$N^*(1535)$ contribution in $pp \to pp\eta'$ and $pn \to d\phi$ *

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Abstract In an effective Lagrangian model we find that the $N^*(1535)$ resonance contribution might be important to the interpretation of the present data of the $pp \to pp\eta'$ and $pn \to d\phi$ reactions. The strong coupling strength of $N^*(1535)$ to η' and ϕ are indicated, and the possible implication to the intrinsic component of $N^*(1535)$ is explored. These results may provide hints to the real origin of the OZI rule violation. It is stressed that further measurements could be performed at the Cooling Storage Ring (CSR) at Lanzhou of China.

Key words meson production, nucleon-nucleon collision, resonance

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1 Introduction

Strange meson production processes in nucleon-nucleon collisions have attracted considerable theoretical interest since high precision data have been published in the past few years[1, 2]. The Cooler Synchrotron (COSY) at Juelich and the Cooling Storage Ring (CSR) at Lanzhou are in the same energy region, and they can both provide accurate data on these channels. This field is fascinating for its potential to search for missing resonances and explore the properties of the known resonances. Besides, strange meson production processes may provide information on the strange components of the nucleon and deepen our knowledge on the internal structure of nucleon. Furthermore, for the short life time of hyperon, it is difficult to accumulate a large set of scattering events and obtain accurate scattering parameters. Final state interaction (FSI) in strange meson production can supply us with assistant information on the meson-hyperon interaction.

It is widely accepted that $N^*(1535)$ resonance is dominant in the near threshold η production because of its large partial decay width of ηN channel. Since the physically observed η and η' mesons, as the mixtures of the pseudoscalar octet and singlet, are both consist of a considerable amount of $s\bar{s}$, one can expect that $N^*(1535)$ resonance should also dominate in the η' production. In the phenomenological analysis $N^*(1535)$ is found to be important for the near threshold Λ and ϕ production in nucleon-nucleon collisions[3, 4], and also in the chiral dynamics large couplings of $N^*(1535)$ to $K\Lambda$ and $K\Sigma$ have also been indicated[5]. These facts support the idea that $N^*(1535)$ should couple strongly to the strange mesons. Actually, the recent high-precision data of the reaction $\gamma p \to \eta' p$ obtained by the CLAS Collaboration suggest for the first time that both the $N^*(1535)$ and $N^*(1710)$ resonances couple to the $\eta' N$ channel[6].

In an effective Lagrangian model, we have calculated the the total and differential cross sections of the $pp \to pp\eta'$ and $pn \to d\phi$ channels based on the assumption the $N^*(1535)$ resonance is predominant. Our results reproduce the data well and give further evidence of the strong coupling of $N^*(1535)$ to strange mesons.

2 Effective lagrangians

The Feynman diagrams of elementary $N + N \to N+N+\text{Meson}$ reaction are depicted in Fig. 1, and

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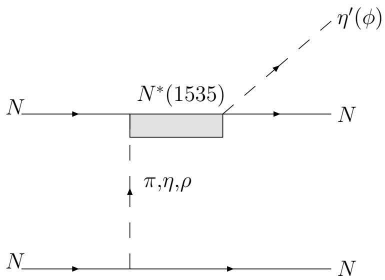

Fig. 1. Feynman diagram for $NN \to NN\eta'(\phi)$. Exchanged diagram should be included.

exchanged diagrams are also included. As to the $pn \to d\phi$ channel, the final two nucleons merge to form the deuteron. We use the commonly used interaction Lagrangians,

$$\mathcal{L}_{\pi NN} = -ig_{\pi NN}\bar{N}\gamma_5\vec{\tau}\cdot\vec{\pi}N, \tag{1}$$

$$\mathcal{L}_{\eta NN} = -ig_{\eta NN}\bar{N}\gamma_5\eta N, \tag{2}$$

$$\mathcal{L}_{\rho NN} = -g_{\rho NN}\bar{N}\left(\gamma_\mu + \frac{\kappa}{2m_N}\sigma_{\mu\nu}\partial^\nu\right)\vec{\tau}\cdot\vec{\rho}^\mu N, \tag{3}$$

