Constraining the mass and width of the $N^*(1685)$ resonance

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We have examined the existence of the $N^*(1685)$ resonance, which is recently listed by the Particle Data Group as a one-star nucleon resonance, by using a covariant isobar model for kaon photoproduction and assuming that the resonance has $J^p = 1/2^+$, in accordance with our previous finding. After the inclusion of this resonance, the changes in the total χ^2 show two clear minima at $M_{N^*} = 1650$ and 1696 MeV, which correspond to two different resonance states. The former corresponds to the narrow nucleon resonance found in our previous investigation, whereas the latter corresponds to a new resonance found as we increase the resonance width. From the latter we derive the mass and width relation of the $N^*(1685)$ resonance. We observe that the properties of both the $N^*(1685)$ and $N^*(1710)P_{11}$ resonances are strongly correlated. Although the best fit of the present work yields $M_{N^*} = 1696$ MeV and $\Gamma_{N^*} = 76$ MeV, the apparently small $N^*(1710)P_{11}$ coupling constant to the $K^+\Lambda$ channel found in previous investigations suggests that $\Gamma_{N^*} \lesssim 35$ MeV, which, according to the mass and width relation, corresponds to $M_{N^*} \lesssim 1680$ MeV.

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In a previous work [1] we have investigated the possibility of observing the $J^p = 1/2^+$ narrow resonance predicted by the chiral soliton model as a member of a baryon antidecuplet [2] by using the kaon photoproduction process $\gamma + p \to K^+ + \Lambda$. For this purpose, an isobar model, for which the background part is constructed from a covariant diagrammatic technique and the resonance part is written in terms of the electric and magnetic multipoles, was fitted to the low energy (near threshold) photoproduction data. A new narrow resonance was added to the model and the effect of the resonance on reducing the χ^2 was investigated by scanning its mass from 1620 to 1730 MeV. By varying the total width from 0.1 to 10 MeV it was found that the most promising mass of the resonance is 1650 MeV, whereas the corresponding width is 5 MeV. The possibility that the resonance has different quantum numbers has been also investigated. Nevertheless, at present, experimental data indicate that the $J^p = 1/2^+$ is the most suitable quantum number for this state [1].

Recently, the $N^*(1685)$ resonance has been listed by the Particle Data Group (PDG) as a new state with one-star status in the 2012 Review of Particle Physics [3]. Its spin and parity are still undetermined. The quoted literatures originate from the recent experimental measurements of the η photoproduction on a neutron by the CBELSA/TAPS Collaborations [4,5] and the quasifree Compton scattering on the neutron by the GRAAL Collaboration [6]. The resonance mass and width extracted from the CBELSA/TAPS experiment are 1670 and 25 MeV, respectively, whereas those from GRAAL data are 1685 and ≤ 30 MeV, respectively.

Interestingly, however, in the 2012 PDG list of the $N^*(1685)$ it is noted that this state does not gain status by being a sought-after member of a baryon antidecuplet [3]. Therefore, the $N^*(1685)$ state should not be considered merely as a member of an antidecuplet narrow resonance; it could belong to the family of usual nucleon resonances in the PDG listings.

In view of this it is obviously important to relax the upper limit of the resonance width in our previous investigation [1]. Furthermore, our previous finding reveals not only one possible resonance mass at 1650 MeV, but also three other minima at 1680, 1700, and 1720 MeV, albeit with weaker signals compared to that at 1650 MeV.

In the present study we use our latest isobar model constructed from appropriate Feynman diagrams for both background and resonance parts [7]. The model fits all the latest available $K^+\Lambda$ photoproduction data up to $W = 2200$ MeV, consisting of differential cross section, recoil polarization, beam-recoil double polarization, as well as photon Σ and target T asymmetries data. In total, the fitting database consists of more than 3500 data points. A more detailed explanation of the model as well as the experimental data used to fit the model can be found in Ref. [7]. Therefore, the presently used isobar model is a fully covariant model and does not only fit the experimental data near threshold. The use of this model has certain advantages compared to the previous one; e.g., it is clearly safe to extend the investigation beyond the threshold energy, and it also provides a good tool for cross checking our previous result [1].

