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# Evidence for a new resonance $\Sigma^*(1380)$ with $J^P=1/2^-$ *

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**Abstract** A new particle $\Sigma^*$ with $J^P=1/2^-$ was predicted by unquenched quark models with its mass around the well established $\Sigma^*(1385)$ with $J^P=3/2^+$. Here we re-examine some old data of the $K^-p\to\Lambda\pi^-\pi^+$ reaction. Firstly we re-fit the data for kaon beam momenta in the range of $1.0-1.8$ GeV. Secondly we study the reaction at the energies around $\Lambda^*(1520)$ peak. Both studies show evidence for the existence of $\Sigma^*$ with $J^P=1/2^-$ around 1380 MeV. Higher statistic data on relevant reactions are needed to clarify the situation.

**Key words** $\Sigma^*$, unquenched quark model, $K^-p\to\Lambda\pi^-\pi^+$ reaction

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## 1 Introduction

There are only three constituent quarks inside each baryon in the classical constituent quark models. These models were very successful to reproduce the mass pattern and many other static properties of spatial ground states of baryons. However, these models met problems as more and more information on baryons accumulated. One problem is about the $\bar{d}/\bar{u}$ asymmetry in the proton. The number of $\bar{d}$ is more than $\bar{u}$ by an amount $\bar{d}-\bar{u}\approx 0.12$ [1]. Another problem is that why the mass of $\Lambda^*(1405)$ is much less than $N^*(1535)$. The $\Lambda^*(1405)$ with (uds)-quarks is obviously expected to be heavier than $N^*(1535)$ with (uud)-quarks in the classical 3-quark models. To solve these problems, one way is to introduce the $q\bar{q}$ components in the baryons. In fact the spatial excitation energy of a quark in a baryon is already comparable to pull a $q\bar{q}$ pair from the gluon field. For example, the $N^*(1535)$ with mainly a [ud] [us]$\bar{s}$ state is heavier than $\Lambda^*(1405)$ with mainly a [ud] [sq]$\bar{q}$ state with $q\bar{q}=(u\bar{u}+d\bar{d})/\sqrt{2}$ in the penta-quark models [2–4].

These unquenched models give a new physical picture for the baryonic excitation. In the penta-quark models [3, 4], there are many new predictions besides the properties of $\Lambda^*(1405)$ and $N^*(1535)$, such as existence of a $\Sigma^*(1/2^-)$ around 1380 MeV and a $\Xi^*(1/2^-)$ around 1520 MeV, which are both absent in the qqq models. The $\Sigma^*(1/2^-)$ is predicted as a non-resonant broad structure in the meson cloud model [5]. These new predictions need to be checked by experiments.

Possible existence of such new $\Sigma^*(1/2^-)$ structure in $J/\psi$ decays was pointed out earlier [6] and is going to be investigated by forthcoming BES3 experiment [7], here we re-examine the old data of $K^-p\to\Lambda\pi^+\pi^-$ reaction to see whether there is evidence for its existence or not.

In the next section, we present the results of refitting the old data of $K^-p\to\Lambda\pi^+\pi^-$ reaction for the kaon beam momenta of $1.0-1.8$ GeV. In the third section, we show results on this reaction for the beam momenta of $0.25-0.6$ GeV. Then we give the summary in the final section.

## 2 The first evidence

Many experiment papers present the results of $K^-p\to\Lambda\pi^-\pi^+$ [8–14]. It is special for the invariant mass spectra of $\Lambda\pi^-$ with beam momentum $P_{K^-}=1.0-1.8$ GeV [11–14]. These spectra cannot be fit

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as perfect as other sets of data with a single Breit-Wigner resonance. Then we re-fit the $\Lambda\pi^-$ mass spectrum and angular distribution of this reaction from Ref. [11] which gives the largest data sample. The details about this fit can be found in Ref. [15]. Here we only discuss the results.

The results of the fits with a single (Fit1) and two (Fit2) $\Sigma^*$ resonances around 1385 MeV are shown in Fig. 1 and the fitted parameters and statistical errors are listed in Table 1. The fit with a single $\Sigma^*$ resonance (Fit1) is already not bad, but the width of $\Sigma^*$ is much larger than the PDG value [16] of 36±5 MeV. The fit with two $\Sigma^*$ resonances (Fit2) gives a less than $3\sigma$ improvement, but the narrower $\Sigma^*$ resonance in Fit2 gives a width compatible with the PDG value for the $\Sigma^*(1385)$ resonance. In the Fit2, there is an additional broader $\Sigma^*$ resonance with a width about 120 MeV. This new particle may be the one predicted in the unquenched models.

