MeV and corresponds to about 5% strength of the a_2. The π_1 production is then expected to scale according to

$$\begin{aligned}\frac{\sigma_{\pi^- p\to\pi_1^0 n}}{\sigma_{\pi^- p\to a_2^0 n}} &\approx \frac{\sigma_{\pi^- p\to\pi_1^- p}}{\sigma_{\pi^- p\to a_2^- p}}\\ &\approx \frac{\sigma_{\pi N\to\pi_1 N\to\rho\pi N}}{\sigma_{\pi N\to a_2 N\to\rho\pi N}}\,\frac{\Gamma_{a_2\to\rho\pi}}{\Gamma_{a_2}}\,\frac{\Gamma_{\pi_1}}{\Gamma_{\pi_1\to\rho\pi}}\\ &\approx 5\% \times 0.7 \times \frac{\Gamma_{\pi_1}}{\Gamma_{\pi_1\to\rho\pi}}.\end{aligned} \tag{5}$$

The above relation enables to determine the $g_{\pi_1\rho\pi}$ coupling. We find that the $\Gamma_{\pi_1\to\rho\pi}$ partial width is approximately 40% of the total $\Gamma_{\pi_1} = 170$ GeV width. The t-dependence of the differential cross section for π_1 production is shown by the dashed line in Fig. 1. As expected it has a similar t-dependence to the a_2 production, since under assumption that the ρ-exchange dominates, the only difference comes from the angular momentum barrier factors,

$$\begin{aligned}\frac{d\sigma_{\pi^- p\to\pi_1^0 N}}{d\sigma_{\pi^- p\to a_2^0 n}} &= \frac{3g^2_{\pi_1\rho\pi}}{5g^2_{a_2\rho\pi}}\left(\frac{2m^2_{a_2}}{m^2_{a_2}-t}\right)^2 \approx 4\frac{3g^2_{\pi_1\rho\pi}}{5g^2_{a_2\rho\pi}}\\ &= 10\%,\end{aligned} \tag{6}$$

in agreement with the E852 result [4] scaled by the coupling to the $\rho\pi$ decay channel. Thus according the the E852 measurement the exotic pion-production cross section is a small fraction of the a_2 production cross section. The corresponding couplings are calculated to be $g_{a2\rho\pi} \approx 75$ and $g_{\pi_1\rho\pi} \approx 16$.

We will now discuss charge exchange photoproduction. The dominant production amplitude is now expected to come from one-pion-exchange with the photon acting, through VMD as a vector meson-ρ beam. On the basis of VMD we would expect

$$g^{\text{VMD}}_{\pi_1\gamma\pi} = \frac{\sqrt{4\pi\alpha}}{f_\rho}C_f\, g_{\pi_1\rho\pi} \approx 0.04 g_{\pi_1\rho\pi} = 0.7. \tag{7}$$

The radiative, a_2 width is known [14], $\Gamma_{a_2\gamma\pi} = 295$ keV which gives $g_{a_2\gamma\pi} = 1.55$. The above VMD relation yields,

$$g^{\mathrm{VMD}}_{a_2\gamma\pi} = \frac{\sqrt{4\pi\alpha}}{f_\rho} C_f\, g_{a_2\rho\pi} \approx 0.04 g_{a_2\rho\pi} = 3. \tag{8}$$

Here $C_f = 1/\sqrt{2} = g_{X^\pm\rho^0\pi^\pm}/g_{X\rho\pi}$. Thus for the radiative widths we expect the VMD to be accurate within a factor of two. The charge-exchange, OPE photoproduction amplitude is given then by

$$\begin{aligned} A_\gamma = {} & m_X g_{X\rho\pi}\sqrt{\frac{2J+1}{4\pi}}\frac{[\sigma^3]_{\lambda_X\lambda_\Gamma}}{\sqrt{2}} g_{\pi NN}\big[\sigma^1\big]_{\lambda'_N\lambda_N} \\ & \times \sqrt{\frac{-t'}{4m_N^2}}\, R_\pi(t,s)\,\mathrm{e}^{b_\pi t/2}\left(\frac{m_X^2 - t}{2m_X^2}\right)^J, \end{aligned} \tag{9}$$

with

$$R(s,t) = \frac{1}{2}\big(1+\mathrm{e}^{\mathrm{i}\pi\alpha_\pi(t)}\big)\Gamma\big(-\alpha_\pi(t)\big)\alpha'(\alpha' s)^{\alpha_\pi(t)} \tag{10}$$

being the π Regge propagator with $\alpha_\rho(t) = \alpha'(t - m_\rho^2)$ and $g_{\pi NN} = 35.5$ GeV.

