SCALAR PHOTOPRODUCTION ON THE PROTON AT CLAS AND GlueX ENERGIES*

M.L.L. da Silva

Instituto de Física e Matemática, Universidade Federal de Pelotas
Caixa Postal 354, CEP 96010-090, Pelotas, RS, Brazil

M.V.T. Machado

Instituto de Física, Universidade Federal do Rio Grande do Sul
Caixa Postal 15051, CEP 91501-970, Porto Alegre, RS, Brazil

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In this work, we present the results of a theoretical analysis of the data on photoproduction of $f_0(980)$ meson in the laboratory photon energy between 3.0 GeV and 3.8 GeV. A comparison is done to the measurements performed by the CLAS Collaboration at JLab accelerator for the exclusive reaction $\gamma p \to p f_0(980)$. The differential and integrated total cross sections are also computed for the cases of the mesons $f_0(1500)$, and $f_0(1710)$, focusing on the GlueX energy regime with photon energy $E_\gamma = 9$ GeV.

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1. Introduction

The spectroscopy of the low mass scalar mesons is an exciting issue in hadronic physics and is still an unsettled question. Such a conflicting interpretation comes from the fact that the situation is complex in low energies where quantitative predictions from QCD are challenging and rely mostly on numerical techniques of lattice QCD. In this context, the photoproduction of exotic mesons [1] can be addressed using arguments based on vector-meson dominance where the photon can behave like an $S = 1$ quark–antiquark system. Therefore, such a system is more likely to couple to exotic quantum number. Such a process could provide an alternative to the direct observation of the radiative decays at low energies. Along those lines, the

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GlueX experiment [2] is being installed and its primary purpose is to understand the nature of confinement in QCD by mapping the spectrum of exotic mesons generated by the excitation of the gluonic field binding the quarks. The mesons $f_0(1500)$ and $f_0(1710)$ are considered good candidates for the scalar glueball [3, 4]. However, in this mass region, the glueball state will mix strongly with nearby $q\bar{q}$ states [5, 6]. The unknown about the mixing parameters still remains, on this way some proposal to set the parameters is very important to determine the structure of these resonances.

The scenarios discussed in this paper consider the $f_0(980)$ as a tetraquark or as a ground state nonet. We focus on the S-wave analysis on the forward photoproduction of $\pi^+\pi^-$ in the final state. We also investigate the mixing in $f_0(1500)$ and $f_0(1710)$ resonances. The theoretical formalism employed is the Regge approach with reggeized ρ and ω exchange [7]. This assumption follows from Regge phenomenology where high-energy amplitudes are driven by t-channel meson exchange.

2. Model and cross section calculation

According to the Regge phenomenology, one expects that only the t-channel meson exchanges are important in such a case. The reaction proposed here is $\gamma p \to p\, f_0(M)$. In the context of the Regge phenomenology, the narrow-width differential cross section for a meson of mass $m_{\rm S}$ is given by [7]

$$\frac{d\hat{\sigma}}{dt}\left(\gamma p \to pM\right) = \frac{|\mathcal{M}(s,t)|^2}{64\pi\,\left(s-m_p^2\right)^2}\,, \tag{1}$$

where $\mathcal{M}$ is the scattering amplitude for the process, s, t are usual Mandelstam variables and m_p is the proton mass. For the exchange of a single vector meson, *i.e.* ρ or ω, one has

$$\begin{aligned}|\mathcal{M}(s,t)|^2 \;=\; & -\tfrac{1}{2}\mathcal{A}^2(s,t)\left[\, s(t-t_1)(t-t_2) + \tfrac{1}{2}t\left(t^2 - 2\left(m_{\rm S}^2+s\right)t + m_{\rm S}^4\right)\right] \\ & -\mathcal{A}(s,t)\mathcal{B}(s,t)m_p s(t-t_1)(t-t_2) \\ & -\tfrac{1}{8}\mathcal{B}^2(s,t)s\left(4m_p^2-t\right)(t-t_1)(t-t_2)\,,\end{aligned}$$

