Evidence of the non-strange partner of pentaquark from the elementary $K^+\Lambda$ photoproduction

Abstract The existence of the $J^p = 1/2^+$ narrow resonance predicted by the chiral soliton model has been investigated by utilizing the new kaon photoproduction data. For this purpose, we have constructed two phenomenological models, which are able to describe kaon photoproduction from threshold up to $W = 1730$ MeV. By varying the resonance mass, width, and $K\Lambda$ branching ratio in this energy range we found that the most convincing mass of this resonance is 1650 MeV. Using this result we estimate the masses of other antidecuplet family members.

Keywords Kaon photoproduction · Pentaquark · Narrow resonance

1 Introduction

The chiral soliton model proposed by Diakonov et al. [1] predicts that the non-strange partner of pentaquark, the $P_{11}(1710)$ narrow resonance, has significant decay widths to the $\eta N$, $\pi N$, and $K\Lambda$ channels. The observation of pentaquark by the LEPS collaboration almost a decade ago [2] has also sparked considerable interest in the investigation of this state. It is obvious that the $\pi N$ and $\eta N$ channels received more attention, since in both channels there has been a large number of experimental data that has been precisely interpreted by a number of phenomenological models such as MAID [3] and SAID [4]. In the $\pi N$ channel a clear signal of this narrow state was observed at 1680 MeV and a weaker one was detected at 1730 MeV [5]. In the $\eta N$ production off a free neutron a substantial enhancement at $W \approx 1670$ MeV is experimentally found [6]. Clearly, such an enhancement could be explained as the presence of the narrow $P_{11}$ resonance. Nevertheless, a different explanation for this enhancement is also possible, i.e., as the contributions of the $K\Lambda$ and $K\Sigma$ loops [7].

We note that there has been no attempt to study this resonance by utilizing kaon photoproduction prior to our previous work [8], although some experimental data with relatively good quality have been recently provided by the CLAS [9] and SAPHIR [10] collaborations. In view of this we are interested in following the procedure developed in Ref. [5], i.e., scanning the changes in the total $\chi^2$ after including a $P_{11}$ narrow resonance with the variation of the resonance mass, width, and $K\Lambda$ branching ratio [8].

Besides the difficult situation in kaon photoproduction, the accuracy of phenomenological model plays a crucial role. Since the energy of interest is very close to the $K^+\Lambda$ threshold, an accurate model that can describe experimental data at low energies would be more suitable for this purpose, rather than a global model that fits to data in a wide energy range but overlooks the appearing structures at low energies.

In this paper we present further results of our calculation which support the evidence of this narrow state. Using this result we estimate the masses of other antidecuplet family members by utilizing the mass splitting of 110 MeV, which is theoretically predicted in Ref. [5].
2 The isobar Model

For the purpose of investigating kaon photo- and electroproduction near threshold, in the previous work [11] we have constructed an isobar model from the standard $s$-, $u$-, and $t$-channel Born terms along with the $K^{*+}(892)$ and $K_1(1270)$ $t$-channel vector mesons, as well as an $S_{11}(1650)$ nucleon- and an $S_{01}(1800)$ hyperon-resonance. The latter is included in order to improve the agreement with experimental data. The model fits nicely all available data from threshold ($W = 1609$ MeV) up to $W = 1660$ MeV. However, as predicted by many soliton models the most convincing mass of the narrow resonance is around 1680 MeV [5, 12]. Therefore, an extension of the model to cover energies between threshold and $W = 1730$ MeV is mandatory. Fortunately, at this energy regime both experimental data from SAPHIR and CLAS collaborations are in agreement with each other and, consequently, the problem of data inconsistency investigated in Ref. [13] does not exist. Moreover, the hadronic form factors required to suppress the diverging Born terms would play a less significant role here.

In the energy range of interest there exist six nucleon resonances which may contribute to this process. Their properties relevant to the present work are mostly available from the Particle Data Book (PDG) [14]. Other unknown coupling constants can be fitted from experimental data. The result of the fit is shown in Fig. 1 where the prediction of Kaon-Maid [15] is also shown for comparison. To investigate the model dependence of the result in the next Section, here we propose two models. In Model 1 we restrict the maximum

![Fig. 1](color online) Comparison between angular distributions of differential cross section obtained from Model 1 (solid lines), Model 2 (dashed lines), and Kaon-Maid (dash-dotted lines) [15] with experimental data. Notation of experimental data can be found in Ref. [11]. The corresponding total c.m. energy $W$ (in GeV) is shown in each panel.

