

Associated strangeness production in the $pp \rightarrow pK^+K^-p$ and $pp \rightarrow pK^+\pi^0\Sigma^0$ reactionsJu-Jun Xie^{1,2,*} and Colin Wilkin^{3,†}¹*Instituto de Física Corpuscular (IFIC), Centro Mixto CSIC—Universidad de Valencia, Institutos de Investigación de Paterna, Aptd. 22085, E-46071 Valencia, Spain*²*Department of Physics, Zhengzhou University, Zhengzhou, Henan 450001, China*³*Physics and Astronomy Department, UCL, London WC1E 6BT, United Kingdom*

(Received 17 May 2010; published 31 August 2010)

The total and differential cross sections for associated strangeness production in the $pp \rightarrow pK^+K^-p$ and $pp \rightarrow pK^+\pi^0\Sigma^0$ reactions have been studied in a unified approach using an effective Lagrangian model. It is assumed that both the K^-p and $\pi^0\Sigma^0$ final states originate from the decay of the $\Lambda(1405)$ that was formed in the production chain $pp \rightarrow p(N^*(1535) \rightarrow K^+\Lambda(1405))$. The available experimental data are well reproduced, especially the ratio of the two total cross sections, which is much less sensitive to the particular model of the entrance channel. The significant coupling of the $N^*(1535)$ to $\Lambda(1405)K$ is further evidence for large $s\bar{s}$ components in the quark wave function of the $N^*(1535)$.

DOI: [10.1103/PhysRevC.82.025210](https://doi.org/10.1103/PhysRevC.82.025210)

PACS number(s): 14.20.Jn, 13.30.-a

I. INTRODUCTION

The $N^*(1535)$ has proved to be a controversial resonance for many years. In the simple three-quark constituent model, the odd parity $N^*(1535)$ ($J^P = 1/2^-$) should be the lowest spatially excited nucleon state, with one quark in a p wave. However, the even parity $N^*(1440)$ has in fact a much lower mass, despite requiring two units of excitation energy. This is the long-standing mass inversion problem of the nucleon spectrum.

The $N^*(1535)$ couples strongly to the ηN channel [1] but a large $N^*(1535)K\Lambda$ coupling has also been deduced [2–4] through the analysis of BES data on $J/\psi \rightarrow p\bar{p}\eta$, $\bar{p}\Lambda K^+$ decays [5] and COSY data on the $pp \rightarrow p\Lambda K^+$ reaction near threshold [6]. Analyses [7,8] of recent SAPHIR [9] and CLAS [10] $\gamma p \rightarrow K^+\Lambda$ data also indicate a large coupling of the $N^*(1535)$ to $K\Lambda$.

In a chiral unitary coupled channel model it is found that the $N^*(1535)$ is dynamically generated, with its mass, width, and branching ratios in fair agreement with experiment [2,11–14]. This approach shows that the couplings of the $N^*(1535)$ to the $K\Sigma$, ηN , and $K\Lambda$ channels could be large compared to those for πN . Data on the $\gamma p \rightarrow p\eta'$ [15] and $pp \rightarrow pp\eta'$ reactions [16] suggest also a coupling of the isobar to $\eta'N$. In addition, there is some evidence for a $N^*(1535)N\phi$ coupling from the $\pi^-p \rightarrow n\phi$ and $pp \rightarrow pp\phi$ reactions [17,18] as well as from the $pn \rightarrow d\phi$ [19] reaction.

The mass inversion problem could be understood if there were significant $s\bar{s}$ components in the $N^*(1535)$ wave function [20,21] and this would also provide a natural explanation of its large couplings to the strangeness $K\Lambda$, $K\Sigma$, $N\eta'$, and $N\phi$ channels. It would furthermore lead to an improvement in the description of the helicity amplitudes in $N^*(1535)$ photoproduction [22]. We wish to argue in this article that a hidden strangeness component in the $N^*(1535)$ might play

a much wider role in associated strangeness production in medium-energy nuclear reactions.