The existing data on a_2 photoproduction comes from two SLAC bubble chamber experiments one at the average photon energy of $E_\gamma = p_L = 4.8$ GeV [17] and other at $E_\gamma = 19$ GeV [18]. The corresponding total cross sections are measured to be $\sigma_{\gamma p\to a_2^+ n} \approx 2.6$ µb and 0.3 µb, respectively. The data for differential cross section for the lower-energy experiment is shown in Fig. 2 after rescaling by a factor of 2.6 as explained in Ref. [18]. This should be compared with the cross section predicted from Eq. (9) (dashed line). The comparison is quite good, indicating, however need for some absorption corrections [17,19]. We will now compare the prediction for the exotic π_1 photoproduction with that for the a_2. We make the comparison for the photon energy, $E_\gamma = 8$ GeV as proposed for the Hall D experiments at JLab. This is shown in Fig. 2. The solid line is the prediction for the a_2 production and the shaded region depicts the expected cross section for the π_1 using the radiative width in the range $300 < \Gamma_{\pi_1\gamma\pi} < 400$ keV which covers the typical range of radiative widths of ordinary mesons in this mass range and includes the VMD prediction, $(\Gamma^{\mathrm{VMD}} = m_X (g^{\mathrm{VMD}}_{\pi_1\gamma\pi})^2 (q/m_X)^3/32\pi^2 = 360\ \mathrm{keV})$.

It is interesting to compare the predicted ratio of the π_1 to a_2 photoproduction cross section. In analogy to Eq. (6), we get

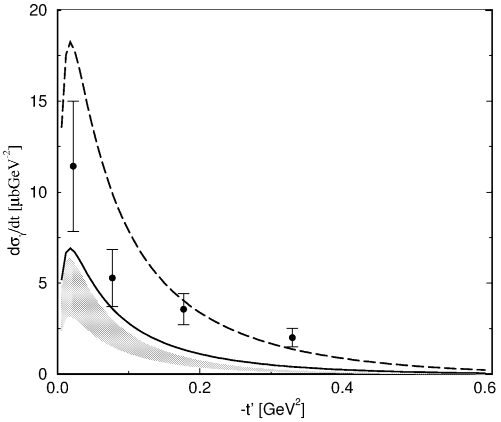

Fig. 2. Comparison of $a_2(1320)$ (solid) and exotic, $\pi_1(1600)$ (shaded region) production cross sections in reaction $\gamma p \to X^+ n$ at $p_\gamma = 8$ GeV. The data correspond to charge exchange a_2 production at 4.8 GeV and the theoretical prediction for a_2 at this energy is shown by the dashed line. The lowest (highest) prediction for exotic meson production given by the shaded region corresponds to $\Gamma_{\pi_1\gamma\pi} = 200(400)$ keV, respectively.

$$\begin{aligned} \frac{\mathrm{d}\sigma_{\gamma p\to\pi_1^+ n}}{\mathrm{d}\sigma_{\gamma p\to a_2^+ n}} &= \frac{3g^2_{\pi_1\gamma\pi}}{5g^2_{a_2\gamma\pi}}\frac{m^2_{\pi_1}}{m^2_{a_2}}\left(\frac{m^2_{\pi_1} - t}{2m^2_\pi}\right)^2\left(\frac{2m^2_{a_2}}{m^2_{a_2} - t}\right)^4 \\ &\approx 4\frac{3g^2_{\pi_1\gamma\pi}}{5g^2_{a_2\gamma\pi}}\frac{m^2_{\pi_1}}{m^2_{a_2}} \approx 50\%\text{–}100\% \end{aligned} \tag{11}$$

and, for small-t,

$$\frac{\mathrm{d}\sigma_{\gamma p\to\pi_1^+ n}/\mathrm{d}\sigma_{\gamma p\to a_2^+ n}}{\mathrm{d}\sigma_{\pi^- p\to\pi_1^0 n}/\mathrm{d}\sigma_{\pi^- p\to a_2^0 n}} \approx 5\text{–}10. \tag{12}$$

3. Conclusions

We have estimated the exotic meson photoproduction rate based on the existing data on hadronic production with pion beams. From the E852 $\pi^- p \to Xp \to \rho\pi p$ data it follows that the exotic production is suppressed by roughly a factor of 10 as compared to the $a_2(1320)$ production. We find, however, this is not the case in reactions with photon beams. Based on the rate estimate from the E852 data we conclude that in photoproduction the π_1 and a_2 production should be comparable.

There main reasons for enhancement of exotic production is that the exotic meson photocoupling is not suppressed. This follows from simple kinematical constraints. The angular momentum barrier factors enhance the ratio of exotic to a_2 photocouplings over the respective ratio of hadronic, $\rho\pi$ couplings. Assuming similar hadronic $X \to \rho\pi$ and radiative, $X \to \gamma\pi$ decay widths,

$$\frac{g^2_{\pi_1\gamma\pi}/g^2_{a_2\gamma\pi}}{g^2_{\pi_1\rho\pi}/g^2_{a_2\rho\pi}} = \left(\frac{\lambda(m_{a_2}, \rho, \pi)/\lambda(m_{\pi_1}, \rho, \pi)}{\lambda(m_{a_2}, 0, \pi)/\lambda(m_{\pi_1}, 0, \pi)}\right)^2 \approx 4. \tag{13}$$

Secondly since the small-t behavior is determined by the helicity structure of the production amplitude, both the exotic and a_2 are enhanced at low-t in photoproduction via OPE as compared to hadronic production via ρ-exchange. This is due to the vector nature of the photon which transfers its helicity to the produced meson. This is not the case for the pion beam, where helicity of the produced meson has to be transferred from the exchanged (vector) meson, and thus making the amplitude suppressed with $\sqrt{-t'}$. These findings are important for exotic mesons searches in future photoproduction experiments in Hall D at the JLab.

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