Analysis of the new Crystal Ball data on $K^- p \to \pi^0 \Lambda$ reaction with beam momenta of $514 \sim 750$ MeV/c

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The Crystal Ball Collaboration has recently reported the differential cross sections for the reaction $K^- p \to \pi^0 \Lambda$ using an incident K^- beam with momenta between 514 and 750 MeV/c. We make a partial wave analysis for this process with an effective Lagrangian approach and study the properties of some Σ resonances around this energy range. In order to reproduce the data well, we need to introduce a new Σ resonance, which can be either $J^P = \frac{1}{2}^+$ with mass near 1530 MeV and width around 500 MeV, or a $\Sigma(\frac{1}{2}^-)$ with mass near 1550 MeV and width around 200 MeV. To distinguish the two schemes, further analysis with more data are required.

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I. INTRODUCTION

The $K^- p$ interactions at resonance region are important methods for the study of resonance spectroscopy and interactions, especially for hyperon with $S = -1$. Recently, the differential cross sections for $K^- + p \to \pi^0 + \Lambda$ are measured with very high precision with the Crystal Ball spectrometer at the BNL Alternating Gradient Synchrotron [1], where neutron and photon final states from $\pi^0 \Lambda$ decays are well detected. The new data provides a good opportunity for studying Σ-hyperon resonances in the experimental energy range, which is between 514 and 750 MeV/c for incident momentum, corresponding to $\sqrt{s} = 1569 - 1676$ MeV for c.m. energy.

The Σ-hyperon resonances in the Particle Data Group (PDG) [2] are mainly known from the analysis of $\overline{K}N$ reactions in the 1970s, and large uncertainties may exist not only for the unestablished resonances with one or two stars, but also for the established ones with three or four stars because of the limited data and knowledge of background contributions. Moreover, there still may be some new resonances that have not been discovered. Past analyses of the reaction $\overline{K}N \to \pi\Lambda$ include the energy dependent partial wave analysis with c.m. energy between 1540 and 2215 MeV [3], and the energy independent analysis with c.m. energy between 1540 and 2150 MeV [4]. Both analyses considered the reaction amplitude parameterized as the sum of resonance terms of Breit-Wigner form and a background term of certain form. Different ways of background extraction may bring large uncertainty to results.

In this work, benefitted from the available new data of high precision, we make a partial wave analysis with an effective Lagrangian approach. We aim at an improvement in the knowledge of the Σ resonances around the energy range concerned, as well as their interactions with some other hadrons.

This paper is organized as follows. In section II, the theoretical framework and amplitudes are presented for the reaction $\overline{K}N \to \pi\Lambda$. In section III, the analysis results are presented and compared with the experimental data, with some discussions. In section IV, we give the summary and conclusion of this work.

II. THEORETICAL FRAMEWORK

The effective Lagrangian method is an important theoretical approach in describing the various processes at resonance region. For the reaction $K^- + p \to \pi^0 + \Lambda$, the Feynman diagrams are shown in Fig. 1, where the incoming momenta are k and p for kaon and proton, respectively, and the outgoing momenta are q and p' for π^0 and the Λ, respectively. The main contributions come from the t-channel K^* meson exchange, the u-channel proton exchange, and the s-channel Σ and its resonances exchanges. Note that in previous analyses, the t-channel and u-channel contributions were treated differently, where they are treated as the background term with certain parametrization.

For the t-channel K^* meson exchange, the effective Lagrangian for $K^* K \pi$ coupling is

$$\mathcal{L}_{K^* K\pi} = i g_{K^* K\pi} K^*_\mu (\pi \cdot \tau \partial^\mu K - \partial^\mu \pi \cdot \tau K)\,, \quad (1)$$

where the isospin structure for $K^* K \pi$ is $\overline{K}^* \pi \cdot \tau K$ with

$$\overline{K}^* = (K^{*-}, \overline{K}^{*0}), \pi\cdot\tau = \begin{pmatrix} \pi^0 & \sqrt{2}\pi^+ \\ \sqrt{2}\pi^- & -\pi^0 \end{pmatrix}, K = \begin{pmatrix} K+ \\ K^0 \end{pmatrix}. \quad (2)$$

Using the decay width $\Gamma_{K^* \to K\pi} = 50.8$ MeV [2], one gets the coupling constant $g_{K^* K\pi} = -3.23$.