$$\mathcal{L}_{\pi NN^*} = ig_{N^*N\pi}\bar{N}\vec{\tau}\cdot\vec{\pi}N^* + \text{h.c.}, \tag{4}$$

$$\mathcal{L}_{\eta NN^*} = ig_{N^*N\eta}\bar{N}\eta N^* + \text{h.c.}, \tag{5}$$

$$\mathcal{L}_{\rho NN^*} = ig_{N^*N\rho}\bar{N}\gamma_5\left(\gamma_\mu - \frac{q_\mu \not{q}}{q^2}\right)\vec{\tau}\cdot\vec{\rho}^\mu N^* + \text{h.c.}, \tag{6}$$

$$\mathcal{L}_{\eta' NN^*} = ig_{N^*N\eta'}\bar{N}\eta' N^* + \text{h.c.}, \tag{7}$$

$$\mathcal{L}_{\phi NN^*} = ig_{N^*N\phi}\bar{N}\gamma_5\left(\gamma_\mu - \frac{q_\mu \not{q}}{q^2}\right)\phi^\mu N^* + \text{h.c.}. \tag{8}$$

The coupling constants are taken as[4, 7]: $g^2_{\pi NN}/4\pi = 14.4$, $g^2_{\eta NN}/4\pi = 0.4$, $g^2_{\rho NN}/4\pi = 0.9$, and $\kappa = 6.1$. The $N^*(1535)N\pi$, $N^*(1535)N\eta$ and $N^*(1535)N\rho$ coupling constants are determined from the experimentally observed partial decay widths of the $N^*(1535)$ resonance, and the coupling strength of $N^*(1535)N\eta'$ and $N^*(1535)N\phi$ are extracted from the data of $pp \to pp\eta'(\phi)$ and $\pi N \to N\eta'(\phi)$[4, 7] as listed in Table 1.

Table 1. Relevant $N^*(1535)$ parameters.

channel	branching ratio	adopted ratio	$g^2/4\pi$
$N\pi$	0.35 – 0.55	0.45	0.033
$N\eta$	0.45 – 0.60	0.53	0.28
$N\rho \to N\pi\pi$	0.02 ± 0.01	0.02	0.10
$N\eta'$	—	—	1.10
$N\phi$	—	—	0.13

At each vertex a relevant off-shell form factor is used,

$$F^{NN}_M(k^2_M) = \left(\frac{\Lambda^2_M - m^2_M}{\Lambda^2_M - k^2_M}\right)^n, \tag{9}$$

with $n = 2$ for for ρNN vertex, and $n = 1$ for all other ones. The cut-off parameters Λ_M are adjusted to the experimental data. The form factor for $N^*(1535)$ resonance, $F_{N^*}(q^2)$, is taken as,

$$F_{N^*}(q^2) = \frac{\Lambda^4}{\Lambda^4 + (q^2 - M^2_{N^*(1535)})^2}, \tag{10}$$

with $\Lambda = 2.0$ GeV.

The usual forms of the propagators of the π, η, ρ and $N^*(1535)$ are used and the enhancement factor from pp final state interaction is factorized to be the Jost function[4, 7].

For the $pn \to d\phi$ reaction, the neutron-proton-deuteron vertex is taken as[8],

$$iS^c_F(p_1)(-i\Gamma_\mu\varepsilon^\mu_d)iS_F(p_2) = \frac{(2\pi)^4}{\sqrt{2}}\delta\left(\frac{p_d\cdot q_r}{m_d}\right)u(p_1,s_1)\phi_s(Q_R)u(p_2,s_2), \tag{11}$$

with $iS_F(p)$ being the nucleon propagator and $q_r = (p_1 - p_2)/2$ the neutron-proton relative four momentum. $Q_R = \sqrt{-q^2_r}$ is the deuteron internal momentum and ε^μ_d is the polarization vector of the deuteron. We neglect the D-state part of the deuteron wave function since it gives only a minor contribution, and the S-state deuteron wave function $\phi_s(Q_R)$ can be parameterized as the Hulthén wave function,