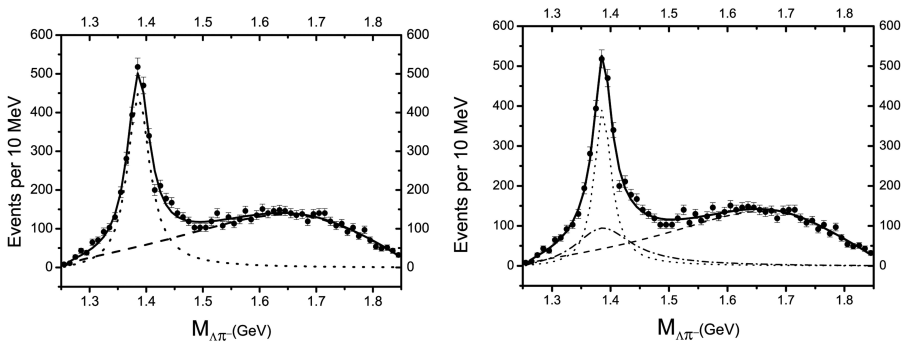


Fig. 1. Fits to the $\Lambda\pi^-$ mass spectrum with a single $\Sigma^*$ (left) and two $\Sigma^*$ resonances (right) around 1385 MeV. The experiment data are from Ref. [11].

Table 1. Fitted parameters with statistical errors and $\chi^2$ over number of degree of freedom (ndf).

| | $M_{\Sigma^*(3/2)}$ | $\Gamma_{\Sigma^*(3/2)}$ | $M_{\Sigma^*(1/2)}$ | $\Gamma_{\Sigma^*(1/2)}$ | $\chi^2$/ndf(Fig. 1) | $\chi^2$/ndf(Fig.2) |
|---|---|---|---|---|---|---|
| Fit1 | $1385.3\pm0.7$ | $46.9\pm2.5$ | | | 68.5/54 | 10.1/9 |
| Fit2 | $1386.1^{+1.1}_{-0.9}$ | $34.9^{+5.1}_{-4.9}$ | $1381.3^{+4.9}_{-8.3}$ | $118.6^{+55.2}_{-35.1}$ | 58.0/51 | 3.2/9 |

Then we also re-fit distribution of the cos $(\Lambda.\mathrm{K})$ for this reaction. These experiment data satisfy three conditions [11]. Only data for $M_{\Lambda\pi^-}$ in the range of $1385\pm45$ MeV and for beam momentum of $1\sim1.45$ GeV are used, so we can reduce the background as low as possible. We also ask for $\cos\theta_{\mathrm{K}\Sigma^*} > 0.95$. For a $\Sigma^*$ with $J = 3/2$, the angular distribution is expected to be of the form $(1+3\cos^2\theta)/2$ [11, 17]; while for a $\Sigma^*$ with $J = 1/2$ and background, a flat constant distribution is predicted. The predictions of Fit1 and Fig. 2 for the angular distribution are shown by the dashed curve and solid curve with $\chi^2$ of 10.1 and 3.2, respectively. In the Fit2, the ratio of contributions from the narrow $\Sigma^*(1385)$ and the broader $\Sigma^*(1/2^-)$ is about 1.6.

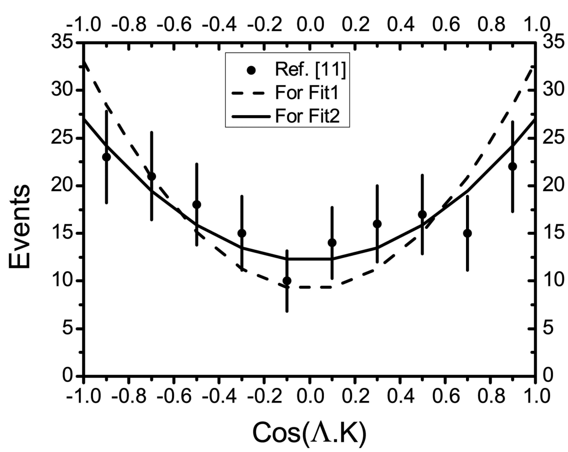


Fig. 2. Predictions for the distribution of cos $(\Lambda.\mathrm{K})$ for the reaction $\mathrm{K}^-\mathrm{p}\to\Lambda\pi^+\pi^-$.