We assume that the state has quantum numbers $J^p = 1/2^+$, i.e., the P_{11}, since our previous study found that these quantum numbers are the most suitable ones for investigation using kaon photoproduction. The state $J^p = 1/2^-$, for instance, can be ruled out by the present experimental data because its existence generates a clear dip at $W = 1650$ MeV in the total and differential cross sections, which are experimentally not observed (see Fig. 1 for the total cross section case as well as Figs. 14 and 15 of Ref. [1] for a more detailed result). The use of the total

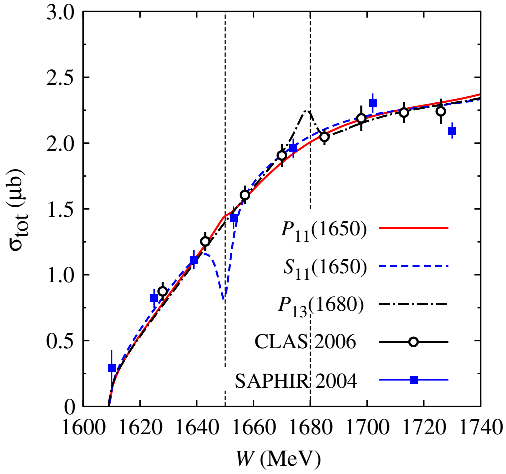

FIG. 1 (color online). Effects of the inclusion of P_{11}, S_{11}, and P_{13} resonances on the total cross section of the $\gamma + p \rightarrow K^+ + \Lambda$ process in our previous calculation [1]. Note that the $P_{13}(1680)$ effect was not reported in Ref. [1]. Experimental data are from the SAPHIR [14] and CLAS [15] Collaborations.

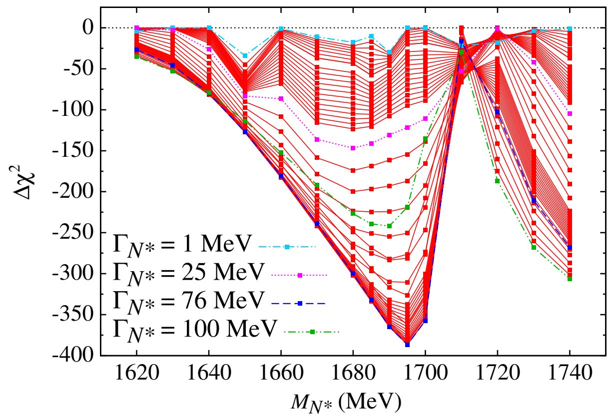

FIG. 2 (color online). Changes of the χ^2 in the fit of the kaon photoproduction data due to the inclusion of the $N^*(1685)P_{11}$ resonance with the corresponding mass and width scanned from 1620 to 1730 MeV and 1 to 100 MeV, respectively.

cross section is necessary at this stage because the effect is small in the differential cross section, whereas in the total cross section the cumulative effect could be larger due to a constructive interference in the S_{11} case or even much smaller due to a destructive one in the P_{11} case (see Fig. 1).

Investigation of the higher spin resonance is somewhat problematic in the current method. As discussed in Ref. [1], for instance, the use of P_{13} state results in weaker and more complicated changes in the total χ^2. In fact, as shown in Fig. 13 of Ref. [1], it replaces the strong signal at 1650 MeV with a rather weaker one at 1680 MeV. It should be emphasized here that the signal of the narrow resonance at 1650 MeV was obtained by using the S_{11} or P_{11} state, independent of the $K\Lambda$ branching ratio and the total decay width used. There are two possible explanations of this phenomenon. First, it shows the limitation of the present approach for investigating the higher spin states due to their complicated structures. Second, the presently available experimental data are not sufficiently accurate for this purpose. For the latter, future kaon photoproduction experiments at MAMI, Mainz, could be expected to overcome this problem. Furthermore, we also observe that the use of the $P_{13}(1680)$ state leads to a clear bump at $W = 1680$ MeV in the total cross section (as shown in Fig. 1) that is also not observed by the presently available experimental data.

