Mass and $K\Lambda$ coupling of $N^*(1535)$

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Abstract

Using resonance isobar model and effective Lagrangian approach, from recent BES results on $J/\psi \to \bar{p}p\eta$ and $\psi \to \bar{p}K^+\Lambda$, we deduce the ratio between effective coupling constants of $N^*(1535)$ to $K\Lambda$ and $p\eta$ to be $R \equiv g_{N^*(1535)K\Lambda}/g_{N^*(1535)p\eta} = 1.3 \pm 0.3$. With previous known value of $g_{N^*(1535)p\eta}$, the obtained new value of $g_{N^*(1535)K\Lambda}$ is shown to reproduce recent $pp \to pK^+\Lambda$ near-threshold cross section data as well. Taking into account this large $N^*K\Lambda$ coupling in the coupled channel Breit-Wigner formula for the $N^*(1535)$, its Breit-Wigner mass is found to be around 1400 MeV, much smaller than previous value of about 1535 MeV obtained without including its coupling to $K\Lambda$. The implication on the nature of $N^*(1535)$ is discussed.
The properties and the nature of the lowest spin-1/2 negative parity \((J^P = 1/2^-)\) nucleon resonance \(N^*(1535)\) are of great interests in many aspects of light hadron physics. In conventional constituent quark models, the lowest \(1/2^-\) \(N^*\) resonance should be the first \(L = 1\) orbital excitation state. But it has been a long-standing problem for these conventional constituent quark models to explain why the mass of \(N^*(1535)\) has a mass higher than the lowest \(J^P = 1/2^+\) radial excitation state \(N^*(1440)\) \[1\]. This was used to argue in favor of the Goldstone-boson exchange quark models \[2\]. In the recent Jaffe-Wilczek diquark picture \[3\] for the \(\theta\) pentaquark, a \(J^P = 1/2^-\) \(N^*\) pentaquark of mass around 1460 MeV is expected \[4\]. Another outstanding property of the \(N^*(1535)\) is its extraordinary strong coupling to \(\eta N\) \[5\], which lead to a suggestion that it is a quasi-bound \((K\Sigma-K\Lambda)\)-state \[6\]. This picture predicts also large effective couplings of \(N^*(1535)\) to \(K\Lambda\) and \(K\Sigma\) \[7\]. Experiment knowledge on these kaon-hyperon couplings is poor, partly because lack of data on experimental side and partly due to the complication of various interfering t-channel exchange contributions \[8\]. Better knowledge on these couplings is definitely useful for understanding the nature of \(N^*(1535)\), the underneath quark dynamics, and also the strangeness production in relativistic heavy-ion collisions as a signature of the quark-gluon plasma \[9, 10, 11\].

Recently various \(N^*\) production processes from \(J/\psi\) decays have been investigated by BES collaboration \[12, 13, 14, 15\]. In the \(J/\psi \rightarrow \bar{p}p\eta\) \[12, 13\] and \(\psi \rightarrow \bar{p}K^+\Lambda\) c.c. \[14, 15\] reactions, there are clear peak structures with \(J^P = 1/2^-\) in the \(p\eta\) and \(K\Lambda\) invariant mass spectra around \(p\eta\) and \(K\Lambda\) thresholds. A nature source for the peak structures is \(N^*(1535)\) coupling to \(N\eta\) and \(K\Lambda\). In this letter, assuming the \(1/2^-\) \(K\Lambda\) threshold peak to be dominantly from the tail of the \(N^*(1535)\), we deduce the ratio between effective coupling constants of \(N^*(1535)\) to \(K\Lambda\) and \(p\eta\), \(R \equiv g_{N^*(1535)K\Lambda}/g_{N^*(1535)p\eta}\) from the new branching ratio results from BES experiment on \(J/\psi \rightarrow \bar{p}p\eta\) and \(\psi \rightarrow \bar{p}K^+\Lambda\), then check the compatibility with recent \(pp \rightarrow pK^+\Lambda\) near-threshold data \[16, 17\]. Taking into account the large \(N^*K\Lambda\) coupling in the coupled channel Breit-Wigner formula for the \(N^*(1535)\), we show it gives a very large influence to the Breit-Wigner mass of the \(N^*(1535)\).

