On $pp \to pK\Lambda, NK\Sigma, pp\phi$ — the basic ingredients for strangeness production in heavy ion collisions

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The strangeness production in heavy ion collisions was proposed to be probes of the nuclear equation of state, Kaon potential in nuclear medium, strange quark matter and quark-gluon plasma, etc. However, to act as reliable probes, proper understanding of the basic ingredients for the strangeness production, such as $pp \to pK^+\Lambda$, $pp \to pp\phi$ and $pp \to nK^+\Sigma^+$ is necessary. Recent study of these reactions clearly shows that previously ignored contributions from the spin-parity $1/2^-$ resonances, $N^*(1535)$ and $\Delta^*(1620)$, are in fact very important for these reactions, especially for near-threshold energies. It is necessary to include these contributions for getting reliable calculation for the strangeness production in heavy ion collisions.

1. Introduction

Strangeness production in heavy ion collisions is presently an issue of intense study since it plays important roles in many aspects. Because $K^+$ mesons have a long mean free path inside the nuclear matter, they are believed to be good messengers to provide information about the high density and temperature phase of the heavy ion collisions.\cite{11} The subthreshold Kaon production was proposed to be a sensitive probe of the nuclear equation of state (EOS)\cite{2} while Kaon flow was proposed to be a probe of the Kaon potential in nuclear medium.\cite{3} The strangeness production was also proposed to be good probe of possible formation of quark-gluon-plasma (QGP)\cite{5,6}. Especially, in Ref.\cite{6} Shor suggested the $\phi$ meson production to be an ideal candidate to study the QGP in nuclear collisions, due to its flavor contents composed of a strange and antistrange quark.

To act as reliable probes, proper understanding of the basic ingredients for the strangeness production, such as $pp \to pK^+\Lambda$, $pp \to pp\phi$ and $pp \to nK^+\Sigma^+$, is necessary. Status for various $pp \to NK^+Y$ reactions\cite{7} is shown by Fig.\cite{11} While a typical resonance model\cite{11,12} fits the older data\cite{10} at high excess energies quite well, it underestimates recent COSY data at near-threshold energies for $pp \to nK^+\Sigma^+$ and $pp \to pK^+\Lambda$ by order(s) of magnitude. Other model calculations\cite{13,14,15,16} su-
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for similar problem for their predictions at near-threshold energies. The situation for $pp \rightarrow pp\phi$ is even worse. The data is scarce due to much smaller cross section. Only recently some near-threshold data appeared\textsuperscript{17,18} with little theoretical study available.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1}
\caption{Total cross section for various $pp \rightarrow NK^+Y$ reactions\textsuperscript{7}. Data in the near-threshold region (full symbols) are from recent COSY experiments\textsuperscript{7,8,9} and data at high excess energies (open symbols) are from older experiments\textsuperscript{10}. Solid curves are the resonance model predictions\textsuperscript{11,12}.}
\end{figure}

Recently these reactions have been restudied by including contributions from previously ignored subthreshold $N^*(1535)$ and $\Delta^*(1620)$ resonances\textsuperscript{19,20,21,22}. The fit to the data are much improved. Although the original motivation for studying these reactions is to improve our understanding of the internal quark structure of relevant baryons\textsuperscript{23}, the results turn out to be also very important for studying strangeness production in heavy ion collisions. Hence we summarize main results from these studies here.

\section{Study on $pp \rightarrow pK^+\Lambda$ reaction}

Recently BES experiment at Beijing Electron-Positron Collider (BEPC) has been producing very useful information on $N^*$ resonances\textsuperscript{24,25,26,27}. In $J/\psi \rightarrow \bar{p}\eta\eta$, as expected, the $N^*(1535)$ gives the largest contribution\textsuperscript{24}. In $J/\psi \rightarrow \bar{p}\eta\pi^+ + c.c.$\textsuperscript{25}, a clear peak containing $N^*(1535)$ contribution is observed around 1.5 GeV in the $n\pi$ invariant mass spectrum as shown in Fig. 2 (left). In addition, a near-threshold enhancement due to subthreshold nucleon pole contribution is clearly there. In $J/\psi \rightarrow pK^-\bar{\Lambda} + c.c.$, a strong near-threshold enhancement is observed for $K\Lambda$ invariant mass spectrum\textsuperscript{26} as shown in Fig. 2 (right). The $K\Lambda$ threshold is 1609 MeV. The near-threshold enhancement is confirmed by $J/\psi \rightarrow nKs\Lambda + c.c.$\textsuperscript{27}. Since the mass spectrum divided by efficiency and phase space peaks at threshold,
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Fig. 2. Invariant mass spectrum divided by efficiency and phase space vs nπ invariant mass for J/ψ → pπ+ + c.c.\textsuperscript{25} and vs M_{\Lambda K} - M_K - M_{\Lambda} for J/ψ → pK^- + c.c.\textsuperscript{26}.

