SCALAR MESON PHOTOPRODUCTION

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Abstract

The scalar mesons $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$ are of interest as there is as yet no consensus of their status, or indeed of the existence of the $f_0(1370)$. Radiative decays to $\rho$ and $\omega$ have been shown to provide effective probes of their structure and to discriminate among models. Scalar-meson photoproduction is proposed as an alternative and it is shown that it represents a feasible approach.

1 Introduction

The fundamental structure of the light scalar mesons is still a subject of debate. The $a_0(1450)$ and the $K^*_0(1430)$ are generally regarded as the $u\bar{d}$ and $u\bar{s}$ members of the same SU(3) flavour nonet, to which the $f_0(1370)$ can be attached as the $(u\bar{u} + d\bar{d})$ member[1]. There then remain two possibilities for the ninth member of the nonet, the $f_0(1500)$ and the $f_0(1710)$. In this picture, it is usually assumed that the surplus of isoscalar scalars in the 1300 to 1700 MeV mass region can be attributed to the presence of a scalar glueball. This assumption has been supported in the past by calculations in quenched LQCD, which predict a scalar glueball in this mass range[2]. The three physical states are then viewed as mixed $q\bar{q}$ and gluonium states, although there is not agreement in detail about the mixing[3, 4]. However calculations in unquenched LQCD[5] suggest that there is a sizeable contribution from glueball interpolating operators to the states around or below 1 GeV, casting some doubt on the mixing models. Further, it has been argued that the $f_0(1370)$ may not exist[6, 7]. This is strongly contested by Bugg[8]. If the $f_0(1370)$ does not exist the lowest scalar nonet can be taken to comprise the $a_0(980)$, the $f_0(980)$, the $f_0(1500)$ and the $K^*_0(1430)$, the $f_0(980)$ and the $f_0(1500)$ being mixed such that the former is close to a singlet and the latter close to an octet. The lightest scalar glueball is then considered to be a broad object extending from 400 MeV to about 1700 MeV. So a variety of interpretations is possible.

Radiative transitions offer a particularly powerful means of probing the structure of hadrons as the coupling to the charges and spins of the constituents reveals detailed
information about wave functions and can discriminate among models. In the case of the \( f_0(1370) \), \( f_0(1500) \) and \( f_0(1710) \) being considered as mixed \( n\bar{n} \), \( s\bar{s} \) and glueball states their radiative decays to a vector meson, \( S \to V\gamma \), are strongly affected by the degree of mixing between the basis \( q\bar{q} \) states and the glueball\[9\]. Three different mixing scenarios have been proposed: the bare glueball is lighter than the bare \( n\bar{n} \) state\[4\]; its mass lies between the bare \( n\bar{n} \) state and the bare \( s\bar{s} \) state\[4\]; or it is heavier than the bare \( s\bar{s} \) state\[3\]. We label these three possibilities \( L \), \( M \), \( H \) respectively. Assuming that the \( q\bar{q} \) basis of the \( f_0(1370) \), \( f_0(1500) \) and \( f_0(1710) \) is in the \( 1^3P_0 \) nonet, the discrimination among the different mixing scenarios is strong\[9\]. Preliminary results on the implications of this particular scenario for photoproduction are presented here.

Photoproduction of the scalar mesons at medium energy provides an alternative to direct observation of the radiative decays. It is this possibility that we explore here and show that it is viable. The dominant mechanism is Reggeized \( \rho \) and \( \omega \) exchange, both of which are well understood in pion photoproduction\[10\]. The energy must be sufficiently high for the Regge approach to be applicable but not too high as the cross section decreases approximately as \( s^{-1} \). In practice this means approximately 5 to 10 GeV photon energy. In addition to photoproduction on protons we consider coherent photoproduction on \(^4\)He, encouraged in this by a recently-approved experiment at Jefferson Laboratory\[11\].

2 The Model

The differential cross section is given by

\[
\frac{d\sigma}{dt} = \frac{|M(s, t)|^2}{64\pi|p|^2s}. \tag{1}
\]

For the exchange of a single vector meson

\[
|M(s, t)|^2 = \frac{1}{2} A^2(s, t)(s(t - t_1)(t - t_2) + \frac{1}{2} st(t - m_s^2)^2) \\
+ A(s, t)B(s, t)m_p(s(t - t_1)(t - t_2) \\
+ \frac{1}{2} B(s, t)^2 s(4m_p^2 - t)(t - t_1)(t - t_2). \tag{2}
\]

where \( t_1 \) and \( t_2 \) are the kinematical boundaries

\[
t_{1,2} = \frac{1}{2s} \left( - (m_p^2 - s)^2 + m_s^2(m_p^2 + s) \right. \\
\pm (m_p^2 - s) \sqrt{((m_p^2 - s)^2 - 2m_s^2(m_p^2 + s) + m_s^4)} \right), \tag{3}
\]