In the effective Lagrangian approach for the resonance isobar model, the Feynman diagram for \(\psi \rightarrow \bar{p}K^+\Lambda\) through \(N^*(1535)\) intermediate is shown in Fig.1. For \(\psi \rightarrow \bar{p}p\eta\), besides a similar diagram through \(N^*(1535)\), a diagram through \(\bar{N}^*(1535)\) should be added.
simultaneously. The relevant interaction Lagrangians are

\[ \mathcal{L}_{N^*AK} = -ig_{N^*AK} \bar{\Psi} A \Psi_K \Psi_{N^*} + h.c., \]  
\[ \mathcal{L}_{N^*N\eta} = -ig_{N^*N\eta} \bar{\Psi} N \Phi_{\eta} \Psi_{N^*} + h.c., \]  
\[ \mathcal{L}^{(1)}_{\psi NN^*} = \frac{ig_T}{M_{N^*}^2 + M_p^2} \bar{\Psi} N^* \gamma_5 \sigma_{\mu\nu} p^\nu \Psi_N \varepsilon^\mu + h.c., \]
\[ \mathcal{L}^{(2)}_{\psi NN^*} = -g_V \bar{\Psi} N^* \gamma_5 \gamma_\mu \Psi_N \varepsilon^\mu + h.c. \]

where \( \Psi_{N^*} \) represents the resonance \( N^*(1535) \) with mass \( M_{N^*} \), \( \Psi_N \) for proton with mass \( M_p \) and \( \varepsilon^\mu \) for \( J/\psi \) with four-momentum \( p_\psi \). According to \[13\], the \( \mathcal{L}^{(2)}_{\psi NN^*} \) term given by Eq.(4) makes insignificant contribution for \( N^*(1535) \), hence we drop this kind of coupling in our calculation. The amplitudes for \( J/\psi \to \bar{p}K^+\Lambda \) and \( \bar{p}p\eta \) via \( N^*(1535) \) resonance are then

\[ M_{\psi \to \bar{p}K^+\Lambda} = \frac{ig_T g_{N^*KA}}{M_{N^*}^2 + M_p^2} \bar{u}(p_\Lambda, s_\Lambda)(p_{N^*} + m_{N^*}) BW(p_{N^*}) \gamma_5 \sigma_{\mu\nu} p_\psi^\nu \varepsilon^\mu v(p_\bar{p}, s_\bar{p}), \]  
\[ M_{\psi \to \bar{p}p\eta} = \frac{ig_T g_{N^*N\eta}}{M_{N^*}^2 + M_p^2} \bar{u}(p_p, s_p)(p_{N^*} + m_{N^*}) BW(p_{N^*}) \gamma_5 \sigma_{\mu\nu} p_\psi^\nu \varepsilon^\mu + \gamma_5 \sigma_{\mu\nu} p_\psi^\nu \varepsilon^\mu (-p_{N^*} + m_{N^*}) BW(p_{N^*}) v(p_\bar{p}, s_\bar{p}), \]

respectively. Here \( BW(p_{N^*}) \) is the Breit-Wigner formula for the \( N^*(1535) \) resonance

\[ BW(p_{N^*}) = \frac{1}{M_{N^*}^2 - s - iM_{N^*}\Gamma_{N^*}(s)} \]

with \( s = p_{N^*}^2 \). According to PDG \[3\], the dominant decay channels for the \( N^*(1535) \) are \( N\pi \) and \( N\eta \). For a resonance with mass close to some threshold of its dominant decay channel, the approximation of a constant width is not very good. Since the \( N^*(1535) \) is quite close to the \( \eta N \) threshold, we take the commonly used phase space dependent width for the resonance as the following

\[ \Gamma_{N^*}(s) = \Gamma_{N^*}^{0} \left( 0.5 \frac{\rho_{\pi N}(s)}{\rho_{\pi N}(M_{N^*}^2)} + 0.5 \frac{\rho_{\eta N}(s)}{\rho_{\eta N}(M_{N^*}^2)} \right) - \Gamma_{N^*}^{0} \left[ 0.8 \rho_{\pi N}(s) + 2.1 \rho_{\eta N}(s) \right], \]