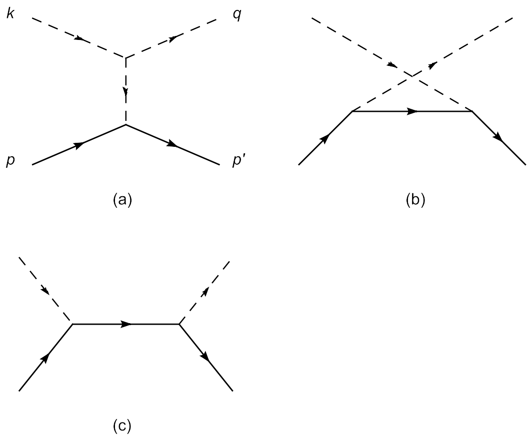

FIG. 1: Feynman diagrams for $K^- + p \to \pi^0 + \Lambda$. (a) t-channel K^{*-} exchange; (b) u-channel proton exchange; (c) s-channel Σ resonances exchange.

The effective Lagrangian for $K^*N\Lambda$ coupling is

$$\mathcal{L}_{K^*N\Lambda} = -g_{K^*N\Lambda}\overline{\Lambda}\big(\gamma_\mu K^{*\mu} - \frac{\kappa_{K^*N\Lambda}}{2M_N}\sigma_{\mu\nu}\partial^\nu K^{*\mu}\big)N + \text{H.c.}\,, \tag{3}$$

where $g_{K^*N\Lambda}$ and $\kappa_{K^*N\Lambda}$ are effective coupling constants and can only be estimated from model predictions or fit to some data. The popular potential model by Stoks and Rijken gave two sets of these coupling constants [5, 6]:

$$\begin{aligned} g_{K^*N\Lambda} &= -4.26 \qquad \kappa_{K^*N\Lambda} = 2.66 \qquad \text{(NSC97a)}, \\ g_{K^*N\Lambda} &= -6.11 \qquad \kappa_{K^*N\Lambda} = 2.43 \qquad \text{(NSC97f)}. \end{aligned} \tag{4}$$

Thus we constrain $g_{K^*N\Lambda}$ between -4.26 and -6.11, and $\kappa_{K^*N\Lambda}$ between 2.43 and 2.66 in our analysis. A recent prediction from light cone QCD sum rules (LCSR) gives a larger range for $g_{K^*N\Lambda} = -5.1 \pm 1.8$, while very different values for $\kappa_{K^*N\Lambda}$ [7]. Some other works for vector meson-baryon couplings also have large deviations on κ_{VBB} [8–10]. For these uncertainties, we also try the parameters in larger range and give the results in discussions.

For the u-channel nucleon exchange, the effective Lagrangians are

$$\mathcal{L}_{\pi NN} = \frac{g_{\pi NN}}{2M_N}\overline{N}\gamma^\mu\gamma_5\partial_\mu\pi\cdot\tau N, \tag{5}$$

$$\mathcal{L}_{KN\Lambda} = \frac{g_{KN\Lambda}}{M_N + M_\Lambda}\overline{N}\gamma^\mu\gamma_5\Lambda\partial_\mu K + \text{H.c.}, \tag{6}$$

where $g_{\pi NN} = 13.26$ and $g_{KN\Lambda} = -13.24$ are estimated from flavor SU(3) symmetry relations [11, 12].

For the s-channel Σ and its resonances exchange, we consider effective couplings up to D-wave, which include intermediate states with $J^P = \frac{1}{2}^\pm$, $\frac{3}{2}^\pm$, and $\frac{5}{2}^-$.

For $\Sigma(1189)$ and its resonance with $J^P = \frac{1}{2}^+$ contributions in s-channel , the effective Lagrangians are

$$\mathcal{L}_{KN\Sigma} = \frac{g_{KN\Sigma}}{M_N + M_\Sigma}\partial_\mu\overline{K\mathbf{\Sigma}}\cdot\tau\gamma^\mu\gamma_5 N + \text{H.c.}, \tag{7}$$

and

$$\mathcal{L}_{\Sigma\Lambda\pi} = \frac{g_{\Sigma\Lambda\pi}}{M_\Lambda + M_\Sigma}\overline{\Lambda}\gamma^\mu\gamma_5\partial_\mu\pi\cdot\Sigma + \text{H.c.}. \tag{8}$$

Where the isospin structure for $KN\Sigma$ coupling is

$$\overline{K} = (K^-, \overline{K}^0), \overline{\mathbf{\Sigma}}\cdot\tau = \begin{pmatrix} \overline{\Sigma}^0 & \sqrt{2}\overline{\Sigma}^+ \\ \sqrt{2}\overline{\Sigma}^- & -\overline{\Sigma}^0 \end{pmatrix}, N = \begin{pmatrix} p \\ n \end{pmatrix}. \tag{9}$$

The coupling constants from SU(3) flavor symmetry relations predict $g_{KN\Sigma} = 3.58$ and $g_{\Sigma\Lambda\pi} = 9.72$ for $\Sigma(1189)$. With consideration of possible SU(3) symmetry breaking effect, we multiply a tunable factor between $1/\sqrt{2}$ and $\sqrt{2}$ to the central value of $g_{KN\Sigma}g_{\Sigma\Lambda\pi}$ in our analysis.

