Appropriate Observables for Investigating Narrow Resonances in Kaon Photoproduction off a Proton*

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Abstract. The existence of non-strange partner of pentaquark, the $J^P = \frac{1}{2}^+$ narrow resonance, has been investigated by utilizing kaon photoproduction off a proton. It is found that the corresponding mass is 1650 MeV and the appropriate observables for investigating this resonance are the recoiled hyperon polarization, the beam-recoil double polarization $C_x$, and differential cross section at backward angles. Future kaon photoproduction experiments at low energies should focus on these observables.

Keywords: Kaon photoproduction, narrow resonance, antidecuplet.
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INTRODUCTION

The nonstrange partner of pentaquark predicted by the chiral quark soliton model ($\chi$QSM), which is originally called the $N(1710)$ resonance (see Fig.1), has a strong decay width to the $\eta N$ channel and angular momentum state $P_{11}$ [1]. However, it has also sizeable decay widths to the $\pi N$ and $K\Lambda$ channels, which therefore provide at least three processes for investigating its existence.

The possibility of its decay to the $\eta N$ channel has been immediately investigated, after the LEPS collaboration reported the observation of pentaquark [2], by using a modified partial wave analysis (modified PWA), since a standard PWA can miss such a resonance [3]. In the $\eta N$ photoproduction off a free neutron a substantial enhancement of cross section at $\omega = 1670$ MeV is confirmed by experiments [4], which could be interpreted theoretically as a direct evidence of this resonance, although different interpretations such as interference effects from well established nucleon resonances are also possible [5].

It is surprising that before our previous recent papers [6,7] there had been no investigation on the existence of this resonance in the $K\Lambda$ channel. This is presumably due to the higher kaon mass, which makes this reaction channel more difficult to study, both theoretically and experimentally.

![FIGURE 1. Masses of the antidecuplet member as (a) suggested by Ref. [1] and (b) obtained in our work with the mass splitting of 110 MeV [7].](image)

In our recent papers [6,7] we have reported the result of our investigation on this resonance by utilizing the $KA$ photoproduction off a proton. Since the predicted resonance mass is very close to the reaction threshold, we found that a simple model that can accurately describe the process at low energies is more useful than a model that fits all experimental data with the energy up to 2.5 GeV, but tends to overlook small structures indicated by experimental data near the threshold region. By using such a simple model we have investigated the existence of this narrow resonance in kaon photoproduction. It is found that the corresponding mass is 1650 MeV. Starting from the

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mass of this resonance we predict masses of other
antidecuplet members as shown in Fig.1.

In this paper we briefly review the finding in our
previous papers and present the most promising
observables to observe this narrow resonance in kaon
photoproduction. For more detailed formalism and
discussion of the isobar models used in this paper we
refer the reader to our previous reports [6,7].

ELEMENTARY PHOTOPRODUCTION
MODEL

In this study the photoproduction process
\[ \gamma + p \rightarrow K^+ + \Lambda \]
is described by an isobar model for low energy region
as discussed in details in our previous paper [8]. The
background amplitudes of this model is constructed
from the standard s-, u-, and t-channel Born terms
along with the K*(892) and K(1270) t-channel vector
mesons. In addition, we have also included the
S01(1800) hyperon resonance in order to improve the
agreement with experimental data [8]. The Feynman
diagrams for this background are shown in Fig.2.

Since the energy of interest is limited up to 1730 MeV,
only six nucleon resonances might contribute to the
process, i.e. the S11(1650), D15(1675), F15(1680),
D13(1700), P11(1710), and P13(1720). All these
resonances are considered in the model by using the
resonant electric multipoles in the Breit-Wigner form.
Nevertheless, as reported in our previous paper [6],
contribution from the S11(1650) state is proven to be
dominant.

RESULTS AND DISCUSSION

Having obtained reliable models for elementary
process of kaon photoproduction, we insert a narrow
nucleon resonance in the model and fit its free
parameters, i.e. the helicity photon coupling, kaon
branching ratio, as well as the phase angle, by fixing
its mass and total width. This procedure is repeated for
different values of resonance mass and width. In order
to obtain the position of resonance mass and width
with the smallest \( \chi^2 \), more than 1000 fits have been
performed. In Fig. 4, the change of \( \chi^2 \) after the
inclusion of the P11(1650) state in both isobar models
is exhibited, where we can clearly see that the

substantially simplify the reaction amplitudes and,
hence, remove some uncertainties in the model.