it is natural to assume it comes from the sub-threshold nearby N\textsuperscript{*}(1535) resonance decaying into KΛ with relative S-wave. Then from BES branching ratio results on J/ψ → pp\eta\textsuperscript{24} and J/ψ → pK^- + c.c.\textsuperscript{26} the ratio between effective coupling constants of N\textsuperscript{*}(1535) to KΛ and p\eta is deduced to be\textsuperscript{19} 3.0 ± 0.3.

A previous well-known property of N\textsuperscript{*}(1535) is its extraordinary strong coupling to \eta N\textsuperscript{28}, which leads to a suggestion that it is a quasi-bound (KΛ − KΣ) state\textsuperscript{29}. This picture predicts large effective coupling of N\textsuperscript{*}(1535) to both KΛ and KΣ\textsuperscript{30}. While the large KΛ coupling seems confirmed here, the evidence for large KΣ coupling is still missing. An alternative picture for the N\textsuperscript{*}(1535) is that it contains large admixture of [ud][us]\bar{s} > pentaquark component having [ud], [us] scalar diquarks and \bar{s} in the ground state\textsuperscript{19,31}. The new picture expects large coupling to KΛ, but small coupling to KΣ.

No matter what picture is correct for the internal structure of the N\textsuperscript{*}(1535), its large coupling to KΛ should also play a role in other relevant reactions. Hence its possible contribution to pp → pK^+\Lambda reaction is examined\textsuperscript{19} in the effective Lagrangian framework with relevant Feynman diagrams as plotted in Fig. 3 (left) including t-channel exchange of \pi^0, \eta and \rho^0 mesons. The calculated results are shown in Fig. 3 (right). While the dotted line is taken from Ref.\textsuperscript{15} which includes the contributions from N\textsuperscript{*}(1650), N\textsuperscript{*}(1710) and N\textsuperscript{*}(1720) resonances, the dashed line is the contribution from the N\textsuperscript{*}(1535) with its KΛ coupling deduced from BES data, and the solid line is the sum. We can see that the new results with the contribution from N\textsuperscript{*}(1535) resonance reproduce the experiment data very well especially near threshold.

The work\textsuperscript{19} got a comment from A.Sibirtsev et al.\textsuperscript{32} They pointed out that the work\textsuperscript{19} and previous calculation\textsuperscript{15} have not included the pΛ final state interaction...
Fig. 3. Feynman diagrams (left) and calculated total cross section vs the excess energy compared with data (right) for the reaction $pp \to pK^+\Lambda^{19}$.

Fig. 4. Dalitz plot\textsuperscript{33} of the data at $p_{\text{beam}}=2.85$ GeV/c (a), in comparison with the adjusted model of Sibirtsev (b), model calculation only with the resonance part without FSI (c), and only with $p$-final-state interaction without resonances (d).

(FSI). After including possible $p\Lambda$ FSI, they can also reproduce the $pp \to pK^+\Lambda$ near-threshold total cross section data without inclusion of the $N^*(1535)$ contribution. However, recent COSY-TOF data on Dalitz plot\textsuperscript{33} clearly demonstrated that besides the $p\Lambda$ near-threshold enhancement due to $p\Lambda$ FSI there is also a $K\Lambda$ near-threshold enhancement as shown in Fig. 4(a) which cannot be reproduced by the
Sibirtsev model simulation without including the $N^*(1535)$ (Fig. 4(b)). Obviously both $p\Lambda$ FSI and $N^*(1535)$ contribution are necessary. With $p\Lambda$ FSI included, the large $K\Lambda$ coupling deduced from BES data for $N^*(1535)$ is still found compatible with $pp \rightarrow pK^+\Lambda$ data.[20]

There are also indications for the large $g_{N^*(1535)K\Lambda}$ from partial wave analysis of $\gamma p \rightarrow K\Lambda$ reactions[34] and evidence for large $g_{N^*(1535)N\eta'}$ coupling from $\gamma p \rightarrow p\eta'$ reaction at CLAS[35].