For intermediate Σ state with $J^P = \frac{1}{2}^-$, the effective Lagrangians are

$$\mathcal{L}_{KN\Sigma(\frac{1}{2}^-)} = -ig_{KN\Sigma(\frac{1}{2}^-)}\overline{K\mathbf{\Sigma}}\cdot\tau N + \text{H.c.}, \tag{10}$$

and

$$\mathcal{L}_{\Lambda\pi\Sigma(\frac{1}{2}^-)} = -ig_{\Lambda\pi\Sigma(\frac{1}{2}^-)}\overline{\Sigma}\Lambda\pi + \text{H.c.}. \tag{11}$$

The product of the coupling constants $g_{KN\Sigma(\frac{1}{2}^-)}g_{\Lambda\pi\Sigma(\frac{1}{2}^-)}$ is set to be a free parameter in our analysis.

For intermediate Σ^* state in s-channel with $J^P = \frac{3}{2}^+$, the effective Lagrangians are

$$\mathcal{L}_{KN\Sigma^*} = \frac{f_{KN\Sigma^*}}{m_K}\partial_\mu\overline{K\mathbf{\Sigma}}^{*\mu}\cdot\tau N + \text{H.c.}\,, \tag{12}$$

and

$$\mathcal{L}_{\Sigma^*\Lambda\pi} = \frac{f_{\Sigma^*\Lambda\pi}}{m_\pi}\partial_\mu\overline{\pi}\cdot\overline{\Sigma}^{*\mu}\Lambda + \text{H.c.}\,, \tag{13}$$

For $\Sigma^*(1385)$, the coupling constant $f_{\Sigma^*\Lambda\pi} = 1.27$ can be calculated from the decay width $\Gamma_{\Sigma^*\to\Lambda\pi} \approx 31$ MeV [2], and $f_{KN\Sigma^*} = -3.22$ can be estimated from flavor SU(3) symmetry relation [12]. With consideration of possible SU(3) symmetry breaking effect, we multiply a factor between $\sqrt{2}$ and $1/\sqrt{2}$ as a free parameter to the central value of $f_{KN\Sigma^*}$, and thus $f_{KN\Sigma^*}f_{\Sigma^*\Lambda\pi}$ is constrained between -2.9 and -5.8 in our analysis.

For intermediate Σ state in s-channel with $J^P = \frac{3}{2}^-$, the effective Lagrangians are

$$\mathcal{L}_{KN\Sigma(\frac{3}{2}^-)} = \frac{f_{KN\Sigma(\frac{3}{2}^-)}}{m_K}\partial_\mu\overline{K\mathbf{\Sigma}}^\mu\cdot\tau\gamma_5 N + \text{H.c.}, \tag{14}$$

and

$$\mathcal{L}_{\Lambda\pi\Sigma(\frac{3}{2}^-)} = \frac{f_{\Lambda\pi\Sigma(\frac{3}{2}^-)}}{m_\pi}\partial_\mu\pi\overline{\Sigma}^\mu\gamma_5\Lambda + \text{H.c.}. \tag{15}$$

The $\Sigma(1670)D_{13}$ is a four-star resonance in PDG. The above coupling constants can be estimated from the decay width $\Gamma_{\Sigma(1670)\to KN}$ and $\Gamma_{\Sigma(1670)\to\pi\Lambda}$, which still have large uncertainties. We constrain $f_{KN\Sigma(1670)}f_{\Lambda\pi\Sigma(1670)}$ between -1.5 and -3.7 in our analysis.

For intermediate Σ state in s-channel with $J^P = \frac{5}{2}^-$, the effective Lagrangians are

$$\mathcal{L}_{KN\Sigma(\frac{5}{2}^-)} = g_{KN\Sigma(\frac{5}{2}^-)}\partial_\mu\partial_\nu\overline{K\mathbf{\Sigma}}^{\mu\nu}\cdot\tau N + \text{H.c.}, \quad (16)$$

and

$$\mathcal{L}_{\Lambda\pi\Sigma(\frac{5}{2}^-)} = g_{\Lambda\pi\Sigma(\frac{5}{2}^-)}\partial_\mu\partial_\nu\pi\cdot\overline{\Sigma}^{\mu\nu}\Lambda + \text{H.c.}. \quad (17)$$

The $\Sigma(1775)D_{15}$ is a four-star resonance in PDG. The coupling constants can be estimated from the decay width $\Gamma_{\Sigma(1775)\to KN}$ and $\Gamma_{\Sigma(1775)\to\pi\Lambda}$, and thus we have the product of the coupling constants $g_{KN\Sigma(1775)}g_{\Lambda\pi\Sigma(1775)}$ constrained between 36 and 56 GeV^{-4} in our analysis.