The $\Lambda(1405)$ ($J^P = 1/2^-$) can be considered as the strangeness $S = -1$ counterpart of the $N^*(1535)$ and its structure is possibly even more controversial. In quark model calculations, it is described as a p -wave q^3 baryon [23], but it can also be explained as a $\bar{K}N$ molecule [24] or a $q^4\bar{q}$ pentaquark state [25]. On the other hand, within unitary chiral theory [2,11,26], two overlapping $I = 0$ states are dynamically generated and in this approach the shape of any observed $\Lambda(1405)$ might depend upon the production process. In a recent study of the $pp \rightarrow pK^+\Lambda(1405)$ reaction [27] the resonance was clearly identified through its $\pi^0\Sigma^0$ decay and no obvious mass shift was found. However, this result is inconclusive in the sense that the data could also be well described in the two-resonance scenario [28]. For simplicity we shall here work within the single $\Lambda(1405)$ framework with parameters as reported in the Particle Data Group (PDG) review [1].

In parallel with the $\Lambda(1405)$ measurement, Maeda *et al.* also extracted differential and total cross sections for kaon pair production in the $pp \rightarrow ppK^+K^-$ reaction [29]. These results show clear evidence for the excitation and decay of the ϕ meson sitting on a smooth K^+K^- background, whose shape resembles phase space. It has been suggested [30] that the $\Lambda(1405)$ could be important for the non- ϕ kaon pair production through the $pp \rightarrow pK^+(\Lambda(1405) \rightarrow K^-p)$ reaction. This would, of course, only be relevant for the isospin $I = 0$ K^-p contribution, but this is likely to dominate the low-mass region because of the presence of the $\Lambda(1405)$. It is therefore the purpose of the present article to analyze simultaneously the available data on $pp \rightarrow K^+p\Sigma^0\pi^0$ and $pp \rightarrow K^+pK^-p$ production at a beam energy of 2.83 GeV [27,29] within a unified phenomenological model, where the $N^*(1535)$ acts as a doorway state for both production processes.

The foundation of the model is the assumption that there are large $s\bar{s}$ components in the quark wave function of the $N^*(1535)$ and that these induce a significant $N^*(1535) : \Lambda(1405)K$ coupling. This in turn allows the possibility that

* xiejun@ific.uv.es

† cw@hep.ucl.ac.uk

the production of the $\Lambda(1405)$ in proton-proton and $\pi^- p$ collisions could be dominated by the excitation and decay of the $N^*(1535)$ below the $\Lambda(1405)K$ threshold. Within this picture, we calculate the $pp \rightarrow pK^+\Lambda(1405) \rightarrow pK^+(K^-p/\pi^0\Sigma^0)$ and $\pi^- p \rightarrow \Lambda(1405)K^0$ reactions using an effective Lagrangian approach. We show that the pion-induced data are indeed compatible with the large $N^*(1535) : \Lambda(1405)K$ coupling resulting from the $s\bar{s}$ components in the $N^*(1535)$. The resulting theoretical estimates of the $pp \rightarrow pK^+K^-p$ and $pp \rightarrow pK^+\pi^0\Sigma^0$ differential and total cross sections describe well the available COSY experimental data [27,29]. In particular, the ratio of these two cross sections, where many of the theoretical uncertainties cancel, is reproduced within the total theoretical and experimental uncertainties.

Section II presents the formalism and ingredients required for the calculation, with the numerical results and discussions being given in Sec. III. A short summary and a presentation of our conclusions then follows in Sec. IV.

II. FORMALISM AND INGREDIENTS

We study the $pp \rightarrow pK^+\Lambda(1405) \rightarrow pK^+(K^-p/\pi^0\Sigma^0)$ and $\pi^- p \rightarrow \Lambda(1405)K^0$ reactions in an effective Lagrangian approach on the assumption that the production of the $K\Lambda(1405)$ pair is dominantly through the excitation and decay of the subthreshold $N^*(1535)$. It is generally assumed that the production of η mesons in nucleon-nucleon collisions near threshold passes mainly through the $N^*(1535)$, which has a very strong coupling to $N\eta$. However, there is far from unanimity in the modeling of these processes within a meson-exchange picture, with different groups considering π , ρ , η , and ω exchanges to be important [18,31]. Fortunately, the estimation of the $pp \rightarrow pK^+\Lambda(1405)$ cross section in our model is only sensitive to the production rate of the $N^*(1535)$, and single-pion exchange is sufficient for this purpose. By neglecting η and ρ exchanges, we can present a unified picture of pion- and proton-induced production processes, though our results are more general than this would suggest.