Result of the fitting to experimental data is shown
in Fig.3, where we compare differential cross sections
calculated from two different isobar models, obtained
merely from different strategies in limiting the free
parameters in the models, with Kaon-Maid [10] and
experimental measurement [11-13]. In the fitting
database, there exist 704 data points within the energy
range of interest, i.e. from threshold up to \( W = 1730 \)
MeV. By limiting the values of resonance parameters
in the fit to vary within 10% of their original PDG
values, the total \( \chi^2 \) can be reduced to 859, i.e. \( \chi^2/N = 1.22 \) (Model 1). Smaller \( \chi^2/N \) (i.e. 1.00) would be
obtained if we removed this limit (Model 2). As shown
in Fig.3, both models provide a significant
improvement to the Kaon-Maid [10].

FIGURE 3. Comparison between differential cross sections
calculated from Model 1 (solid lines), Model 2 (dashed lines)
and Kaon-Maid [10] (dash-dotted lines) with experimental
data from the SAPHIR (open circles) [11], CLAS2006 (solid
squares) [12] and CLAS2010 (solid triangles) [13]
collaborations. The corresponding kaon scattering angle is
shown in each panel [6].
minimum at $m_{N^*} = 1650$ MeV seems to be model independent. This is in contrast to other minima at 1700 and 1720 MeV. The significant improvement of $\chi^2$ shown in Fig.4 indicates that a narrow resonance with a certain total width is required in order to explain the experimental data.

The possibility that the indication of the narrow resonance in kaon photoproduction originates from another state, i.e. the $P_{11}(1650)$ state, has been also investigated [6]. In this case, it is found that the minimum at 1650 MeV becomes weaker and another minimum at 1680 MeV appears. Thus, the structure appearing at 1650 MeV in the hyperon polarization data presumably does not originate from this state.

As reported in our previous paper [6], the minimum shown in Fig.4 originates from the recoiled $\Lambda$ polarization data. In Fig.5 we plot the clear effect of this narrow resonance, where we compare the calculated polarization with and without this resonance. Although this observable indicates a clear structure at 1650 MeV, new measurements with higher statistics are required in order to precisely constrain the mass, width, and helicity photon couplings of this resonance.

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Other promising observables for investigating the existence of narrow resonance at 1650 MeV are the differential cross section shown in Fig.6 and the beam-recoil double polarization $C_x$ shown in Fig.7. In Fig.6 we compare differential cross sections obtained from calculations without this resonance, along with the $P_{11}(1650)$ and $S_{11}(1650)$ resonances, with the available experimental data of elementary $K\Lambda$ photoproduction. It is clear from this figure that both $P_{11}(1650)$ and $S_{11}(1650)$ states could become good candidates for this narrow resonance. However, the two states produce a quite different effect on the differential cross section, i.e. whereas the $P_{11}(1650)$ resonance produces a peak at $W = 1650$ MeV, the $S_{11}(1650)$ state leads to a dip at this energy point. Since in the effect of the $P_{11}$ changes sign at $\theta_K \approx 90^\circ$, its contribution disappears in the
total cross section after an integration over a complete angle. This is clearly in contrast to the effect of the $S_{11}$ state. Thus, it is obvious that experimental data, especially at backward angles, are able to pin down the correct state of this resonance.

Another possible observable is the beam-recoil double polarization shown in Fig.7. This polarization can be directly measured once we have polarized beam, since the polarization of recoiled $\Lambda$ can be determined directly from its decay. Comparison between the result of our calculation and experimental data is shown in Fig.7, where we can see that clear signal is produced by the two states. Since both states produce almost a similar effect, this observables apparently cannot be used to determine the correct resonance state as in the case of differential cross section. Nevertheless, measurement of this observable is still desired to eliminate the uncertainties in the resonance mass and total decay width. Furthermore, as seen in Fig.7 the accuracy of the presently available data is still unable to resolve the effect of this resonance. In view of this, it is important to improve the statistic of the future experiments.

**SUMMARY AND CONCLUSION**

We have investigated kaon photoproduction near its reaction threshold by using isobar models and found a structure in the recoiled hyperon polarization data which corresponds to a narrow resonance with a mass of 1650 MeV. The possible states of this resonance are $P_{11}(1650)$ and $S_{11}(1650)$. Since both states produce different effects in the experimental observables, future experimental measurements are able to resolve this issue. To this end, the most promising observables are the differential cross section at backward direction, recoiled hyperon polarization, and the beam-recoil double polarization. Such an experiment is apparently well suited for the Jefferson Lab as well as MAMI Mainz.

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