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

B. C. Liu[1,3] and B. S. Zou[2,1]

[1]Institute of High Energy Physics, P.O. Box 918(4), Beijing 100049, China
[2]CCAST (World Laboratory), P.O. Box 8730, Beijing 100080, China
[3]Graduate School of the Chinese Academy of Sciences, Beijing 100049, China

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Using a resonance isobar model and an 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 the 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 the previous value of about 1535 MeV obtained without including its coupling to $K\Lambda$. The implication on the nature of $N^*(1535)$ is discussed.

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The properties and the nature of the lowest spin-1/2 negative-parity ($J^P = 1/2^-$) nucleon resonance $N^*(1535)$ are of great interest 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 $N^*(1535)$ 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 θ 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 ηN [5], which leads to a suggestion that it is a quasibound ($K\Sigma$-$K\Lambda$) state [6]. This picture predicts also large effective couplings of $N^*(1535)$ to $K\Lambda$ and $K\Sigma$ [7]. Experimental knowledge on these kaon-hyperon couplings is poor, partly because of lacking data on the 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 [9–11].

Recently, various N^* production processes from J/ψ decays have been investigated by the BES Collaboration [12–15]. In the $J/\psi \to \bar{p}p\eta$ [12,13] and $J/\psi \to \bar{p}K^+\Lambda$ + 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 natural 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 dominant 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 the BES experiment on $J/\psi \to \bar{p}p\eta$ and $J/\psi \to \bar{p}K^+\Lambda$, then check its compatibility with recent $pp \to pK^+\Lambda$ 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 $\psi \to \bar{p}K^+\Lambda$ through $N^*(1535)$ intermediate is shown in Fig. 1. For $\psi \to \bar{p}p\eta$, besides a similar diagram through $N^*(1535)$, a diagram through $\bar{N}^*(1535)$ should be added simultaneously. The relevant interaction Lagrangians are [18,19]

$$\mathcal{L}_{N^*\Lambda K} = -ig_{N^*\Lambda K}\bar{\Psi}_\Lambda \Phi_K \Psi_{N^*} + \text{H.c.}, \tag{1}$$

$$\mathcal{L}_{N^*N\eta} = -ig_{N^*N\eta}\bar{\Psi}_N \Phi_\eta \Psi_{N^*} + \text{H.c.}, \tag{2}$$

$$\mathcal{L}^{(1)}_{\psi NN^*} = \frac{ig_T}{M_{N^*} + M_p}\bar{\Psi}_{N^*}\gamma_5\sigma_{\mu\nu}p^\nu_\psi \Psi_N \varepsilon^\mu + \text{H.c.}, \tag{3}$$

$$\mathcal{L}^{(2)}_{\psi NN^*} = -g_V\bar{\Psi}_{N^*}\gamma_5\gamma_\mu\Psi_N\varepsilon^\mu + \text{H.c.}, \tag{4}$$

where Ψ_{N^*} represents the resonance $N^*(1535)$ with mass M_{N^*}, Ψ_N for proton with mass M_p, and ε^μ for ψ with four-momentum p_ψ. According to Ref. [13], the $\mathcal{L}^{(2)}_{\psi NN^*}$ term

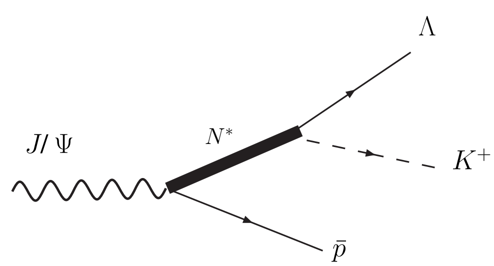

FIG. 1. Feynman diagram for $\psi \to \bar{p}K^+\Lambda$ through N^* resonance.