where t_1 and t_2 are the kinematical boundaries

$$\begin{aligned}t_{1,2} \;=\; & \frac{1}{2s}\Big[-\left(m_p^2-s\right)^2 + m_{\rm S}^2\left(m_p^2+s\right) \\ & \pm\left(m_p^2-s\right)\sqrt{\left(m_p^2-s\right)^2 - 2m_s^2\left(m_p^2+s\right)+m_{\rm S}^4}\,\Big]\,,\end{aligned} \tag{2}$$

and where one uses the standard prescription for Reggeising the Feynman propagators assuming a linear Regge trajectory $\alpha_{\rm V}(t) = \alpha_{\rm V0} + \alpha'_{\rm V} t$ for writing down the quantities $\mathcal{A}(s,t)$ and $\mathcal{B}(s,t)$

$$\begin{aligned} \mathcal{A}(s,t) &= g_A \left(\frac{s}{s_0}\right)^{\alpha_{\rm V}(t)-1} \frac{\pi\alpha'_{\rm V}}{\sin(\pi\alpha_{\rm V}(t))} \frac{1-e^{-i\pi\alpha_{\rm V}(t)}}{2\,\Gamma(\alpha_{\rm V}(t))}\,, \\ \mathcal{B}(s,t) &= -\frac{g_B}{g_A}\,\mathcal{A}(s,t)\,. \end{aligned} \tag{3}$$

It is assumed non-degenerate ρ and ω trajectories $\alpha_{\rm V}(t) = \alpha_{\rm V}(0) + \alpha'_{\rm V} t$, with $\alpha_{\rm V}(0) = 0.55\,(0.44)$ and $\alpha'_{\rm V} = 0.8\,(0.9)$ for ρ (ω). In Eq. (3) above, one has that $g_A = g_{\rm S}(g_{\rm V} + 2m_p g_{\rm T})$ and $g_B = 2g_{\rm S}g_{\rm T}$. The quantities $g_{\rm V}$ and $g_{\rm T}$ are the VNN vector and tensor couplings, $g_{\rm S}$ is the γVN coupling. For the ωNN couplings, we have set $g^{\omega}_{\rm V} = 15$ and $g^{\omega}_{\rm T} = 0$ [7] and for the ρNN couplings, we used $g^{\rho}_{\rm V} = 3.4$, $g^{\rho}_{\rm T} = 11$ GeV^{-1}. The $SV\gamma$ coupling, $g_{\rm S}$, can be obtained from the radiative decay width through [8]

$$\Gamma(S \to \gamma V) = g_{\rm S}^2 \frac{m_{\rm S}^3}{32\pi}\left(1 - \frac{m_{\rm V}^2}{m_{\rm S}^2}\right)^3 . \tag{4}$$

This model was applied on $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$ mesons which was considered as mixing of $n\bar{n}$, $s\bar{s}$ and glueball states [9]. In this case, their radiative decays to a vector meson are expected to be highly sensitive to the degree of mixing between the $q\bar{q}$ basis and the glueball. The numerical values for the widths having effects of mixing on the radiative decays of the scalars on ρ and ω can be found in Table 1 of Ref. [7]. In this way, it is clear that the width is strongly model dependent and different approaches must be taken into account. For instance, we quote the work in Ref. [10], where the decays of a light scalar meson into a vector mesons and a photon, $S \to V\gamma$, are evaluated in the tetraquark and quarkonium assignments of the scalar states. The coupling now reads

$$\Gamma(S \to \gamma V) = g_{\rm S}^2 \frac{\left(m_{\rm S}^2 - m_{\rm V}^2\right)^3}{8\,\pi\, m_{\rm S}^3}\,. \tag{5}$$

The different nature of the couplings corresponds to distinct large-$N_{\rm c}$ dominant interaction Lagrangians. For more details on this calculation, see Refs. [7, 11].