3. Study on $pp \rightarrow pp\phi$ reaction

In the naive quark model, the nucleon and nucleon resonances have no strangeness contents, whereas the $\phi$ meson is an ideally mixed pure $s\bar{s}$ state. From the point of view of the naive quark model the $pp \rightarrow pp\phi$ reaction involves disconnected quark lines and is an Okubo-Zweig-Iizuka (OZI) rule suppressed process. The study of $\phi$ meson production in nucleon-nucleon reactions may provide information on the strangeness degrees of freedom in the nucleon or nucleon resonances and is of importance both experimentally and theoretically. Since $N^*(1535)$ resonance has strong coupling to $N\eta$, $K\Lambda$ and maybe also $N\eta'$, there may be a significant $s\bar{s}$ configuration in the quark wave function of the $N^*(1535)$ resonance. So the $N^*(1535)$ resonance may also have a significant coupling to the $\phi N$ channel. Assuming that the productions of the $\phi$ meson in $pp$ and $\pi^-p$ collisions are predominantly through the excitation and decay of the sub-$\phi N$-threshold $N^*(1535)$ resonance, we calculated the $pp \rightarrow pp\phi$ and $\pi^-p \rightarrow n\phi$ reactions in the framework of an effective lagrangian approach[22]. A Lorentz covariant orbital-spin (L-S) scheme[36] is used for the effective interaction vertices involving the $N^*(1535)$ resonance. The relevant Feynman diagrams considered in our computation are shown in Fig. 5.

![Feynman diagrams](image)

There is no information for the coupling constant of the $N^*(1535)N\phi$ vertex. We determine it from the $\pi^-p \rightarrow n\phi$ reaction. We calculated the total cross section of
the reaction based on $s$-channel $N^*(1535)$ excitation since contributions from the $u$-channel $N^*(1535)$ excitation and $t$-channel $\rho$-meson exchange are also checked and are found to be negligible. By adjusting the $N^*(1535)N\phi$ coupling constant, we can compare the theoretical results with the experimental data. Theoretical results with $g_{N^*(1535)N\phi} = 0.13$ are compared with the experimental data by the solid curve in Fig. 6 (left). We find an excellent agreement between our results and the experimental data.

Then we calculated the total cross section of the $pp \rightarrow pp\phi$ reaction with $\pi^0$, $\eta$ and $\rho^0$ mesons exchange for $N^*(1535)$ excitation. The numerical results are shown in Fig. 6 (right) together with the experimental data. The double dotted-dashed, dotted, dashed-dotted and dashed curves stand for contributions from $\pi^0$, $\eta$, $\rho^0$-meson exchanges and their simple sum, respectively. To show the effect from the $pp$ final state interaction (FSI), we give the results with the $^1S_0$ pp FSI by solid line in the figure. One can see that the contribution from the $\pi$ meson exchange is dominant to the $pp \rightarrow pp\phi$ reaction in our model. The $\rho$ meson exchange has a significant contribution to this reaction, while the contribution from the $\eta$ meson exchange is negligible.

In our calculation we only include the contribution of the $N^*(1535)$ in the intermediate state. In previous calculations, the $\pi p \rightarrow \phi N$ through t-channel $\rho$ exchange and/or sub-threshold nucleon pole contributions are assumed to be dominant. However these contributions are very sensitive to the choice of off-shell form factors for the t-channel $\rho$ exchange and the $g_{NN\phi}$ couplings and can be reduced by orders of magnitude within the uncertainties of these ingredients. Considering the ample evidence for large coupling of the $N^*(1535)$ to the strangeness and the $N^*(1535)$ resonance is closer than the nucleon pole to the $\phi N$ threshold, it
is more likely that the $N^*(1535)$ plays dominant role for near threshold $\phi$ production from $\pi p$ and $pp$ collisions instead of the nucleon pole or the OZI suppressed $\phi\rho\pi$ coupling. Our calculation with the $N^*(1535)$ domination reproduces energy dependence of the $\pi^- p \rightarrow \phi n$ and $pp \rightarrow pp\phi$ cross sections better than previous calculations. The significant coupling of the $N^*(1535)$ resonance to $N\phi$ may be the real origin of the significant enhancement of the $\phi$ production from $\pi p$ and $pp$ reactions over the naive OZI-rule predictions. This makes it difficult to extract the properties of the strangeness in the nucleon from these reactions proposed by J.Ellis et al\textsuperscript{42}. There are also some suggestions\textsuperscript{43,44} for possible existence of an $N\phi$ bound state just below the $N\phi$ threshold. However, contribution of such bound state with width less than 100 MeV will give a much sharper dropping structure for the $\pi^- p \rightarrow \phi n$ cross section at energies near threshold. If such $N\phi$ bound state does exist, it should have weak coupling to $\pi N$ and only gives small contribution to the $\pi^- p \rightarrow \phi n$ reaction. However, we cannot exclude alternative solutions with significant contributions from $N^*(1900)$ or $N^*(1650)$ although there are some arguments favoring the solution with the dominant $N^*(1535)$ contribution. For a better understanding of the dynamics of these reactions, more experimental data at other excess energies with Dalitz plots and angular distributions are desired.