From above results, we find that it seems improving the fit to experimental data with an additional $\Sigma^*(1/2^-)$. Although the evidence is weak, the possible existence of such new $\Sigma^*(1/2^-)$ resonance cannot be excluded while all previous analyses only considered one resonance there.

## 3 The second evidence

Now we show results for our re-analysis of $\mathrm{K}^-\mathrm{p}\to\Lambda\pi^-\pi^+$ in the energy region around the $\Lambda^*(1520)$ peak. We list the Feynman diagrams in Fig. 3. The detailed calculation about these Feynman diagrams can be found in Ref. [18].

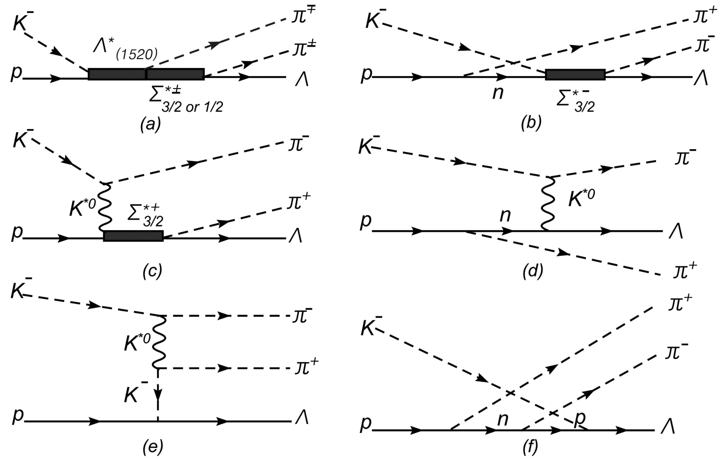


Fig. 3. Feynman diagrams for $K^- p \to \Lambda\pi^-\pi^+$.

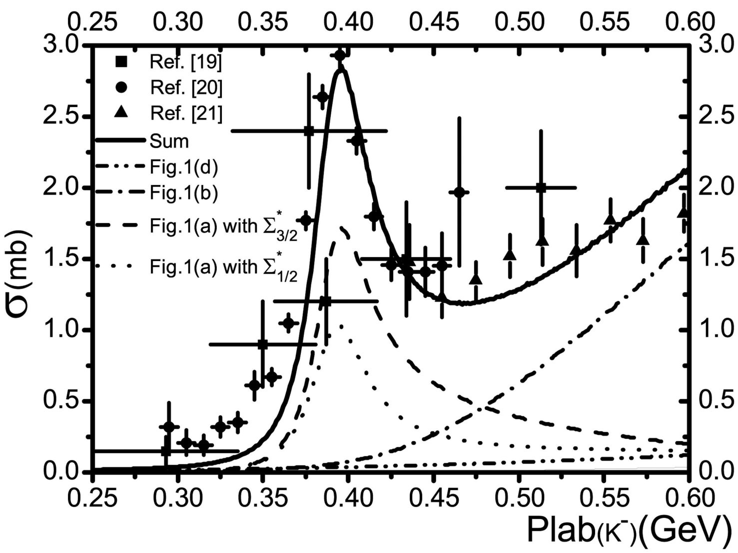


Fig. 4. Theoretical total cross section vs beam momentum $\mathrm{Plab}_{(K^-)}$ for the $K^-p \to \Lambda\pi^+\pi^-$ reaction with 60% $\Sigma^*_{3/2}$ and 40% $\Sigma^*_{1/2}$. Curves close to zero for Fig. 3(c,e,f).

We consider two cases. Firstly, we assume that the $\Sigma^*$ peak is purely due to the $J^P = \frac{3}{2}^+$ resonance. Then we consider there is an additional $J^P = \frac{1}{2}^-$ resonance of 40% portion, similar to the case as in the previous section. For both cases, the total cross sections are fitted very well, especially for the beam momenta in the range of 0.355 to 0.42 GeV, where the main contribution comes from the decay $\Lambda^*(1520) \to \Sigma^{*\pm}\pi^{\mp}$. Therefore the decay $\Lambda^*(1520) \to \Sigma^{*\pm}\pi^{\mp}$ is the interesting place to search for the evidence of $\Sigma^*_{1/2^-}$.