$$\phi_s(Q_R) = \sqrt{\frac{\alpha\beta(\alpha+\beta)}{\pi^2(\alpha-\beta)^2}}\left(\frac{1}{Q^2_R+\alpha^2} - \frac{1}{Q^2_R+\beta^2}\right), \tag{12}$$

with $\alpha = 0.2316\ \text{fm}^{-1}$ and $\beta = 1.268\ \text{fm}^{-1}$. Then we make the approximation that the dirac spinors $\bar{u}(p_1,s_1)$ and $\bar{u}(p_2,s_2)$ do not depend strongly on the relative momentum q_r since the deuteron wave function $\phi_s(Q_R)$ decreases rapidly with increasing Q_R[8].

The invariant amplitude can be calculated by above prescription, and the integration over the phase space can be performed by a Monte Carlo program.

3 The $pp \to pp\eta'$ reaction

In this channel, the cut-off parameters are determined from the combined analysis to the $NN \to NK\Sigma(\Lambda)$, $pp \to pp\eta$ and $pp \to pp\eta'$ channels[1, 7]. Our model agrees well with the measured data with $\Lambda_\pi = 1.05$ GeV for πNN, $\Lambda_\eta = 2.0$ GeV for ηNN, $\Lambda_\rho = 0.92$ GeV for ρNN and $\Lambda_M = 0.8$ GeV for MNR vertexes.

We get some similar conclusions to the $pp \to pp\eta$ and $pp \to pp\eta'$ reactions. In both channels, π-meson exchange is dominant in the near threshold region and the contribution from ρ- and η-meson exchange are very small. However, the relative contribution of these mesons still varies from one model to other due to the uncertainty of the coupling constants and the adjustable cut-off parameters. The data of the isospin and polarized reaction are helpful to set down this problem.

The invariant mass spectrum of pp → ppη′ are presented in Fig. 2, and the invariant mass distributions have similar structures to the pp → ppη, both of which have a bump in S_{pp} distribution caused by the pp FSI and a bump in $S_{p\eta'}$ distribution arising from N*(1535) resonance. This comparability is confirmed by the recent COSY-11 data[11] measured at the excess energy of about 16 MeV, and gives support to our assumption that N*(1535) resonance is dominant in the near threshold η′ production.

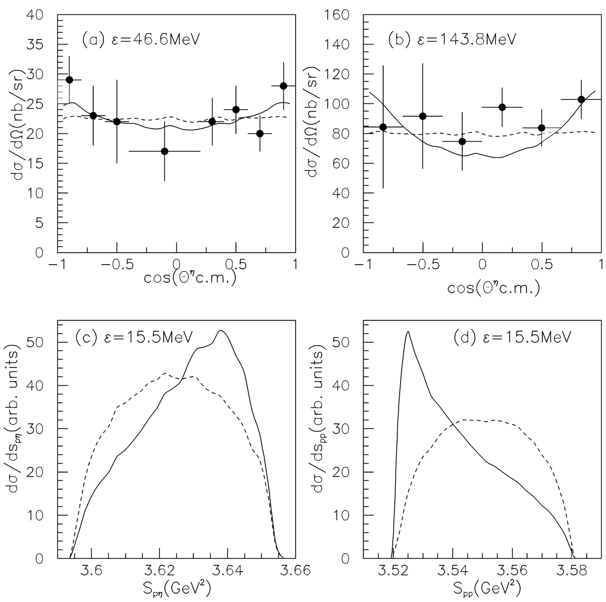

Fig. 2. Invariant mass spectrum for pp → ppη′[12]. The data are from Ref. [9] (a) and Ref. [10] (b). The dashed curve is the pure phase-space distribution.