given by Eq. (4) makes an insignificant contribution for $N^*(1535)$; hence, we drop this kind of coupling in our calculation. The amplitudes for $\psi \to \bar{p}K^+\Lambda$ and $\bar{p}p\eta$ via $N^*(1535)$ resonance are then

$$M_{\psi\to\bar{p}K^+\Lambda} = \frac{ig_T g_{N^*K\Lambda}}{M_{N^*} + M_p} \bar{u}(p_\Lambda, s_\Lambda)(\not{p}_{N^*} + m_{N^*}) \times \mathrm{BW}(p_{N^*})\gamma_5 \sigma_{\mu\nu} p_\psi^\nu \varepsilon^\mu v(p_{\bar{p}}, s_{\bar{p}}), \quad (5)$$

$$M_{\psi\to\bar{p}p\eta} = \frac{ig_T g_{N^*N\eta}}{M_{N^*} + M_p} \bar{u}(p_p, s_p)[(\not{p}_{N^*} + m_{N^*})\mathrm{BW}(p_{N^*}) \times \gamma_5 \sigma_{\mu\nu} p_\psi^\nu \varepsilon^\mu + \gamma_5 \sigma_{\mu\nu} p_\psi^\nu \varepsilon^\mu (-\not{p}_{\bar{N}^*} + m_{N^*}) \times \mathrm{BW}(p_{\bar{N}^*})] v(p_{\bar{p}}, s_{\bar{p}}), \quad (6)$$

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

$$\mathrm{BW}(p_{N^*}) = \frac{1}{M_{N^*}^2 - s - iM_{N^*}\Gamma_{N^*}(s)}, \quad (7)$$

with $s = p_{N^*}^2$. According to PDG [5], 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 good. Since the $N^*(1535)$ is quite close to the ηN threshold, we take the commonly used phase space dependent width for the resonance as the following:

$$\Gamma_{N^*}(s) = \Gamma_{N^*}^0 \left(0.5 \frac{\rho_{\pi N}(s)}{\rho_{\pi N}(M_{N^*}^2)} + 0.5 \frac{\rho_{\eta N}(s)}{\rho_{\eta N}(M_{N^*}^2)}\right) = \Gamma_{N^*}^0 [0.8\rho_{\pi N}(s) + 2.1\rho_{\eta N}(s)], \quad (8)$$

where $\rho_{\pi N}(s)$ and $\rho_{\eta N}(s)$ are the phase space factors for πN and ηN final states, respectively, e.g.,

$$\rho_{\eta N}(s) = \frac{2q_{\eta N}(s)}{\sqrt{s}} = \frac{\sqrt{(s - (M_N + M_\eta)^2)(s - (M_N - M_\eta)^2)}}{s}, \quad (9)$$

where $q_{\eta N}$ is the momentum of η or N in the center-of-mass system of ηN. According to PDG [5], $M_{N^*} \approx 1535$ MeV and $\Gamma_{N^*}^0 = \Gamma_{N^*}(M_{N^*}^2) \approx 150$ MeV.

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

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

On the other hand, from PDG and recent BES results, we have the J/ψ decay branching ratio for the $\bar{p}K^+\Lambda$ channel as $(0.89 \pm 0.16) \times 10^{-3}$ [5] with (15–22)% [15] via the near-threshold N^* resonance and for the $\bar{p}p\eta$ channel as $(2.09 \pm 0.18) \times 10^{-3}$ [5] with $(56 \pm 15)\%$ [13] via the $N^*(1535)$ resonance. Therefore,

$$\frac{\Gamma(\psi \to \bar{p}N^* \to \bar{p}K^+\Lambda)}{\Gamma(\psi \to \bar{p}N^* + p\bar{N}^* \to \bar{p}p\eta)} = \frac{(0.89 \pm 0.16) \times (15\text{–}22)}{(2.09 \pm 0.18) \times (56 \pm 15)}. \quad (11)$$

From Eqs. (10) and (11), we get

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

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 0.8–2.6, 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/ψ decays. Another relevant reaction is $pp \to pK^+\Lambda$. Some very precise near-threshold data are now available from the Cooler Synchrotron (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. First, we adopt the relevant effective Lagrangian and form factors used in Ref. [20] and reproduce their results by including $N^*(1650)1/2^-$, $N^*(1710)1/2^+$, and $N^*(1720)3/2^+$ resonances. Their prediction prior to the COSY data [16,17] is shown by the dotted line in Fig. 3, which is obviously underestimating the data near threshold. 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 widths [5]. Then the coupling constant for the $N^*K\Lambda$ is obtained by our new ratio $|g_{N^*(1535)K\Lambda}/g_{N^*(1535)N\eta}| = 1.3$ 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