FIG. 1: Feynman diagram for \( \psi \to \bar{p}K^+\Lambda \) through \( N^* \) resonance
where $\rho_{\pi N}(s)$ and $\rho_{\eta N}(s)$ are the phase space factors for $\pi N$ and $\eta N$ final states, respectively, e.g.,

$$\rho_{\eta N}(s) = \frac{2q_{\eta N}(s)}{\sqrt{s}} = \frac{\sqrt{(s - (M_N + M_\eta)^2)(s - (M_N - M_\eta)^2)}}{s}$$

where $q_{\eta N}$ is the momentum of $\eta$ or $N$ in the center-of-mass system of $\eta N$. According to PDG [5], $M_{N^*} \approx 1535\text{MeV}$ and $\Gamma_{N^*} = \Gamma_{N^*}(M_{N^*}^2) \approx 150\text{MeV}$.

From the amplitudes given above, we can calculate the decay widths of $J/\psi \to \bar{p}K^+\Lambda$ and $J/\psi \to \bar{p}p\eta$ via $N^*(1535)$ resonance, and get their ratio as

$$\frac{\Gamma(\psi \to \bar{p}N^* \to \bar{p}K^+)\Lambda)}{\Gamma(\psi \to \bar{p}N^* + pN^* \to \bar{p}p\eta)} = \frac{1}{12.6} \left| \frac{g_{N^*K\Lambda}}{g_{N^*N\eta}} \right|^2.$$  \hspace{1cm} (10)

On the other hand, from PDG and recent BES results, we have $J/\psi$ decay branching ratio for the $\bar{p}K^+\Lambda$ channel as $(0.89 \pm 0.16) \times 10^{-3}$ with $(15 \sim 22)\%$ via the near threshold $N^*$ resonance and for the $\bar{p}p\eta$ channel as $(2.09 \pm 0.18) \times 10^{-3}$ with $(56 \pm 15)\%$ via the $N^*(1535)$ resonance. Therefore

$$\frac{\Gamma(\psi \to \bar{p}N^* \to \bar{p}K^+)\Lambda)}{\Gamma(\psi \to \bar{p}N^* + pN^* \to \bar{p}p\eta)} = \frac{(0.89 \pm 0.16) \times (15 \sim 22)}{(2.09 \pm 0.18) \times (56 \pm 15)}.$$  \hspace{1cm} (11)

From Eq(10) and Eq(11), we get

$$R \equiv \left| \frac{g_{N^*(1535)K\Lambda}}{g_{N^*(1535)N\eta}} \right| \approx 1.3 \pm 0.3.$$  \hspace{1cm} (12)

Previous knowledge on this ratio from $\pi N \to K\Lambda$ and $\gamma N \to K\Lambda$ reactions is poor. While Ref.[8] gave a range of $0.8 \sim 2.6$, others found the contribution from the $N^*(1535)$ is not important for reproducing the data [11]. It seems that those data are not sensitive to the $N^*(1535)$ contribution due to the complication of various interfering t-channel contributions which are absent in the $J/\psi$ decays. Another relevant reaction is $pp \to pK^+\Lambda$. Some very precise near-threshold data are now available from COSY experiments [16, 17]. In the following we will check the compatibility of the large R value given by Eq.(12) with the recent $pp \to pK^+\Lambda$ near-threshold data.