As in the previous study we perform fits by adjusting the whole unknown coupling constants in the model and scan the resonance mass from 1620 to 1740 MeV, with 10 MeV step, and calculate the changes in the total χ^2 after including the P_{11} resonance. Near the global minimum we decrease the step to 5 MeV in order to increase the accuracy. However, different from the previous study, here we vary the total width from 1 to 100 MeV. The result is displayed in Fig. 2. In total, we have performed 780 fits to produce this figure. Figure 2 clearly exhibits that we recover the finding in our previous study [1], i.e., the 1650 MeV narrow resonance, which is indicated by the first minimum at $M_{N^*} = 1650$ MeV. This provides a proof that our present covariant isobar model is consistent with the model used in the previous study. Surprisingly, however, this minimum only exists for the total width $\Gamma_{N^*} \leq 25$ MeV. As the total width increases beyond this value, the minimum at 1650 MeV gradually vanishes. This fact was not observed in our previous study because the width was limited only up to 10 MeV. Thus, we believe that our present finding still supports the existence of a narrow resonance at 1650 MeV. Although the width could be larger, the upper limit of 25 MeV obviously exhibits that the corresponding resonance remains narrow. The second (global) minimum is our best fit and found at $M_{N^*} = 1696$ MeV with the corresponding width $\Gamma_{N^*} = 76$ MeV (see Fig. 2). There is a sign of another minimum for $M_{N^*} > 1740$ MeV, which is, however, beyond our present interest.

Figure 3 graphically displays the effect of inclusion of the $N^*(1685)P_{11}$ resonance on the improvement of the model. Note that the choice of the total cross section here is trivial and only for the sake of convenience, because improvements after including this resonance are not only found in cross sections, but also in polarization observables. Moreover, the total cross section data shown in Fig. 3 were not included during the fitting process.

Obviously, the $N^*(1685)P_{11}$ resonance is important in improving the agreement between experimental data and model calculation at $W \approx 1700$ MeV. However, there might be a question regarding the large contribution of the $N^*(1685)P_{11}$ resonance as shown by the dash-dotted line in Fig. 3, whereas, on the other hand, the effect in decreasing the cross section at $W \approx 1700$ MeV seems to be relatively small. This originates from the fact that in obtaining the solid line [model with the $N^*(1685)P_{11}$ resonance] all

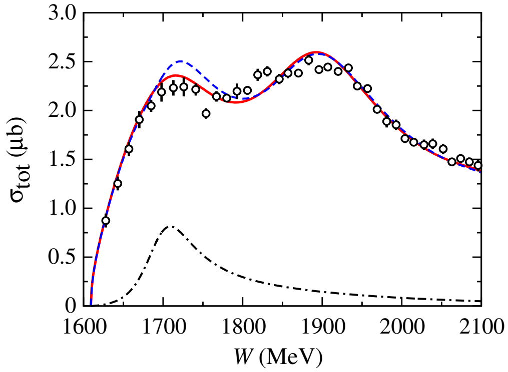

FIG. 3 (color online). Total cross sections obtained by the model calculations with (solid red line) and without (dashed blue line) the $N^*(1685)P_{11}$ resonance compared with experimental data [15]. In the former, the total cross section is calculated by using the best fit result, i.e., with $M_{N^*} = 1696$ MeV and $\Gamma_{N^*} = 76$ MeV. The dash-dotted black line exhibits the $N^*(1685)P_{11}$ resonance contribution.

background and resonance coupling constants in the model are refitted. In fact, only by a destructive interference with the contribution of the $N^*(1710)P_{11}$ resonance can the large $N^*(1685)P_{11}$ contribution be compensated. We will discuss this problem later, when we explain the relation between the mass and the total width of the resonance.

There is another interesting phenomenon revealed by Fig. 2; i.e., the position of the second minimum varies as functions of the mass and width of the resonance. The four different lines for $\Gamma_{N^*} = 1$, 25, 76, and 100 MeV in this figure clearly suggests that there is a unique relation between the mass and the width of the resonance which can be obtained by fixing the value of the total width Γ_{N^*} during the fitting process and finding the minimum value of χ^2 per number of degrees of freedom, which is denoted from now on by $\chi^2_{\rm min}/N_{\rm d.o.f.}$. By repeating this procedure for $\Gamma_{N^*} = 1, \ldots, 100$ MeV, within the range of $M_{N^*} =$ 1660–1710 MeV in order to exclude other minima, we obtain this relation which is plotted by using a solid (red) line in panel (a) of Fig. 4. Note that the uncertainty of this relation, displayed by the shaded (blue) area, is obtained from the fitted mass uncertainty given by MINUIT.