![Fig. 2](color online) Change of the $\Delta \chi^2$ in the fit of Model 1 (top panels) and Model 2 (bottom panels) due to the inclusion of the $P_{11}$ resonance with the mass scanned from 1620 to 1730 MeV (step 10 MeV) and $\Gamma_{tot}$ taken from 1 to 10 MeV (step 1 MeV) for different $KA$ branching ratios ($\Gamma_{KA}/\Gamma_{tot} = 0.1$, 0.2, and 0.4). The three vertical lines in each panel indicate the values of $m_N^* = 1650, 1700$ and 1720 MeV.
variation of the photon amplitudes during the fitting process to 10% of the original PDG values, whereas in Model 2 all parameters are allowed to vary within the PDG error bars. From Fig. 1 it is clear that both models display a good agreement with experimental data and might provide a significant improvement of Kaon-Maid in the energy range of interest. Results of both models for other polarization observables can be found in our previous paper [8].

3 Searching for the narrow resonance

In order to observe the existence of a $P_{11}$ narrow resonances in kaon photoproduction we scan the changes in the total $\chi^2$ after including this resonance with the variation of its mass, width (1 to 10 MeV with 1 MeV step), and $K\Lambda$ branching ratio. The results for both Model 1 and 2 are shown in Fig. 2. In all three values of the $K\Lambda$ branching ratios selected, we can see that three minima at $m_{N^*} = 1650, 1700, and 1720$ MeV appear consistently. Nevertheless, the minimum $\Delta \chi^2$ at $m_{N^*} = 1650$ MeV seems to be the most convincing one. It is found that the lowest values of $\Delta \chi^2$ can be obtained by using $\Gamma_{tot} = 5$ MeV. Variation of the $K\Lambda$ branching ratio changes these values only slightly. We have also investigated the possibility that the extracted resonance not a $P_{11}$ state, but an $S_{11}$ or even a $P_{13}$ state. It is shown that the latter is less likely, whereas most available observables are able to distinguish the effect of $S_{11}$ and $P_{11}$ states [8].

To investigate model dependence of our result we display the the same changes in the total $\chi^2$, but calculated by using Model 2, in the bottom panels of Fig. 2. Once again, we see a similar pattern as in Model 1. We, therefore, conclude that the minimum at $m_{N^*} = 1650$ seems to be model independent, whereas the minima at 1700 and 1720 MeV become much weaker in Model 2. Although this might imply that the possibility of a narrow $P_{11}$ resonance with a mass of 1700 or 1720 MeV could not be excluded, we believe that investigation of this resonance at energies around 1700 MeV by using the present mechanism is difficult due to the opening of $K\Sigma$, $\rho p$, and $\omega p$ channels. It is also important to mention here that by including the $P_{11}$ state in Model 1 the number of fitted parameters increases from 41 to 45, whereas the total $\chi^2$ decreases from 859 to 834. This corresponds to a statistical significance of 4σ.

By scrutinizing the contributions of individual data to the $\chi^2$ in our fits we found that the minimum at 1650 MeV originates mostly from the $\Lambda$ recoil polarization data [16] as shown in Fig. 3. From this figure we can see that there exists a dip at $W \approx 1650$ MeV in the whole angular distribution of data. It is also apparent that both

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1 The author is indebted to Prof. Takashi Nakano for clarifying this issue.
$P_{11}$ and $S_{11}$ states can nicely describe this dip. Although the recoil polarization is not a suitable observable to distinguish different states at 1650 MeV, more precise data in this case are still urgently required to remove uncertainties in the position of the dip.

4 Further consequence

Although previous investigations using pion and eta photoproductions obtained the $P_{11}$ mass around 1680 MeV, the 1650 MeV mass obtained in the present work corroborates the calculation utilizing the Gell-Mann-Okubo rule [5] and is in a good agreement with the prediction of the topological soliton model of Walliser and Kopeliovich [12]. Nevertheless, all previous calculations have used the pentaquark mass obtained by Nakano et al. [2] in order to determine the masses of the whole antidecuplet family members. It is naturally interesting to ask: how this result would change if we used the mass of the non-strange member $P_{11}$ obtained in the present work to estimate the masses of the rest family members. The answer is given in Fig. 4 where we compare the masses predicted by Diakonov et al. [1] with those of the present result. Note that in obtaining this result we have used the mass splitting proposed in Ref. [5] (i.e. 110 MeV), which is also compatible with the prediction of Walliser and Kopeliovich [12]. As expected, the mass of the pentaquark does not change from its original value [2], whereas the masses of other family members are significantly reduced. However, it is important to emphasize here that our finding is in a good agreement with the theoretical prediction of Ref. [5].

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