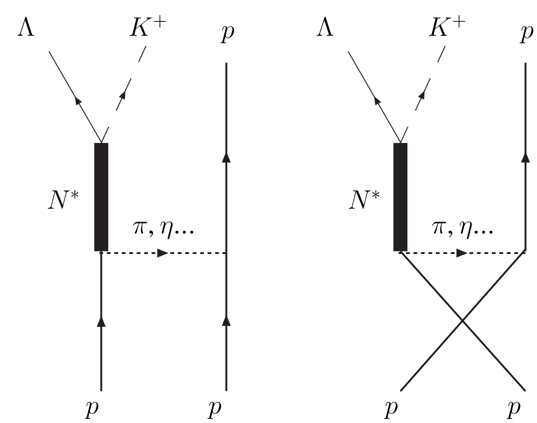

FIG. 2. Feynman diagrams for reaction $pp \to pK^+\Lambda$.

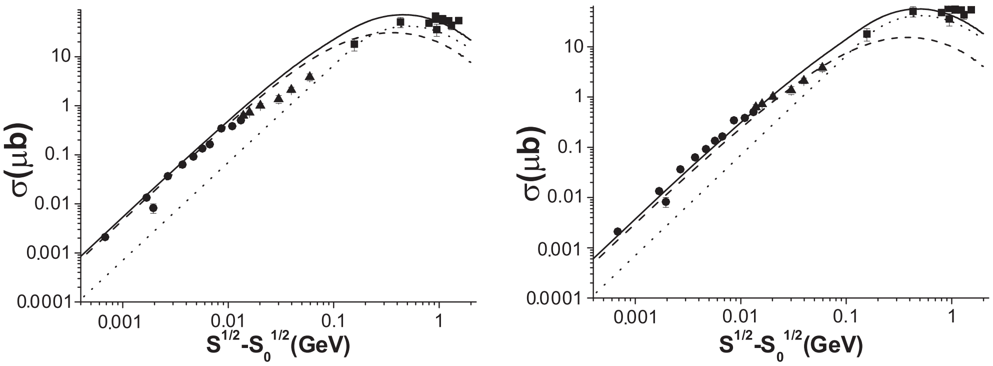

FIG. 3. The cross section of the reaction $pp \to pK^+\Lambda$ as a function of the excess energy with data from Refs. [16] (circles), [17] (triangles), and [26] (squares). The dashed and dotted lines represent the contribution from $N^*(1535)$ and other N^* resonances, respectively. The solid line is the sum. The left and right graphs, respectively, are the results without and with including ΛK term in the $\Gamma_{N^*}(s)$ for $N^*(1535)$.

COSY near-threshold data very well. Note that we have not introduced any free parameters in this calculation. In the calculation, we ignored the t-channel exchange of heavier mesons as well as the nonresonant $p\Lambda$ and Kp final state interactions. In some studies [21] of $pp \to pp\eta$ reaction, ρ meson exchange and other short-range contributions were found to be important, while others [22] gave contrary results. We have examined the ρ meson exchange contribution and found its relative strength to the η meson exchange depends on the relevant coupling constants ($N^*N\rho$, $NN\eta$) and off-shell form factors one assumes. Within the uncertainty of these constants and form factors from other relevant sources, one can reproduce the $pp \to pK^+\Lambda$ data equally well no matter whether one includes the ρ meson exchange and other short-range contribution or not. The same is true for considering the nonresonant $p\Lambda$ and KN interactions. The important point is that the large $N^*(1535)K\Lambda$ coupling obtained from BES data can be compatible with the present $pp \to pK^+\Lambda$ data.

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 the $K\Lambda$ 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

$$\Gamma_{N^*}(s) = \Gamma^0_{N^*}[0.8\rho_{\pi N}(s) + 2.1\rho_{\eta N}(s) + 3.5\rho_{\Lambda K}(s)] \quad (13)$$

instead of Eq. (8). In order to give a similar Breit-Wigner amplitude squared $|BW(p_{N^*})|^2$ as using Eq. (8) with $M_{N^*} = 1535$ MeV and $\Gamma^0_{N^*} = 150$ MeV, we need $M_{N^*} \approx 1400$ MeV and $\Gamma^0_{N^*} \approx 270$ MeV when using Eq. (13). Note that the two-body phase space factors $\rho_{\eta N}(s)$ and $\rho_{\Lambda K}(s)$ are extended to below their corresponding thresholds to be pure imaginary as the Flatté formulation for the $f_0(980)$ meson [23].