In Fig. 4 all curves are started from 4 MeV since below this point the minimum mass is immediately shifted to 1690 MeV, causing a discontinuity in the plot. We may consider this minimum as another case of narrow resonance, the same as the one we found at 1650 MeV. As a consequence, it does not belong to the same second minimum. In our previous study [1] we carefully stated that around $W \approx 1690$ MeV there are threshold energies of the $K^+\Sigma^0$, $K^+\Sigma^-$, $K^0\Sigma^+$, and $K^0\Sigma^0$ channels. This could provide an alternative explanation of this minimum, although experimental cross section data do not show any discontinuity at this energy point.

The $\chi^2_{\rm min}/N_{\rm d.o.f.}$ plotted in panel (b) of Fig. 4 obviously advocates that $M_{N^*} = 1696$ MeV and $\Gamma_{N^*} = 76$ MeV

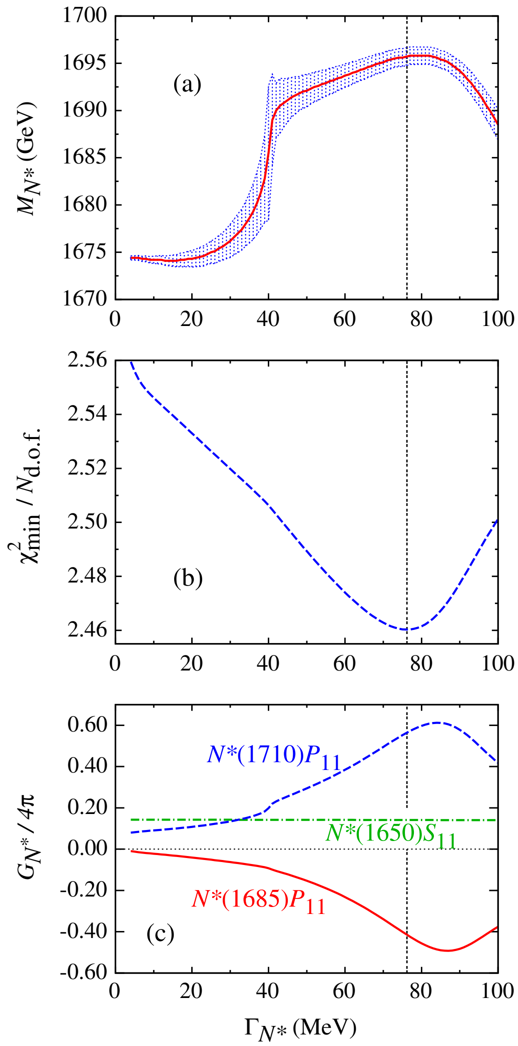

FIG. 4 (color online). (a) Mass and width relation of the $N^*(1685)P_{11}$ resonance extracted from Fig. 2 (solid red line). The uncertainty of this relation is indicated by the dotted (blue) area. (b) $\chi^2_{\rm min}$ per number of degrees of freedom ($N_{\rm d.o.f.}$) obtained for each of the Γ_{N^*} values. The vertical dotted line locates the position of the minimum value of the $\chi^2_{\rm min}/N_{\rm d.o.f.}$. (c) Coupling constants of the dominant resonances that contribute to the first peak of the $\gamma p \to K^+\Lambda$ total cross section (see Fig. 3). Notation of the coupling constants can be found in Ref. [7].

would be the best result of the present work, consistent with that obtained from Fig. 2. They are, however, substantially larger than those found in the latest η photoproduction experiment ($M_{N^*} = 1670$ MeV and $\Gamma_{N^*} = 25$ MeV) [4,5], as well as those extracted from the quasifree Compton scattering on the neutron ($M_{N^*} = 1685$ MeV and $\Gamma_{N^*} \leq$ 30 MeV) [6]. These discrepancies may raise a serious problem. However, the minimum value of $\chi^2_{\rm min}/N_{\rm d.o.f.}$ is not by any means the only criterion for a best result.