For each vertex of these channels, a form factor is attached to describe the off-shell properties of the amplitudes. For all the channels considered, we adopt the form factor [12]

$$F_B(q_{ex}^2, M_{ex}) = \frac{\Lambda^4}{\Lambda^4 + (q_{ex}^2 - M_{ex}^2)^2}\,, \quad (18)$$

where the q_{ex} and M_{ex} are the 4-momenta and the mass of the exchanged hadron, respectively. The cutoff parameter Λ is constrained between 0.8 and 1.5 GeV for all channels.

For the propagators with 4-momenta p, we use

$$\frac{-g^{\mu\nu} + p^\mu p^\nu/m_{K^*}^2}{p^2 - m_{K^*}^2} \quad (19)$$

for K^* meson exchange (μ and ν are polarization index of K^*);

$$\frac{\not{p} + m}{p^2 - m^2} \quad (20)$$

for spin-1/2 propagator;

$$\frac{\not{p} + m}{p^2 - m^2}\Big(-g^{\mu\nu} + \frac{\gamma^\mu\gamma^\nu}{3} + \frac{\gamma^\mu p^\nu - \gamma^\nu p^\mu}{3m} + \frac{2p^\mu p^\nu}{3m^2}\Big) \quad (21)$$

for spin-3/2 propagator; and

$$\frac{\not{p} + m}{p^2 - m^2}S_{\alpha\beta\mu\nu}(p, m) \quad (22)$$

for spin-5/2 propagator, where

$$S_{\alpha\beta\mu\nu}(p,m) = \frac{1}{2}(\overline{g}_{\alpha\mu}\overline{g}_{\beta\nu} + \overline{g}_{\alpha\nu}\overline{g}_{\beta\mu}) - \frac{1}{5}\overline{g}_{\alpha\beta}\overline{g}_{\mu\nu}$$
$$-\frac{1}{10}(\overline{\gamma}_\alpha\overline{\gamma}_\mu\overline{g}_{\beta\nu} + \overline{\gamma}_\alpha\overline{\gamma}_\nu\overline{g}_{\beta\mu} + \overline{\gamma}_\beta\overline{\gamma}_\mu\overline{g}_{\alpha\nu} + \overline{\gamma}_\beta\overline{\gamma}_\nu\overline{g}_{\alpha\mu}), \quad (23)$$

with

$$\overline{g}_{\mu\nu} = g_{\mu\nu} - \frac{p_\mu p_\nu}{m^2},$$
$$\overline{\gamma}_\mu = \gamma_\mu - \frac{p_\mu}{m^2}\not{p}. \quad (24)$$

For unstable resonances, we replace the denominator $\frac{1}{p^2-m^2}$ in the propagators by the Breit-Wigner form $\frac{1}{p^2-m^2+im\Gamma}$, and replace m in the rest of the propagators by $\sqrt{p^2}$. The m and Γ in the propagators represent the mass and total width of a resonance, respectively.

The differential cross section for $K^- + p \to \pi^0 + \Lambda$ at c.m. frame with $s = (p+k)^2$ can be expressed as

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{2\pi d\cos\theta} = \frac{1}{64\pi^2 s}\frac{|\mathbf{q}|}{|\mathbf{k}|}\overline{|\mathcal{M}|}^2, \quad (25)$$

where θ denotes the angle of the outgoing π^0 relative to beam direction in the c.m. frame, and $\mathbf{k}$ and $\mathbf{q}$ denote the 3-momenta of K^- and π^0 in the c.m. frame, respectively. The averaged amplitude square $\overline{|\mathcal{M}|}^2$ can be expressed as

$$\overline{|\mathcal{M}|}^2 = \frac{1}{2}\sum_{r_1,r_2}|\mathcal{M}|^2$$
$$= \frac{1}{2}\text{Tr}\big[(\not{p}' + m_\Lambda)\mathcal{A}(\not{p} + m_N)\gamma^0\mathcal{A}^+\gamma^0\big], \quad (26)$$

where r_1 and r_2 denote polarization of initial and final state, respectively; and p and p' denote the 4-momenta of proton and Λ in the reaction. $\mathcal{A}$ is part of the total amplitude, which can be expressed as

$$\mathcal{M} = \overline{u}_{r_2}(p')\ \mathcal{A}\ u_{r_1}(p) = \sum_i \mathcal{M}_i$$
$$= \overline{u}_{r_2}(p')\big(\sum_i \mathcal{A}_i\big)u_{r_1}(p). \quad (27)$$

where i denotes the ith channel that contributes to the total amplitude.