and

\[
A(s, t) = \frac{gs(g_V - 2m_pgr)}{m_V^2 - t}, \quad B(s, t) = -\frac{2gsgr}{m_V^2 - t}. \tag{4}
\]
In (4), $g_V$ and $g_T$ are the $VNN$ vector and tensor couplings, $g_S$ is the $\gamma VN$ coupling. The $\omega NN$ couplings are rather well defined\cite{12}, with $13.8 < g_\omega^V < 15.8$ and $g_\omega^T \approx 0$. We have used $g_\omega^V = 15$ and $g_\omega^T = 0$ as this gives a good description of $\pi^0$ photoproduction\cite{10}. The $\rho NN$ couplings are not so well defined, with two extremes: strong coupling\cite{12} or weak coupling\cite{13}. We are again guided by pion photoproduction\cite{10} and choose the strong coupling solution with $g_\rho^V = 3.4$, $g_\rho^T = 11$ GeV$^{-1}$. The $SV\gamma$ coupling, $g_S$, can be obtained from the radiative decay width through\cite{14}

$$\Gamma(S \rightarrow \gamma V) = g_S^2 \frac{m_S^3}{32\pi} \left(1 - \frac{m_V^2}{m_S^2}\right)^3.$$  

(5)

Obviously in practice the amplitudes for $\rho$ and $\omega$ exchange are added coherently. The standard prescription for Reggeising the Feynman propagators in (2), assuming a linear Regge trajectory $\alpha_V(t) = \alpha_{\nu_0} + \alpha_V^\prime t$, is to make the replacement

$$\frac{1}{t - m_V^2} \rightarrow \left(\frac{s}{s_0}\right)^{\alpha_V(t) - 1} \frac{\pi \alpha_V^\prime}{\sin(\pi \alpha_V(t))} \left(-1 + \frac{1}{2} e^{-i\pi \alpha_V(t)}\right) \frac{1}{\Gamma(\alpha_V(t))}.$$  

(6)

This simple prescription automatically includes the zero observed at $t \approx -0.6$ GeV$^2$ in both $\rho$ and $\omega$ exchange and provides a satisfactory description of the $\rho$ and $\omega$ exchange contributions to pion photoproduction\cite{10}.

For photoproduction on $^4\text{He}$ we assume that the cross section is given by

$$\frac{d\sigma(\gamma N \rightarrow f_0\text{He})}{dt} = \frac{d\sigma(\gamma N \rightarrow f_0N)}{dt} \left(4F_{\text{He}}(t)\right)^2,$$  

(7)

where $F_{\text{He}}(t)$ is the helium form factor\cite{15}, $F_{\text{He}}(t) \approx e^{0t}$. The justification for the assumption\cite{17} is the low level of nuclear shadowing observed on $^4\text{He}$ at the energies with which we are concerned, for both pion and photon total cross sections\cite{16}.

Figure 1: Differential photoproduction cross section on hydrogen for $f_0(1500)$ at $E_\gamma = 5$ GeV. The glueball masses are L (solid), M (dashed) and H (dotted).
Table 1: Integrated photoproduction cross sections in nanobarns on protons and $^4$He at $E_\gamma = 5$ GeV for the three different mixing scenarios: light glueball (L), medium-weight glueball (M) and heavy glueball (H).

| Scalar $f_0$ | proton |  |  | $^4$He |  |  |
|------------|-------|---|---|-------|---|---|
|            | L     | M | H | L     | M | H |
| $f_0(1370)$| 27.1  | 68.6 | 94.2 | 0.64  | 1.63 | 2.23 |
| $f_0(1500)$| 89.9  | 52.1 | 17.0 | 1.55  | 0.90 | 0.29 |
| $f_0(1710)$| 0.7   | 1.6 | 11.8 | 0.001 | 0.002 | 0.016 |

We assume non-degenerate $\rho$ and $\omega$ trajectories

$$\alpha_\rho = 0.55 + 0.8t, \quad \alpha_\omega = 0.44 + 0.9t.$$  \quad (8)

### 3 Cross Sections

The differential cross sections have the structure expected, that is vanishing in the forward direction due to the helicity flip at the photon-scalar vertex and having a deep dip at $-t \approx 0.6$ GeV$^2$ due to the zeroes in the exchange amplitudes in (6). It does not go to zero in the dip because of the non-degenerate trajectories (8). This is illustrated for $f_0(1500)$ photoproduction at $E_\gamma = 5$ GeV in figure 1. The integrated cross sections for photoproduction of the scalars on protons and $^4$He at $E_\gamma = 5$ GeV are given in table 1 for light (L), medium (M) and heavy (H) glueball masses. In the case of $^4$He the integration over $d\sigma/dt$ is for $|t| > 0.1$ GeV$^2$ due to the experimental requirement that $|t| \gtrsim 0.1$ GeV$^2$ for the recoiling helium to be detected. The cross sections for photoproduction on protons at higher energies are similar in shape, but the magnitude decreases with energy at the rate expected from (6). For example the cross sections at $E_\gamma = 10$ GeV are about half those in table 1. However the cross sections for photoproduction on $^4$He do not decrease, and for the $f_0(1500)$ and $f_0(1710)$ actually increase. This is due the combined effect of the $^4$He form factor enhancing the contribution from small $t$ and the maximum of the differential cross section on protons moving to smaller $|t|$ with increasing energy.