We note that if we could fix the width of the resonance to 25 MeV, the mass and width relation would yield $M_{N^*} \approx$ 1675 MeV, which is very close to that obtained from the recent η photoproduction experiment [4,5]. On the other hand, we also observe that our best fit ($M_{N^*} = 1696$ MeV and $\Gamma_{N^*} = 76$ MeV) is obtained by increasing the contribution of the $N^*(1685)P_{11}$ resonance. This is shown in panel (c) of Fig. 4, where we can see that the absolute value of the coupling constant increases as we increase Γ_{N^*} up to $\sim$85 MeV, whereas the $N^*(1650)S_{11}$ coupling is almost unaffected. To reproduce the experimental data this process must be followed by increasing the $N^*(1710)P_{11}$ coupling constant, where the coupling sign should be different in order to produce a destructive interference between the $N^*(1685)P_{11}$ and $N^*(1710)P_{11}$ amplitudes.

Previous studies [7–10] have indicated that the $N^*(1710)P_{11}$ contribution to kaon photoproduction tends to be small. For instance, our previous study [7] yields $G_{N^*(1710)}/4\pi \approx 0.08$, which is smaller than that of the $N^*(1650)S_{11}$, i.e., $G_{N^*(1650)}/4\pi \approx 0.14$. The small $N^*(1710)P_{11}$ contribution to the kaon photo- and electroproduction has been also pointed out in a recent investigation by Maxwell [10]. Although Maxwell found that both $N^*(1650)S_{11}$ and $N^*(1710)P_{11}$ resonances have comparable contributions, they are relatively smaller than those of other nucleon resonances. A recent Bayesian analysis of the $K^+\Lambda$ photoproduction has also excluded the $N^*(1710)P_{11}$ from the list of resonances that have the highest probability of contributing to the reaction [11]. Finally, the latest GWU analysis has found no evidence for the $N^*(1710)P_{11}$ state, in contrast to the $N^*(1650)S_{11}$ and $N^*(1720)P_{13}$ resonances [12], although the Bonn-Gatchina group [13] could draw a different conclusion.

Therefore, by referring to panel (c) of Fig. 4 and considering the fact that the $N^*(1710)P_{11}$ contribution should be smaller than, or at least comparable to, the $N^*(1650)S_{11}$ contribution, we may estimate that the largest, but still reasonable, total width of the $N^*(1710)P_{11}$ resonance is $\Gamma_{N^*} \approx 35$ MeV, for which the $N^*(1710)P_{11}$ and $N^*(1650)S_{11}$ contributions are almost equal. According to the mass and width relation given in panel (a) of Fig. 4 this result corresponds to $M_{N^*} \approx 1680$ MeV, which is certainly consistent with the recent PDG estimate [3].

In conclusion, we have investigated the existence of the $N^*(1685)$ resonance by using a covariant isobar model and calculating the changes in the total χ^2 after including this resonance. We assume that the resonance has $J^p = 1/2^+$, which is in accordance with our previous finding of the narrow resonance in kaon photoproduction. Two clear signals are found at $M_{N^*} = 1650$ and 1696 MeV, which correspond to two different nucleon resonances. The former is the same narrow resonance found in our previous study and only exists for $\Gamma_{N^*} \leq 25$ MeV, whereas the latter is related to the best $\chi^2_{\rm min}$ found in the present calculation and is obtained with $\Gamma_{N^*} = 76$ MeV. From the changes in the total χ^2 we have derived the relation between the mass and width of the resonance. Our finding indicates that the properties of the $N^*(1685)$ and $N^*(1710)$ resonances are strongly correlated, since the best $\chi^2_{\rm min}$ would be obtained by increasing the contributions of both $N^*(1685)$ and $N^*(1710)$ resonances, albeit with different coupling signs, in order to produce the required destructive interference. By considering the $N^*(1710)$ coupling found in previous investigations we estimate the largest resonance width to be 35 MeV, with the corresponding mass 1680 MeV. However, if we used the width obtained from the latest η photoproduction experiment, i.e., 25 MeV, the resonance mass would be 1675 MeV, which is consistent with the recent PDG estimate.

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