III. RESULTS AND DISCUSSIONS

In this analysis, the t-channel K^* exchange and the u-channel proton exchange amplitudes are fundamental ingredients, which may be different from some other analysis without consideration of these channels. The $\Sigma(1189)\frac{1}{2}^+$, $\Sigma^*(1385)\frac{3}{2}^+$, $\Sigma(1670)\frac{3}{2}^-$ and $\Sigma(1775)\frac{5}{2}^-$ contributions in s-channel are always included in our analysis, partly because these channels should contribute to the reaction by the knowledge of their existence (they are four-star resonances), partly because the present data favor the inclusion of them. Still some parameters in the above channels have uncertainties and are to be fitted in the analysis. The ranges of the parameters have been constrained from the PDG estimates or model predictions, which have been explained in section II. From the above 6 channels of 17 tunable parameters constrained in the allowed range, the best fit gives a χ^2 of about 245 for the total 128 data points, which is shown by the (blue) dashed lines in Fig.2. Although the fit looks already quite good qualitatively, from detailed comparison with the very precise data and the quite large χ^2, some systematic deviations still exist.

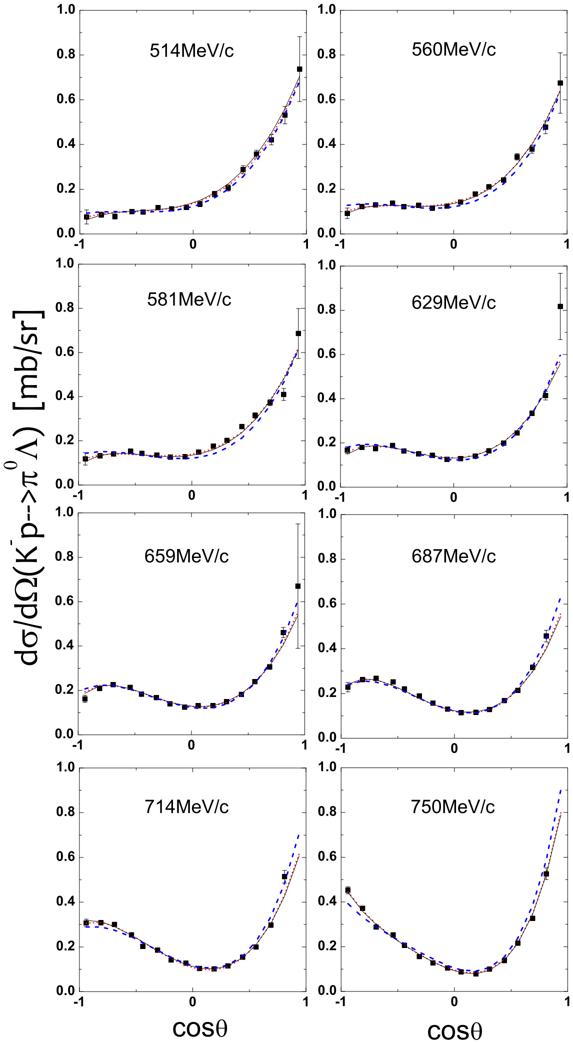

FIG. 2: The best fits for the differential cross sections of the reaction $K^- + p \to \pi^0 + \Lambda$ compared with the experimental data [1], where θ denotes the angle of the outgoing π^0 with respect to beam direction in the c.m. frame. The dashed lines (blue) are results with inclusion of only well established Σ resonances in s-channel, and the χ^2 is 245 for the 128 data points; the solid lines are results of scheme I, in which a new $\Sigma(\frac{1}{2}^+)$ resonance is included in s-channel with mass near 1530 MeV and width around 500 MeV, and the χ^2 is 78.2 for the 128 data points; the dotted lines (red) are results of scheme II, in which a new $\Sigma(\frac{1}{2}^-)$ resonance is included in s-channel with mass near 1550 MeV and width around 200 MeV, and the χ^2 is 78.3 for the 128 data points.

For a better description of the data, we need to introduce some other Σ resonances in s-channel. We try them in the analysis with their coupling constants, mass, and width as free parameters and check if they are favored by the present data.

A. $\Sigma(1530)$ with $J^P = \frac{1}{2}^+$

Among the $J^P = \frac{1}{2}^\pm, \frac{3}{2}^\pm$ Σ resonances in s-channel, our best fit comes from the inclusion of a $J^P = \frac{1}{2}^+$ Σ resonance with mass near 1530 MeV, and width around 500 MeV (we call it scheme I).