The relevant Feynman diagrams for the process $pp \to pK^+\Lambda$ are shown in Fig.2. Since we are mainly interested in the near-threshold behavior where contribution from $\pi$ and $\eta$ meson exchange dominates [20], here for simplicity we ignore the small contribution from heavier mesons. We adopt the relevant effective Lagrangian and form factors used in Ref. [20].
First we have reproduced the results of Ref. [20] by including \(N^*(1650)1/2^-\), \(N^*(1710)1/2^+\) and \(N^*(1720)3/2^+\) resonances. Their prediction prior COSY data [16, 17] is shown by the dotted line in Fig. 3, which is obviously underestimating the near-threshold data of COSY. In their work, all parameters have been fixed by previous study on other relevant reactions. A natural reason for the underestimation is their ignorance of the contribution from \(N^*(1535)\). Here we calculate the contribution from \(N^*(1535)1/2^-\) for the process. The coupling constants for the vertices \(N^*(1535)N\pi\) and \(N^*(1535)N\eta\) are determined by the relevant partial decay width [5]. Then the coupling constant for the \(N^*K\Lambda\) is obtained by our new result \(|g_{N^*(1535)K\Lambda}/g_{N^*(1535)N\eta}| = 1.3\) from BES data. The result is shown by the dashed line in Fig. 3 (left). Adding the contribution to the previous results of Ref. 20, the solid line in Fig. 3 (left) reproduces the COSY near-threshold data very well. So the ratio given by Eq. (12) is also compatible with the data on \(pp \to pK^+\Lambda\). Note we have not introduce any free parameters in this calculation.

The large \(|g_{N^*(1535)K\Lambda}/g_{N^*(1535)N\eta}|\) ratio has important implications on other properties of the \(N^*(1535)\). First, in previous calculations, the coupling of \(N^*(1535)\) to \(K\Lambda\) channel is usually ignored in the Breit-Wigner formula for the \(N^*(1535)\). Considering this coupling, the width in its Breit-Wigner formula should be

\[
\Gamma_{N^*}(s) = \Gamma_{N^*}^0 [0.8\rho_{\pi N}(s) + 2.1\rho_{\eta N}(s) + 3.5\rho_{\Lambda K}(s)]
\]

instead of Eq. (5). In order to give a similar Breit-Wigner amplitude squared \(|BW(p_{N^*})|^2\) as using Eq. (5) with \(M_{N^*} = 1535\text{MeV}\) and \(\Gamma_{N^*}^0 = 150\text{MeV}\), we need \(M_{N^*} \approx 1400\text{MeV}\) and
FIG. 3: The cross section of the reaction $pp \rightarrow pK^{+}\Lambda$ as a function of the excess energy with data from Refs. [16] (circle), [17] (triangle) and [21] (square). The dashed and dotted lines represent the contribution from $N^{*}(1535)$ and other $N^{*}$ resonances, respectively. The solid line is the sum. The left and right graphs are the results without and with including $\Lambda K$ term in the $\Gamma_{N^{*}}(s)$ for $N^{*}(1535)$.

$\Gamma^{0}_{N^{*}} = 270MeV$ when using Eq. (13). Note that the two-body phase space factors $\rho_{nN}(s)$ and $\rho_{\Lambda K}(s)$ are extended to below their corresponding thresholds to be pure imaginary as the Flatté formulation for $f_{0}(980)$ meson [22].

In Fig.4, we show the Breit-wigner amplitude squared vs $s^{1/2}$ for the two cases without (dashed line) and with (dotted line) $\Lambda K$ channel contribution included in the energy-dependent width for the $N^{*}(1535)$. As a comparison, we also show the case assuming a constant width $\Gamma_{N^{*}}(s) = 98 MeV$ with $M_{N^{*}} = 1515 MeV$ (solid line). The three kinds of parametrization for the $N^{*}(1535)$ amplitude give a similar amplitude squared, hence do not influence much on previous calculations on various processes involving the $N^{*}(1535)$ resonance by using the Breit-Wigner formula without including the $\Lambda K$ channel in the width. As an example, we show in Fig.3 (right) the results including the $\Lambda K$ channel in $\Gamma_{N^{*}}(s)$. Comparing results in Fig.3 (left) without including the $\Lambda K$ channel in $\Gamma_{N^{*}}(s)$, while the fit to the data for the energies between 10 MeV and 400 MeV improves a little bit, the overall shape looks very similar. However, the important point is that by including the large $N^{*}K\Lambda$ coupling in the coupled channel Breit-Wigner formula for the $N^{*}(1535)$, its Breit-Wigner mass is reduced to be around 1400 MeV, much smaller than previous value of about 1535.
MeV obtained without including its coupling to $K\Lambda$. This will have important implication on various model calculations on its mass.