3. Results and discussions

In what follows, we present the numerical results for the direct $f_0(980)$ photoproduction considered in the present study and the consequence of

the tetraquark and quarkonium assignments of the scalar states discussed in previous section and in Ref. [11]. The results presented here will consider five distinct scenarios, three of them assuming that $f_0(980)$ is a quarkonium and two assuming that $f_0(980)$ is a tetraquark. In scenarios 1, 2 and 3, the $f_0(980)$ will be interpreted as a ground-state nonet and in scenarios 4 and 5, as a tetraquark. The g_S coupling can be obtained from the radiative decay width in Table 1 of Ref. [11] using Eq. (4) for scenario 1 and using Eq. (5) for the remaining scenarios. The radiative decay in scenarios 3 and 5 have considered f_0 resonance as quarkonium and tetraquark including Vector Meson Dominance as discussed in Ref. [10].

The partial S-wave differential cross sections for the $f_0(980)$ are presented in Fig. 1 (left panel) at $E_\gamma = 3.4 \pm 0.4$ GeV and integrated in the $M_{\pi\pi}$ mass range 0.98 ± 0.04 GeV. The dip at $-t \approx 0.7$ GeV^2 related to the reggeized meson (ρ and ω) exchange. The scenarios 1 and 4 are represented by the solid and dot-dashed lines, respectively. Both of them fairly reproduce the trend of CLAS data. The remaining scenarios are above or below the CLAS data points by a factor of 50.

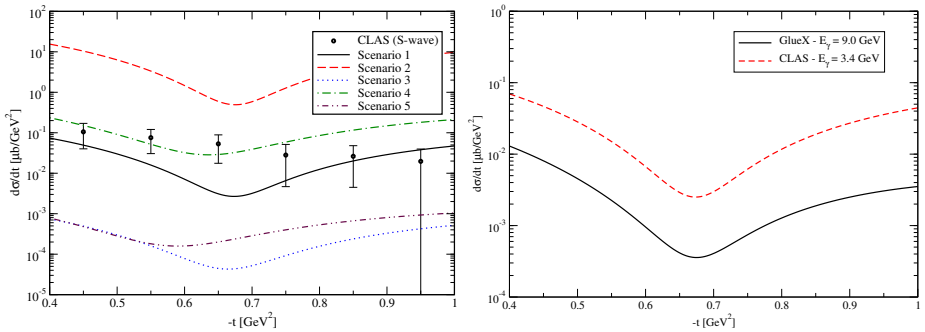

Fig. 1. The S-wave differential photoproduction cross section for $f_0(980)$ photoproduction as a function of momentum transfer squared at CLAS experiment energy $E_\gamma = 3.4$ GeV (left panel). We show a comparison between the differential cross section for $f_0(980)$ in scenario 1 at CLAS and GlueX energies (right panel).

The theoretical predictions are compared to the CLAS analysis at the Jefferson Lab [12], where the $\pi^+\pi^-$ photoproduction at photon energies between 3.0 and 3.8 GeV has been measured in the interval of momentum transfer squared $0.4 \leq |t| \leq 1.0$ GeV^2. There, the first analysis of S-wave photoproduction of pion pairs in the region of the $f_0(980)$ was performed. The interference between P and S waves at $M_{\pi\pi} \approx 1$ GeV clearly indicated the presence of the f_0 resonance. The exclusive reaction $\gamma p \to p f_0$ was measured through the most sizable decay mode which is $f_0(980) \to \pi^+\pi^-$.

In figure 1 (right panel), we show a comparison between the S-wave differential photoproduction cross section for $f_0(980)$ in the CLAS ($E_\gamma = 3.4$ GeV) and GlueX ($E_\gamma = 9$ GeV) energies. In this plot, we consider the coupling $g_{K\bar{K}} = 0.4$, $g_{\pi\pi} = 1.31$ GeV and the g_S coupling for scenario 1. The results in Fig. 1 (right panel) show that the differential cross section for $E_\gamma = 9$ GeV is about an order of magnitude smaller than for $E_\gamma = 3.4$ GeV.