The basic Feynman diagrams for the t -channel exchanges in the $pp \rightarrow pK^+\Lambda(1405) \rightarrow pK^+(K^-p/\pi^0\Sigma^0)$ reaction and the s -channel diagram for the $\pi^- p \rightarrow \Lambda(1405)K^0$ reaction are depicted in Figs. 1 and 2, respectively. For the $pp \rightarrow pK^+\pi^0\Sigma^0$ reaction, only the diagrams in Figs. 1(a) and 1(b) need to be considered, while for the $pp \rightarrow pK^+K^-p$ reaction the exchange terms in Figs. 1(c) and 1(d) must also be included.

We employ the commonly used interaction Lagrangian for the πNN vertex,

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

with an off-shell form factor taken from the Bonn potential model [32],

$$F_{\pi}^{NN}(k_{\pi}^2) = \frac{\Lambda_{\pi}^2 - m_{\pi}^2}{\Lambda_{\pi}^2 - k_{\pi}^2}, \quad (2)$$

where k_{π} , m_{π} , and Λ_{π} are the four-momentum, mass, and cutoff parameter for the exchanged pion. The coupling constant

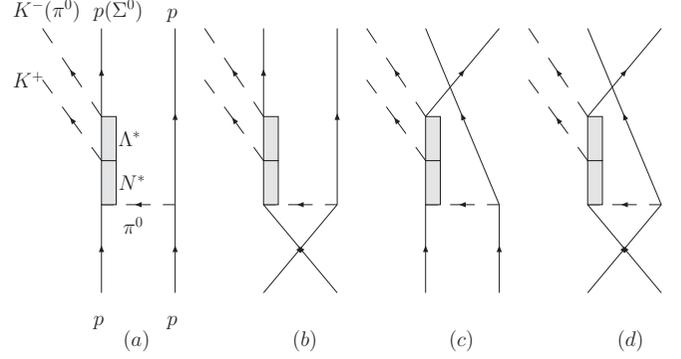


FIG. 1. Feynman diagrams for the $pp \rightarrow pK^+\Lambda(1405) \rightarrow pK^+(K^-p/\pi^0\Sigma^0)$ reaction.

and the cutoff parameter are taken to be $g_{\pi NN}^2/4\pi = 14.4$ and $\Lambda_{\pi} = 1.3 \text{ GeV}/c^2$ [32,33].

To evaluate the invariant amplitudes corresponding to the diagrams of Figs. 1 and 2, we also need to know the interaction Lagrangians involving the $N^*(1535)$ and $\Lambda(1405)$. In Ref. [34], a Lorentz-covariant orbital-spin (L - S) scheme for N^*NM couplings was studied in detail. Within this approach, the $N^*(1535)N\pi$, $N^*(1535)\Lambda(1405)K$, $\Lambda(1405)\bar{K}N$, and $\Lambda(1405)\pi\Sigma$ effective couplings become

$$\begin{aligned} \mathcal{L}_{N^*N\pi} &= -ig_{N^*N\pi} \bar{N}^* \vec{\tau} \cdot \vec{\pi} N + \text{H.c.}, \\ \mathcal{L}_{N^*\Lambda^*K} &= \frac{g_{N^*\Lambda^*K}}{m_K} \bar{N}^* \gamma_5 \gamma_{\mu} \partial^{\mu} K \Lambda^* + \text{H.c.}, \\ \mathcal{L}_{\Lambda^*\bar{K}N} &= -ig_{\Lambda^*\bar{K}N} \bar{N} \bar{K} \Lambda^* + \text{H.c.}, \\ \mathcal{L}_{\Lambda^*\pi\Sigma} &= -ig_{\Lambda^*\pi\Sigma} \bar{\Lambda}^* \vec{\pi} \cdot \vec{\Sigma} + \text{H.c.} \end{aligned} \quad (3)$$

To minimize the number of free parameters, a dipole form factor similar to that of Eq. (2) is used for the $N^*(1535)N\pi$ vertex, with the same value of the cutoff parameter.