The second important implication of the large $N^*K\Lambda$ coupling is that the $N^*(1535)$ should have large $s\bar{s}$ component in its wave function. It has been suggested to be a quasi-bound ($K\Sigma-K\Lambda$)-state [6]. Based on this picture, the effective coupling of $N^*(1535)$ to $K\Lambda$ is predicted to be about $0.5 \sim 0.7$ times of that for $N^*(1535)$ to $\eta N$ [7], which is about a factor 2 smaller than the value obtained here. Alternatively, the strangeness may mix into the $N^*(1535)$ in the form of some pentaquark configuration [23]. According to Ref. [23], the $[4_x][31]_{FS}[211]_F[22]_S(qqq\bar{s})$ pentaquark configuration has the largest negative flavor-spin dependent hyperfine interaction for $1/2^- N^*$ resonance. Hence the $1/2^- N^*(1535)$ resonance may have much larger $(qqq\bar{s})$ pentaquark configuration than $1/2^+ N^*$ resonances, for which the penta-quark configurations with the largest negative flavor-spin dependent hyperfine interaction are non-strange ones, such as $[31]_{x}[4_x]_{FS}[22]_F[22]_S(qqq\bar{q})$ configuration [23]. This will result in a large $N^*\Lambda\Lambda$ coupling. A concrete calculation in this picture should be very useful for understanding the nature of the $N^*(1535)$. A recent study of the strangeness in the proton [24] suggests that the strangeness in the nucleon and its excited states $N^*$ are
most likely in the form of pentaquark instead of meson-cloud configurations.

Another implication of the large $N^*(1535)K\Lambda$ coupling is that many previous calculations on various $K\Lambda$ production processes without including this coupling properly should be re-examined. A proper treatment of the $N^*(1535)$ contribution may help to extract properties of other $N^*$ resonances more reliably.

In summary, from the recent BES data on $J/\psi \rightarrow \bar{p}p\eta$ and $\psi \rightarrow \bar{p}K^+\Lambda$, the $g_{N^*(1535)K\Lambda}/g_{N^*(1535)p\eta}$ ratio is deduced to be $1.3 \pm 0.3$ which is also compatible with data from $pp \rightarrow pK^+\Lambda$, $\pi p \rightarrow K\Lambda$ and $\gamma p \rightarrow K\Lambda$ processes. By including the large $N^*(1535)K\Lambda$ coupling into the Breit-Wigner formula for the $N^*(1535)$, a much lower Breit-Wigner mass ($\sim 1400 MeV$) is obtained for the $N^*(1535)$. These new properties have important implication on the nature of the lowest negative-parity $N^*$ resonance. The $N^*(1535)1/2^-$ could be the lowest $L = 1$ orbital excited (3$q$) state with a large admixture of $[4]_X[31]_F[22]_S(qqq\bar{s})$ pentaquark component while the $N^*(1440)$ could be the lowest radial excited (3$q$) state with a large admixture of $[31]_X[4]_F[22]_S(qqqq\bar{q})$ pentaquark component. While the lowest $L = 1$ orbital excited (3$q$) state should have a mass lower than the lowest radial excited (3$q$) state, the $(qqq\bar{s})$ pentaquark component has a higher mass than $(qqqq\bar{q})$ pentaquark component. This makes the $N^*(1535)$ having an almost degenerate mass with the $N^*(1440)$.

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