The differential cross sections for $f_0(1500)$ and $f_0(1710)$ are presented in Fig. 2 at $E_\gamma = 9$ GeV, and showing the consequences of distinct mixing scenarios. In scenario (I) the cross section is higher than in the other scenarios. That is, a light glueball mass implies a larger cross section for the $f_0(1500)$ mesons. On the other hand, the inverse situation occurs for the $f_0(1710)$ mesons, where the large cross section comes from the heavy glueball mass component. The cross sections reflect directly the radiative decay widths as can be verified from simple inspection of Table 1 of Ref. [7]. For completeness, the integrated cross sections for photoproduction of the scalars on protons at $E_\gamma = 9$ GeV are given in Table I for light (I), medium (II) and heavy (III) glueball masses.

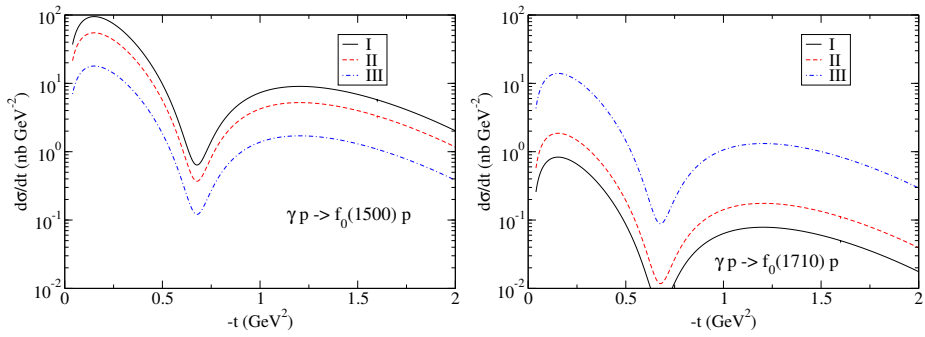

Fig. 2. Differential photoproduction cross section on proton for $f_0(1500)$ (left panel) and $f_0(1710)$ (right panel) at GlueX energy $E_\gamma = 9$ GeV. The results for the distinct three mixing scenarios are presented: (I) — solid line, (II) — dashed line and (III) — dot-dashed line.

TABLE I

Integrated photoproduction cross sections in nanobarns on protons at $E_\gamma = 9$ GeV for the three different mixing scenarios: light (I), medium-weight (II) and heavy glueball (III) (see the text).

Scenario	(I)	(II)	(III)
$f_0(1500)$	34.98	20.25	6.61
$f_0(1710)$	0.30	0.68	5.08

In summary, we have studied the photoproduction of $f_0(980)$ resonance for photon energies considered in the CLAS experiment, $E_\gamma = 3.4 \pm 0.4$ GeV and in the GlueX experiment, $E_\gamma = 9$ GeV. It provides a test for current understanding of the nature of the scalar resonances. We have calculated the differential cross sections as function of effective masses and momentum transfers. The effect of distinct scenarios in the calculation of coupling $S \to V\gamma$ were investigated. This investigation shows that we need to know more precisely the radiative decay rates for $f_0(980) \to \gamma V$ which are important to this calculation. Our predictions of the cross sections are somewhat consistent with the experimental analysis from the CLAS Collaboration. The present experimental data are able to exclude some possibilities for the $S \to V\gamma$ coupling. An estimation of the differential cross section for the GlueX experiment is also presented. We also have studied the photoproduction of the $f_0(1500)$ and $f_0(1710)$ resonances for photon energies relevant for the GlueX experiment at photon energy of 9 GeV. It would provide novel tests for our understanding of the nature of the scalar resonances and about current ideas on glueball and $q\bar{q}$ mixing. The meson differential and integrated cross sections were evaluated and the effect of distinct mixing scenarios were investigated. Although large backgrounds are expected, the signals could be visible by considering only the all-neutral channels, that is their decays on $\pi^0\pi^0$, $\eta^0\eta^0$ and $4\pi^0$. The theoretical uncertainties are still large, with $f_0(1500)$ the more optimistic case. Finally, an experiment in nuclei would also lead to the f_0 and a_0 excitation mostly from the collision of protons with protons.

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