The $N^*(1535)N\pi$ and $\Lambda(1405)\pi\Sigma$ coupling constants are determined from the partial decay widths of these two resonances [1]. With the effective interaction Lagrangians of Eqs. (3), the coupling constants are related to the partial decay widths by

$$\Gamma_{N^*(1535) \rightarrow N\pi} = \frac{3g_{N^*N\pi}^2(m_N + E_N)p_N^{\text{c.m.}}}{4\pi M_{N^*}},$$

where

$$p_N^{\text{c.m.}} = \frac{\lambda^{1/2}(M_{N^*}^2, m_N^2, m_{\pi}^2)}{2M_{N^*}},$$

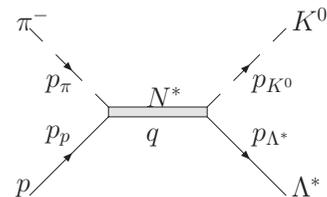


FIG. 2. Feynman diagram for the $\pi^- p \rightarrow \Lambda(1405)K^0$ reaction. Here p_{π} , p_p , p_{K^0} , p_{Λ^*} , and q are the four-momenta of the π^- , proton, K^0 , $\Lambda(1405)$, and intermediate $N^*(1535)$, respectively.

with

$$E_N = \sqrt{(p_N^{\text{c.m.}})^2 + m_N^2}, \quad (4)$$

and correspondingly for the $\Lambda(1405) \rightarrow \pi \Sigma$ decay in terms of the $g_{\Lambda^* \pi \Sigma}$ coupling constant. Here λ is the triangle function,

$$\lambda(x, y, z) = x^2 + y^2 + z^2 - 2xy - 2xz - 2yz. \quad (5)$$

Although the mass differences do not allow one to obtain directly similar results for the $N^*(1535)\Lambda(1405)K$ vertex, the requisite information can be extracted from $\pi^- p \rightarrow \Lambda(1405)K^0$ data, provided that this reaction is dominated by the s -channel $N^*(1535)$ pole of Fig. 2. The corresponding invariant amplitude \mathcal{A} becomes

$$\mathcal{A} = \frac{\sqrt{2}g_{N^*N\pi}g_{N^*\Lambda^*K}}{m_K} F_{N^*}(q^2)\bar{u}(p_\Sigma, s_\Sigma) \times \gamma_5 \not{p}_{K^0} G_{N^*}(q)u(p_p, s_p), \quad (6)$$

where s_Σ and s_p are the baryon spin projections.

The form factor for the $N^*(1535)$, $F_{N^*}(q^2)$, is taken in the form advocated in Refs. [7,35]:

$$F_{N^*}(q^2) = \frac{\Lambda_{N^*}^4}{\Lambda_{N^*}^4 + (q^2 - M_{N^*}^2)^2}, \quad (7)$$

with $\Lambda_{N^*} = 2.5 \text{ GeV}/c^2$.

The $N^*(1535)$ propagator is written in a Breit-Wigner form [36]:

$$G_{N^*}(q) = \frac{i(\not{q} + M_{N^*})}{q^2 - M_{N^*}^2 + iM_{N^*}\Gamma_{N^*}(q^2)}, \quad (8)$$

where $\Gamma_{N^*}(q^2)$ is the energy-dependent total width. Keeping only the dominant πN and ηN decay channels [1], this can be decomposed as

$$\Gamma_{N^*}(q^2) = a_{\pi N} \rho_{\pi N}(q^2) + b_{\eta N} \rho_{\eta N}(q^2), \quad (9)$$

where $a_{\pi N} = 0.12 \text{ GeV}/c^2$, $b_{\eta N} = 0.32 \text{ GeV}/c^2$, and the two-body phase space factors, $\rho_{\pi(\eta)N}(q^2)$, are

$$\rho(q^2) = 2p^{\text{c.m.}}(q^2) \Theta(q^2 - q_{\text{thr}}^2) / \sqrt{q^2}, \quad (10)$$

and q_{thr} is the threshold value for the decay channel.