The angular distributions of the η′-meson in C.M. system in Fig. 2(a), (b) show some structures, and this is compared to the isotropic shape of those of η-meson in the pp → ppη reaction. The underlying reason for this difference is that N*(1535) is far below the η′N threshold while it is very close to the ηN threshold.

4 The pn → dϕ reaction

We found that $\Lambda_\pi = \Lambda_\eta = 1.3$ GeV and $\Lambda_\rho = 1.6$ GeV could give a nice reproduce fit to the data of both pp → ppϕ and pn → dϕ reactions[4, 12].

As to the total cross section, the two-body phase space behavior is dominant in the considered energy of pn → dϕ channel. No near-threshold enhancement is found and it indicates that ϕN interaction must be weak. The π- and ρ-meson exchange are found to be important while η-meson exchange is negligible, and the contribution from ρ-meson exchange is about three times larger than that of π-meson. It should be noted that nearly all the former calculations underestimated the data of total cross section, though some of them only slightly.

As shown in Fig. 3, our calculated ϕ-meson polar angular distributions are compatible with the experimental data and show obvious upward bending at high excess energy. Since the measured angular dependence are also compatible with an isotropic shape within the given experimental uncertainties, nucleon pole and ϕρπ-vertex may also have some minor contribution.

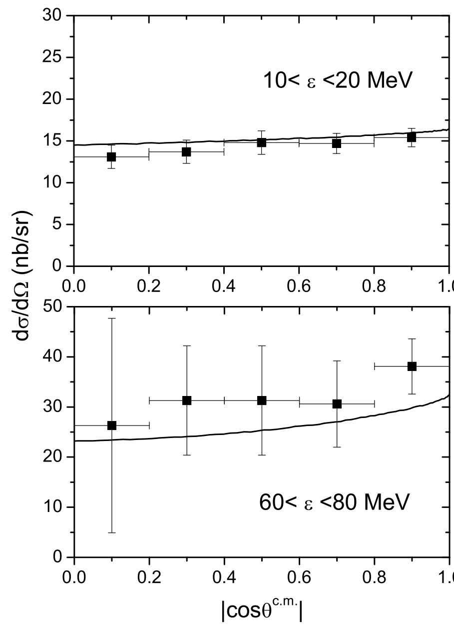

Fig. 3. Angular distributions of ϕ meson polar angular in the overall c.m. system. The data are from Ref. [13].

Though our analysis indicate some evidence of the N*(1535) contribution, we have to admit that other S_{11} resonance can also well fit the pn → dϕ data by choosing suitable model parameters, and the shape of the given angular distributions are analogous to those of N*(1535) for their same quantum numbers. The clarification of this problem is left to the further experimental and theoretical efforts.

5 Discussion and summary

In summary, we have phenomenologically investigated the role of the $N^*(1535)$ resonance in $pp \to pp\eta'$ and $pn \to d\phi$ reactions near threshold, and gave a nice reproduce to the experimental data with the dominance of the $N^*(1535)$.

The strange meson production was closely related to the OZI rule violation[13], and varieties of mechanisms were put forward to account for its origin. Based on our above analysis, the significant $N^*(1535)N\eta'$ and $N^*(1535)N\phi$ coupling would be enough to explain the enhancement in the η'- and ϕ-meson production in pN collisions and might be the real origin of the OZI rule violation. Since $N^*(1535)$ resonance tends to couple strongly to the strange meson, it is probable that its quark wave function has large $s\bar{s}$ component. The role of the five-quark components in $N^*(1535)$ resonance has been extensive discussed in the quark model[14], and many of its properties were explained with including obvious $qqqs\bar{s}$ components.

Further measurements of these channels are being conducted at COSY. Besides, a significant improvement is to be expected through the installation of Cooling Storage Ring (CSR) at Lanzhou of China, which is designed for the study of heavy-ion collisions. It can provide 1—2.8 GeV proton beam and perform accurate measurement to differential observables and invariant mass spectrum with the detector Proton-Induced SpAllation (PISA) at the internal beam facility of CSR. The situation as our discussed above is about to definitely clarified by new data in the near future.

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