The solid lines in Fig. 2 shows this best result compared with the experimental data of the differential cross sections. The analysis includes 21 tunable parameters in the allowed range and the χ^2 for this best fit is 78.2 for the total 128 data points. From the solid lines in Fig. 2 one can see that scheme I can describe the experimental data very well with the inclusion of a single broad $\Sigma(\frac{1}{2}^+)$ resonance.

Table I shows the central values and statistic uncertainties for 9 of the parameters on the s-channel resonances in this scheme. From Table I, the mass of $\Sigma(1670)$ is precisely around 1669 MeV, and its width is around 80 MeV, which are consistent with the PDG estimates [2]. The coupling constant for this channel tends to be close to the upper bound, and hence so does the $(\Gamma_{\pi\Lambda}\Gamma_{KN})^{\frac{1}{2}}/\Gamma_{\rm tot}$ for $\Sigma(1670)$, but still within the PDG range. The mass of $\Sigma(1775)$ is much larger than the c.m. energies of this experiment, and thus the parameters of $\Sigma(1775)$ may be insensitive to the data. We constrain the parameters of $\Sigma(1775)$ according to the ranges of PDG. The $J^P = \frac{1}{2}^+$ $\Sigma(1530)$ from our analysis is a new resonance that is not listed in PDG. The statistic uncertainties are large, wiht its mass ranging from 1440 to 1600 MeV, and its width ranging from 400 to 900 MeV from our analysis. By including this resonance, the χ^2 drops from about 245 to 78.2 for the total 128 data points.

The other 12 free parameters of this scheme includes 5 coupling constants and 7 cutoff parameters in the form factors of the total 7 channels. In Table II we list the fitted results of the 5 free parameters on the couplings of the t-channel, u-channel and s-channel $\Sigma(1189)$ and $\Sigma(1385)$ contributions. Note that the first two parameters are couplings of the t-channel K^* exchange, and their ranges are constrained by the potential model [5]. As one may doubt about this model, we also set the two parameters free to check what can happen. We find that the χ^2 goes from 78.2 to 77.5, and the central value of $g_{K^*N\Lambda}$ become larger (11.7) and $g_{K^*N\Lambda}\kappa_{K^*N\Lambda}$ become smaller (-7.3), while the central values of the other parameters shift very little. Thus the uncertainties with the two parameters does have very little influence to the main results of our analysis in this scheme.

From Table II, one can see that couplings $g_{\pi NN}g_{KN\Lambda}$ and $f_{KN\Sigma^*}f_{\Sigma^*\Lambda\pi}$ in u- and s-channel are similar (a little smaller) to the flavor SU(3) prediction. The contribution from s-channel $\Sigma(1189)$ exchange is very small and thus tuning its coupling within the range in Table II has very little effect to the analysis.

The research for the possible new $\Sigma(\frac{1}{2}^-)$ near 1380 MeV has always been our concern, and previous

scheme I	mass(MeV)(PDG estimate)	$\Gamma_{\rm tot}$(MeV) (PDG estimate)	$(\Gamma_{\pi\Lambda}\Gamma_{KN})^{\frac{1}{2}}/\Gamma_{\rm tot}$ (PDG range)
$\Sigma(1670)\frac{3}{2}^-$	1669 ± 2 (1665,1685)	83^{+6}_{-11} (40,80)	$0.126^{+0.019}_{-0.038}$ $(0.02, 0.17)$
$\Sigma(1775)\frac{5}{2}^-$	1780^{+0}_{-10} (1770,1780)	100^{+30}_{-0} (105,135)	$0.297^{+0.156}_{-0.147}$ $(0.25, 0.32)$
$\Sigma(1530)\frac{1}{2}^+$	1531^{+70}_{-90}	530^{+370}_{-130}	$0.064^{+0.216}_{-0.062}$

TABLE I: Adjusted parameters for high mass Σ resonances in scheme I, which includes a new $\Sigma(1530)\frac{1}{2}^+$ resonance. Statistic uncertainties and PDG estimates are also listed.