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) a ΛK 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 and, hence, do not have much influence on previous calculations on various processes involving the $N^*(1535)$ resonance by using the Breit-Wigner formula without including the ΛK channel in the width. As an example, we show in Fig. 3 (right) the results including the ΛK channel in $\Gamma_{N^*}(s)$. Comparing results in Fig. 3 (left) without including the ΛK channel in $\Gamma_{N^*}(s)$, while the fit to the data for the energies between 10 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 around 1400 MeV, much smaller than the previous value of about 1535 MeV obtained without including its coupling to $K\Lambda$. This will have important implications 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 a large $s\bar{s}$ com-

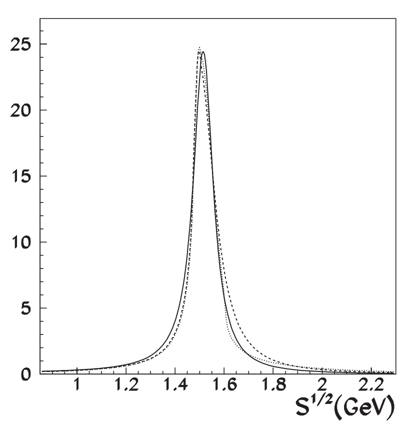

FIG. 4. Breit-Wigner amplitude squared vs $s^{1/2}$ with a constant width (solid line) and an energy-dependent width without (dashed line) and with (dotted line) ΛK channel contribution included.

ponent in its wave function. It has been suggested to be a quasibound ($K\Sigma$-$K\Lambda$) state [6]. Based on this picture, the effective coupling of $N^*(1535)$ to $K\Lambda$ is predicted to be about 0.5–0.7 times that for $N^*(1535)$ to ηN [7], which is about a factor of 2 smaller than the value obtained here. Alternatively, the strangeness may mix into the $N^*(1535)$ in the form of some pentaquark configuration [24,25]. According to Ref. [24], the $[4]_X[31]_{FS}[211]_F[22]_S(qqqs\bar{s})$ pentaquark configuration has the largest negative flavor-spin dependent hyperfine interaction for the $1/2^- N^*$ resonance. Hence, the $1/2^- N^*(1535)$ resonance may have a much larger $(qqqs\bar{s})$ pentaquark configuration than the $1/2^+ N^*$ resonances, for which the pentaquark configurations with the largest negative flavor-spin dependent hyperfine interaction are nonstrange ones, such as the $[31]_X \times [4]_{FS}[22]_F[22]_S(qqqq\bar{q})$ configuration [24]. This will result in a large $N^*(1535)K\Lambda$ 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 [25] 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 reexamined. 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 $J/\psi \to \bar{p}p\eta$ and $\psi \to \bar{p}K^+\Lambda$, the $g_{N^*(1535)K\Lambda}/g_{N^*(1535)p\eta}$ ratio is deduced to be 1.3 ± 0.3, which is also compatible with data from $pp \to pK^+\Lambda$, $\pi p \to K\Lambda$, and $\gamma p \to K\Lambda$ 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 implications on the nature of the lowest negative-parity N^* resonance. The $N^*(1535)1/2^-$ could be the lowest $L = 1$ orbital excited $(3q)$ state with a large admixture of $[4]_X \times [31]_{FS}[211]_F[22]_S(qqqs\bar{s})$ pentaquark component, while the $N^*(1440)$ could be the lowest radial excited $(3q)$ state with a large admixture of $[31]_X[4]_{FS}[22]_F[22]_S(qqqq\bar{q})$ pentaquark component. While the lowest $L = 1$ orbital excited $(3q)$ state should have a mass lower than the lowest radial excited $(3q)$ state, the $(qqqs\bar{s})$ pentaquark component has a higher mass than the $(qqqq\bar{q})$ pentaquark component. This makes the $N^*(1535)$ have an almost degenerate mass with the $N^*(1440)$. The large admixture of the $(qqqs\bar{s})$ component in the $N^*(1535)$ also gives a natural explanation of its large couplings to the channels with strangeness, such as $N\eta$ and $K\Lambda$.

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