4. Study on $pp \rightarrow nK^+\Sigma^+$ reaction

The spectrum of isospin $3/2$ $\Delta^{++\ast}$ resonances is of special interest since it is the most experimentally accessible system composed of 3 identical valence quarks. However, our knowledge on these resonances mainly comes from old $\pi N$ experiments and is still very poor\textsuperscript{28}. A possible new excellent source for studying $\Delta^{++\ast}$ resonances is $pp \rightarrow nK^+\Sigma^+$ reaction, which has a special advantage for absence of complication caused by $N\phi$ contribution because of the isospin and charge conservation.

At present, little is known about the $pp \rightarrow nK^+\Sigma^+$ reaction. Experimentally there are only a few data points about its total cross section versus energy\textsuperscript{7,10}. Theoretically a resonance model with an effective intermediate $\Delta^{++\ast}(1920)$ resonance\textsuperscript{12} and the Jülich meson exchange model\textsuperscript{16} reproduce the old data at higher beam energy pretty well, but their predictions for the cross sections close to threshold fail by order of magnitude compared with very recent COSY-11 measurement\textsuperscript{7}.

Recently this reaction was restudied\textsuperscript{21}. For the $pp \rightarrow nK^+\Sigma^+$, the basic Feynman diagrams are depicted in Fig.\textsuperscript{7} Besides the ingredients considered in previous calculations\textsuperscript{12,16,45}, the sub-$K$-threshold $\Delta^{++\ast}(1620)$ resonance is added by taking into account both $\pi^+$ and $\rho^+$ mesons exchange.

The numerical results are shown in Fig.\textsuperscript{8} together with the experimental data\textsuperscript{7,10}. For comparison. In the left of Fig.\textsuperscript{8} contributions from $\Delta^\ast(1620)(\pi^+\text{ exchange})$, $\Delta^\ast(1620)(\rho^+\text{ exchange})$ and $\Delta^\ast(1920)(\pi^+\text{ exchange})$ are shown sep-
Fig. 7. Feynman diagrams for the reaction $pp \rightarrow nK^+\Sigma^+$.

Fig. 8. The total cross section vs $T_p$ for the $pp \rightarrow nK^+\Sigma^+$ reaction compared with the relevant experimental data.

arately by dot-dashed, dashed and dotted curves, respectively. The contribution from the $\Delta^+(1620)$ production by the $\rho^+$ exchange is found to be very important for the whole energy range, in particular, for the two lowest data points close to the threshold. This gives a natural source for the serious underestimation of the near-threshold cross sections by previous calculations [12,16,45], which have neglected either $\Delta^+(1620)$ resonance contribution [12,45] or $\rho^+$ exchange contribution [16]. The solid curve in the figure is the incoherent sum of the three contributions and reproduces the experimental data quite well.

To show the effect from the $n-\Sigma^+$ final state interaction (FSI), we give the result
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without including the FSI factor by the dashed curve in the right figure of Fig. 8. Comparing dashed curve with the solid curve which includes the FSI factor, we find that the FSI enhances the total cross section by a factor of about 3 for the two lowest data points. So the FSI is indeed making a significant effect at energies close to threshold. But it does not change the basic shape of the curve very much.

In previous calculations \[12,45\], only \(\Delta^*(1920)\) contribution is considered with a free scaling parameter to fit the data. In Fig. 8 (right), we also show the results from only \(\Delta^*(1920)(\pi^\pm\text{exchange})\) scaled by a factor \(5\) for comparison. It reproduces the data for \(T_P\) above \(2.8\) GeV quite well, but underestimates the two lowest data points by orders of magnitude no matter whether including the FSI (dotted curve) or not (dot-dashed curve).