The reasons for the cross sections for scalar photoproduction on $^4$He being very much smaller than those for scalar photoproduction on protons are (i) switching off $\rho$ exchange for photoproduction on protons reduces the cross section by a factor of about 16, cancelling the factor 16 from coherent production (ii) the helium form factor suppresses the cross section except at very small $t$ (iii) there is the experimental requirement that $|t| \gtrsim 0.1$ GeV$^2$ for the recoiling helium to be detected.

The cross sections in table 1 reflect directly the radiative decay widths and, if it were practical, ratios of cross sections $f_0(1370) : f_0(1500) : f_0(1710)$ would give an immediate result and “weigh” the glueball. In practice there are several problems in realising this ideal scenario. It is unlikely that the decay modes of the scalars
with charged particles can be considered because of the very much larger cross sections in $\pi^+\pi^-$, $K^+K^-$, $2\pi^+2\pi^-$ and $\pi^+\pi^-\pi^0$ from vector-meson production. The contribution from vector mesons can be eliminated by considering only the all-neutral channels, that is the $\pi^0\pi^0$, $\eta\eta^0$ and $4\pi^0$ decays of the $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$. A further difficulty is the uncertainty in the branching fractions of the $f_0(1370)$ and $f_0(1710)$, particularly the former\[1, 6\], and the small cross section for the $f_0(1710)$.

In contrast the cross sections for photoproduction of the $f_0(1500)$ on protons are reasonable and the branching fractions are well defined. This is demonstrated in table 2 in which the branching fractions, in percent, are given from the PDG\[1\], the WA102 experiment[17] as obtained in the analysis of Close and Kirk[4] and the Crystal Barrel experiment[18] (CB).

Photoproduction of the $f_0(1370)$ can help resolve the ambiguities discussed in the Introduction. Quite apart from the possibility that it does not exist\[6, 7\], there is considerable variance in the branching fractions. In the analysis of Close and Kirk[4] $4\pi$ is the dominant decay mode, with a branching fraction of about 95%, and the $\pi\pi$ branching fraction is very small, $(2.7 \pm 1.2)\%$. This pattern is replicated by Crystal Barrel[18], with a $4\pi$ branching fraction of about 85% and a $\pi\pi$ branching fraction of $(7.9 \pm 2.9)\%$. In direct contrast, $\pi\pi$ is the dominant decay mode in the analysis of Bugg[8] and $4\pi$ is small. At resonance the ratio $2\pi : 4\pi$ is given as 6 : 1. However for the $f_0(1500)$ the $2\pi : 4\pi$ ratio is 0.9 : 1 so is not incompatible with table 2.

Of course the scalars are not produced in isolation. For example in the $\pi^0\pi^0$ channel there is a continuum background arising from the process $\gamma \rightarrow \pi^0\omega(\rho)$ with subsequent rescattering of the $\omega(\rho)$ on the proton by $\rho(\omega)$ exchange to give the second $\pi^0$. The new ingredients here are the $\gamma\pi^0\omega(\rho)$ and $\omega\pi^0\rho$ couplings, which can be estimated from[19]. The $\rho(\omega)$ exchange is Reggeised as before. Figure 2 shows the

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**Table 2:** Branching fractions in percent for the $f_0(1500)$ from the PDG[1], the WA102 experiment[17] from the analysis of Close and Kirk[4] (CK) and the Crystal Barrel experiment[18] (CB).

| Channel | PDG          | WA102/CK    | CB          |
|---------|--------------|-------------|-------------|
| $\pi\pi$| $34.9 \pm 2.3$| $33.7 \pm 3.4$| $33.9 \pm 3.7$|
| $\eta\eta$| $5.1 \pm 0.9$| $6.1 \pm 0.1$| $2.6 \pm 0.3$|
| $\eta\eta'$| $1.9 \pm 0.8$| $3.2 \pm 0.7$| $2.2 \pm 0.1$|
| $K\bar{K}$| $8.6 \pm 0.1$| $10.7 \pm 2.4$| $6.2 \pm 0.5$|
| $4\pi$  | $49.5 \pm 3.3$| $46.3 \pm 8.5$| $55.1 \pm 16.9$|
Figure 2: Continuum $\pi^0\pi^0$ background (dotted) and combined with $f_0(1500)$ at $E_\gamma = 5$ GeV (solid (L), large dashed (M), small dashed (H)) for constructive interference.

result of this calculation together with the result of constructive interference with the $f_0(1500)$ signal.

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