In Fig. 5, the dotted lines are for the pure $\Sigma^*(1385)$ with $J^P = \frac{3}{2}^+$; the solid lines include 40% $\Sigma^*_{1/2}$; the thin lines are for the pure phase-space distribution. It is obvious that the solid curves with both $\Sigma^*_{3/2}$ and $\Sigma^*_{1/2}$ contributions give much better agreement with the experiment data. To understand the reason for this improvement, we show the Dalitz plots for the two reaction $K^-p \to \Lambda^* \to \Sigma^{*\pm}_{3/2}\pi^{\mp} \to \Lambda\pi^+\pi^-$ and $K^-p \to \Lambda^* \to \Sigma^{*\pm}_{1/2}\pi^{\mp} \to \Lambda\pi^+\pi^-$ at $\mathrm{Plab}_{(K^-)} =$ 0.394 GeV in Figs. 6(a) and (b), respectively. From Fig. 6 we see that, the contribution of $\Sigma^*_{3/2}$ is distributed at two corners, but of $\Sigma^*_{1/2}$ is in the middle. The reason is that the final state particles are in the relative S-wave for the decay $\Lambda^* \to \Sigma^{*\pm}_{3/2}\pi^{\mp}$ with narrow $\Sigma^{*\pm}_{3/2}$ width, while they are in the relative P-wave with large $\Sigma^{*\pm}_{1/2}$ width. Thus we conclude that there should be contribution from the $\Sigma^*_{1/2}$ for the reaction at energies around the $\Lambda^*(1520)$ peak.

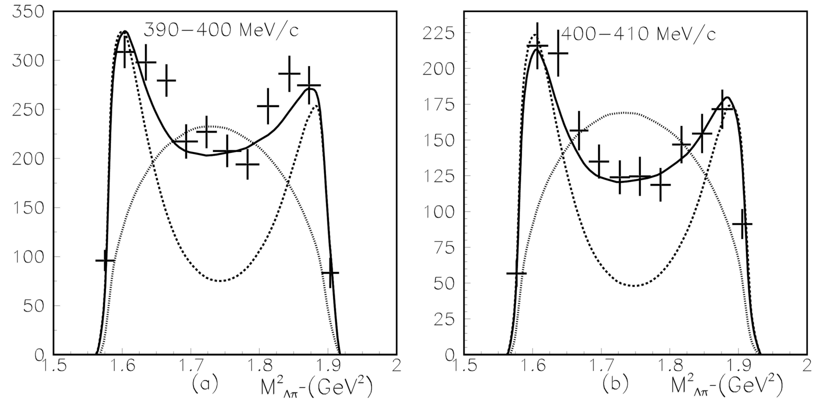


Fig. 5. Theoretical $\Lambda\pi^-$ invariant mass squared distribution for various $K^-$ beam momenta compared with data [20].

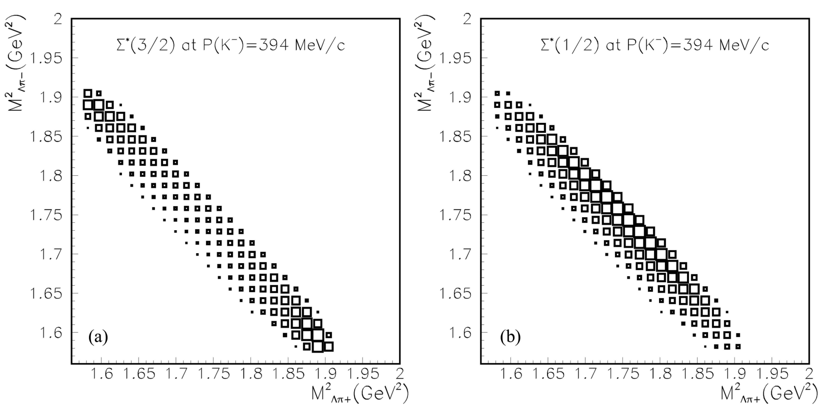


Fig. 6. Dalitz plots (a) and (b) for $\Sigma^{*\pm}_{3/2}$ and $\Sigma^{*\pm}_{1/2}$, respectively.

## 4 Summary

In summary, we study the $K^-p\to\Lambda\pi^-\pi^+$ reaction at the $\mathrm{Plab}_{(K^-)}=1.0-1.8$ GeV and $\mathrm{Plab}_{(K^-)}=0.25-0.60$ GeV. In our calculations we find that the results agree much better with the experimental data [11, 20] by including about 40% $\Sigma^*_{1/2}$ contribution. The results of this work strongly suggest that the new particle $\Sigma^*$ with $J^P=\frac{1}{2}^-$ exists in the $K^-p\to\Lambda\pi^-\pi^+$ reaction. Higher statistic experiments are necessary to establish this new resonance and to understand its property.

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