$g_{K^*N\Lambda}$ (model range)	$g_{K^*N\Lambda}\kappa_{K^*N\Lambda}$ (model range)	$g_{\pi NN}g_{KN\Lambda}$ (SU(3))	$g_{KN\Sigma}g_{\Sigma\Lambda\pi}$ (SU(3))	$f_{KN\Sigma^*}f_{\Sigma^*\Lambda\pi}$ (SU(3))
$-5.90^{+0.85}_{-0.21}$ $(-6.11, -4.26)$ [5]	$-11.3^{+0}_{-0.7}$ $(-16.3, -10.4)$ [5]	-163^{+26}_{-23} (-176)	$46.9^{+0}_{-23.5}$ (34.8)	$-3.56^{+0.43}_{-1.44}$ (-4.1)

TABLE II: Adjusted parameters with statistic uncertainties for the couplings in t-channel, u-channel and s-channel $\Sigma(1189)$ and $\Sigma^*(1385)$ exchange of scheme I.

work has shown some evidence of it [13–15]. In this work, we also check whether this data set is compatible with the existence of the $\Sigma(1380)$. We include additional $\Sigma(\frac{1}{2}^-)$ in scheme I, and constrain its mass between 1360 and 1400 MeV. From our analysis, the best fit gives $\chi^2 = 76.8$ with a small coupling constant $g_{KN\Sigma(\frac{1}{2}^-)}g_{\Sigma(\frac{1}{2}^-)\pi\Lambda} \sim 0.5$ and a narrow width 40 MeV. When fix the coupling $g_{KN\Sigma(\frac{1}{2}^-)}g_{\Sigma(\frac{1}{2}^-)\pi\Lambda} = 3$ (which is a moderate size from previous work), we find $\chi^2 = 78$ with a wide width of 330 MeV. This shows that the existence of a $\Sigma(\frac{1}{2}^-)$ near 1380 MeV with sizeable couplings is not ruled out by the present data, although there is no strong evidence of it. This result is understandable since 1380 MeV is much smaller than the energy range of the experiment.

B. $\Sigma(1550)$ with $J^P = \frac{1}{2}^-$

An alternative scheme from our analysis is to include a $J^P = \frac{1}{2}^-$ Σ state in s-channel (scheme II). With the same procedure, the best fit produces its mass about 1550 MeV and width about 200 MeV, with $\chi^2 = 78.3$ for the total 128 data points.

The (red) dotted lines in Fig. 2 shows the result of scheme II, compared with the experimental data of the differential cross sections [1]. From Fig. 3 one can see that the results of scheme II (dotted lines) nearly coincide with that of scheme I (solid lines), and can also give a good description of the data. Table III shows 9 of the parameters on the s-channel resonances of this scheme. From Table III, one can see the mass, width and $(\Gamma_{\pi\Lambda}\Gamma_{KN})^{\frac{1}{2}}/\Gamma_{\rm tot}$ of the $\Sigma(1670)$, $\Sigma(1775)$ and the newly included $\Sigma(\frac{1}{2}^-)$ resonance of this analysis. The parameters of $\Sigma(1670)$ are all well consistent with the PDG estimates [2]. The mass of $\Sigma(1775)$ is also well consistent with the PDG value, while its width tends to the lower bound and the $(\Gamma_{\pi\Lambda}\Gamma_{KN})^{\frac{1}{2}}/\Gamma_{\rm tot}$ tends to the upper bound of the constraint in this analysis. The new $\Sigma(1550)$ has mass near 1550 MeV, width around 200 MeV, and a sizable coupling $(\Gamma_{\pi\Lambda}\Gamma_{KN})^{\frac{1}{2}}/\Gamma_{\rm tot} \sim 0.2$. It might be the $\Sigma(1560)$ bump (two star resonance) listed in PDG [2], which has no J^P information and has a smaller width of about 80 MeV.

Besides the 9 parameters listed above, the results of the other 5 free parameters on the couplings of the t-channel, u-channel and s-channel $\Sigma(1189)$ and $\Sigma(1385)$ exchanges are listed in Table IV for scheme II.

The coupling constants in t-channel are constrained by the model prediction [5]. As one may doubt about this model, we also set the two parameters free to check what can happen. We find that the χ^2 goes from 78.3 to 73.1, and the central value of $g_{K^*N\Lambda}$ become larger (6.0) and $g_{K^*N\Lambda}\kappa_{K^*N\Lambda}$ become smaller (-4.5), while the parameters of the new $\Sigma(1550)$ do not change very much, with the central values 1549 MeV, 197 MeV, and 0.15 for the mass, width and $(\Gamma_{\pi\Lambda}\Gamma_{KN})^{\frac{1}{2}}/\Gamma_{\rm tot}$, respectively.

We also check whether the possible existence of the $\Sigma(1380)\frac{1}{2}-$ is compatible with the present data. Thus we include additional $\Sigma(\frac{1}{2}^-)$ in s-channel with mass constrained between 1360 and 1400 MeV. Similar as in the previous scheme, the best gives a small coupling a small coupling constant $g_{KN\Sigma(\frac{1}{2}^-)}g_{\Sigma(\frac{1}{2}^-)\pi\Lambda} \sim -0.6$ and width around 180 MeV with $\chi^2 = 77$. When fix the coupling $g_{KN\Sigma(\frac{1}{2}^-)}g_{\Sigma(\frac{1}{2}^-)\pi\Lambda} = 3$ (which is a moderate size from previous work), we find $\chi^2 = 78.2$ with a small width of 40 MeV. This shows that the existence of a $\Sigma(\frac{1}{2}^-)$ near 1380 MeV with sizeable couplings is not ruled out by the present data, although there is no strong evidence of it. This result is understandable since 1380 MeV is much far away from the energy range of the experiment.