Meanwhile the extraordinary large coupling of the \(\Delta^*(1620)\) to \(\rho N\) obtained from the \(\pi^\pm p \rightarrow N\pi\pi\) \[28,40\] seems confirmed by the new study \[21\] of the strong near-threshold enhancement of \(pp \rightarrow nK^+\Sigma^+\) cross section. Does the \(\Delta^*(1620)\) contain a large \(\rho N\) molecular component or relate to some \(\rho N\) dynamical generated state? If so, where to search for its SU(3) decuplet partners? Sarkar et al. \[47\] have studied baryonic resonances from baryon decuplet and pseudoscalar meson octet interaction. It would be of interests to study baryonic resonances from baryon octet and vector meson octet interaction. In fact, from PDG compilation \[28\] of baryon resonances, there are already some indications for a vector-meson-baryon SU(3) decuplet. While the \(\Delta^*(1620)1/2^-\) is about \(85\) MeV below the \(N\rho\) threshold, there is a \(\Sigma^*(1750)1/2^-\) about \(70\) MeV below the \(NK^*\) threshold and there is a \(\Xi^*(1950)^?\) about \(60\) MeV below the \(\Lambda K^*\) threshold. If these resonances are indeed the members of the \(1/2^-\) SU(3) decuplet vector-meson-baryon S-wave states, we would expect also a \(\Omega^*1/2^-\) resonance around \(2160\) MeV. All these baryon resonances can be searched for in high statistic data on relevant channels from vector charmonium decays by upcoming BES3 experiments in near future.

5. Summary

In this work, we reviewed the important role played by subthreshold \(N^*(1535)\) and \(\Delta^*(1620)\) resonances to \(pp \rightarrow pK^+\Lambda, pp \rightarrow pp\phi\) and \(pp \rightarrow nK^+\Sigma^+\) reactions. While \(N^*(1535)\) resonance plays a dominant role for the near-threshold total cross sections of \(pp \rightarrow pK^+\Lambda, pp \rightarrow pp\phi\) and \(\pi^- p \rightarrow n\phi\) reactions, the \(\Delta^*(1620)\) resonance plays a dominant role in \(pp \rightarrow nK^+\Sigma^+\) reaction. They are crucial ingredients for reproducing data of the strangeness production in \(pp\) collisions.

The results have many important implications:

1. Since the \(pp \rightarrow pK^+\Lambda, pp \rightarrow nK^+\Sigma^+\) and \(pp \rightarrow pp\phi\) reactions are the basic inputs for the strangeness production in heavy ion collisions \[18,49\], the inclusion of the sub-threshold \(N^*(1535)\) and \(\Delta^*(1620)\) resonances contributions may be essential for such studies.

2. They give new examples that sub-threshold resonances can make extremely important contributions and should not be simply ignored. Many calculations were
used to consider only the resonances above threshold, such as previous calculations for $pp \rightarrow pK^+\Lambda$ and $pp \rightarrow nK^+\Sigma^+$ reactions. There are several more examples from $J/\psi$ decays showing the importance of contribution from sub-threshold particles, such sub-$\pi N$-threshold nucleon pole contribution in $J/\psi \rightarrow \bar{p}n\pi^+$, sub-$K\bar{K}$-threshold contribution in $J/\psi \rightarrow K\bar{K}\pi$ and sub-$\omega\pi$-threshold contribution in $J/\psi \rightarrow \omega\pi\pi$.

(3) The t-channel $\rho$ exchange may play an important role for many meson production processes in $pp$ collisions and should not be ignored.

(4) While the classical 3q constituent quark model works well in reproducing properties of baryons in the spatial ground states, the study of $1/2^-$ baryons seems telling us that the $\bar{q}qqqqq$ in S-state is more favorable than $qqq$ with $L = 1$. In other words, for excited baryons, the excitation energy for a spatial excitation could be larger than to drag out a $q\bar{q}$ pair from gluon field. Whether the $\bar{q}qqqqq$ components are in penta-quark configuration or meson-baryon configuration depends on the strength of relevant diquark or meson-baryon correlations. For $N^*(1535)$ and its $1/2^-$ SU(3) nonet partners, the diquark cluster picture for the penta-quark configuration gives a natural explanation for the longstanding mass-reverse problem of $N^*(1535)$, $N^*(1440)$ and $\Lambda^*(1405)$ resonances as well as the unusual decay pattern of the $N^*(1535)$ resonance. Its predictions of the existence of an additional $\Lambda^* 1/2^-$ around 1570 MeV, a triplet $\Sigma^* 1/2^-$ around 1360 MeV and a doublet $\Xi^* 1/2^-$ around 1520 MeV could be examined by forth coming experiments at BEPC2, CEBAF, JPARC etc.. For $\Delta^{++}(1620)$ and its $1/2^-$ SU(3) decuplet partners, their SU(3) quantum numbers do not allow them to be formed from two good scalar diquarks plus a $\bar{q}$. Then their $\bar{q}qqqqq$ components would be mainly in the meson-baryon configuration. This picture can be also examined by forth coming experiments.

Acknowledgements

We would like to thank B.C.Liu and H.C.Chiang for collaborations on some relevant issues reviewed here. This work is partly supported by the National Natural Science Foundation of China under grants Nos. 10435080, 10521003 and by the Chinese Academy of Sciences under project No. KJCX3-SYW-N2.

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