With the same procedure of the above 2 subsections on $\Sigma(\frac{1}{2}^\pm)$, we also try $\Sigma^*(\frac{3}{2}^\pm)$ states in the analysis. The resulted χ^2 are much larger (between 160 and 245), which shows no evidence of their existences in the energy range of the experiment.

IV. SUMMARY

The differential cross sections for neutral particles production from K^-p interactions have been measured by the Crystal Ball Collaboration for incident momentum

scheme II	mass(MeV)(PDG estimate)	$\Gamma_{\rm tot}$(MeV) (PDG estimate)	$(\Gamma_{\pi\Lambda}\Gamma_{KN})^{\frac{1}{2}}/\Gamma_{\rm tot}$ (PDG range)
$\Sigma(1670)\frac{3}{2}^-$	$1671.7^{+1.4}_{-2.4}$ (1665,1685)	$70.5^{+9}_{-8.5}$ (40,80)	$0.121^{+0.048}_{-0.037}$ $(0.02, 0.17)$
$\Sigma(1775)\frac{5}{2}^-$	1777^{+3}_{-7} (1770,1780)	100^{+10}_{-0} (105,135)	$0.382^{+0.008}_{-0.09}$ $(0.25, 0.32)$
$\Sigma(1550)\frac{1}{2}^-$	1550^{+8}_{-12}	216^{+94}_{-53}	$0.194^{+0.20}_{-0.101}$

TABLE III: Adjusted parameters for high mass Σ resonances in scheme II, which includes a new $\Sigma(1550)\frac{1}{2}^-$ resonance. Statistic uncertainties and PDG estimates are also listed.

$g_{K^*N\Lambda}$ (model range)	$g_{K^*N\Lambda}\kappa_{K^*N\Lambda}$ (model range)	$g_{\pi NN}g_{KN\Lambda}$ (SU(3))	$g_{KN\Sigma}g_{\Sigma\Lambda\pi}$ (SU(3))	$f_{KN\Sigma^*}f_{\Sigma^*\Lambda\pi}$ (SU(3))
$-5.48^{+1.02}_{-0.63}$ $(-6.11, -4.26)$ [5]	$-11.3^{+0}_{-0.03}$ $(-16.3, -10.4)$ [5]	-130^{+6}_{-23} (-176)	$49^{+0}_{-6.4}$ (34.8)	$-5.6^{+0.54}_{-0}$ (-4.1)

TABLE IV: Adjusted parameters with statistic uncertainties for the couplings in t-channel, u-channel and s-channel $\Sigma(1189)$ and $\Sigma^*(1385)$ exchange of scheme II.

of K^- between 514 and 750 MeV/c. Using the high precision new data, we analyze the differential cross sections for the process $K^- + p \to \pi^0 + \Lambda$ with the effective Lagrangian method. We include the contributions from t-channel K^* exchange, u-channel proton exchange, s-channel $\Sigma(1189)$, $\Sigma(1385)$, $\Sigma(1670)$ and $\Sigma(1775)$ exchanges in our analysis. We find that these 6 ingredients are still insufficient, with $\chi^2 \sim 245$ for 128 data points. We try to include some new ingredient in our analysis and two schemes can both describe the data well.

Scheme I suggests the existence of a new Σ resonance with $J^P = \frac{1}{2}^+$, mass near 1530 MeV and width about 500 MeV. With this resonance the χ^2 drops to 78.2 for the 128 data points. In this scheme the other parameters are all in reasonable ranges. A alternative scheme (scheme II) suggest the existence of a $\Sigma(\frac{1}{2}^-)$ with mass near 1550 MeV and width about 200 MeV, which seems similar to the $\Sigma(1560)$ (a two-star resonance) in PDG. Scheme II gives the $\chi^2 = 78.3$ for the 128 data points.

From our analysis, both schemes can well describe the differential cross sections of $K^- + p \to \pi^0 + \Lambda$ at this energy range, and further analysis with more data is needed to distinguish the two possible schemes. Some uncertainty may still exist from the uncertainty in the coupling constants. This analysis can neither support nor exclude the possible existence of the new $\Sigma(1380)\frac{1}{2}^-$. Measurements with wider energy ranges and combined channel analysis in the future will be helpful to provide more information on properties and interactions of the Σ resonances.

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