A similar representation is adopted for the $\Lambda(1405)$ propagator and form factor, with the same value of the cutoff parameter $\Lambda_{\Lambda^*} = 2.5 \text{ GeV}/c^2$. Because the $\Lambda(1405)$ lies slightly below the $\bar{K}N$ threshold, the only nominally allowed decay channel is $\pi \Sigma$. Nevertheless, ever since the pioneering work of Dalitz and Tuan [24] it has been known that there is also a strong coupling to $\bar{K}N$. The ensemble of low-energy data on $K^- p$ and related channels has been described in terms of a separable potential model [37]. In contrast to the unitary chiral approach [28], the separable model produces only a single $\Lambda(1405)$ pole and from this we can investigate its effects above the $\bar{K}N$ threshold. These can be parametrized in terms of an energy-dependent partial width,

$$\Gamma_{\Lambda(1405)}(q^2) = a_{\pi \Sigma} \rho_{\pi \Sigma}(q^2) + b_{\bar{K}N} \rho_{\bar{K}N}(q^2), \quad (11)$$

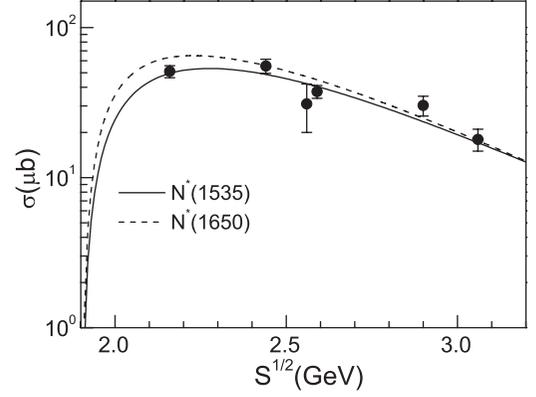


FIG. 3. Total cross section for the $\pi^- p \rightarrow \Lambda(1405)K^0$ reaction as a function of the c.m. energy \sqrt{s} . The solid curve represents the fit of the s -channel $N^*(1535)$ pole of Fig. 2 to the available experimental data [38]. The dashed curve is the corresponding fit if the $N^*(1650)$ were used instead.

where $a_{\pi \Sigma} = 0.22 \text{ GeV}/c^2$, $b_{\bar{K}N} = 0.49 \text{ GeV}/c^2$, and the two-body phase-space factors are given in Eq. (10). By using

$$g_{\Lambda^* \bar{K}N}^2 = \frac{0.49 \times 3 \times [m_\Sigma + E_\Sigma(q^2)]}{0.22 \times 2 \times [m_N + E_N(q^2)]} \times g_{\Lambda^* \pi \Sigma}^2, \quad (12)$$

the width Eq. (11) leads to the $\Lambda(1405)\bar{K}N$ coupling constant $g_{\Lambda^* \bar{K}N}^2/4\pi = 0.27$ at the $\bar{K}N$ threshold.

We now evaluate the $\pi^- p \rightarrow \Lambda(1405)K^0$ total cross section as a function of the center-of-mass energy. The value of the $N^*(1535)\Lambda(1405)K$ coupling constant $g_{N^*\Lambda^*K}^2/4\pi = 0.28$ leads to the predictions that are compared with experimental data [38] in Fig. 3. Although the agreement is reasonable, it must be stressed that the predictions are not very sensitive to the mass of the N^* , provided it lies well below the $K\Lambda(1405)$ threshold. As can be judged from the figure, a very similar shape would be obtained if one used, for example, the second S_{11} resonance, $N^*(1650)$. However, it has been shown [18] that a large $s\bar{s}$ component in the $N^*(1650)$ is not consistent with its smaller coupling to $N\eta$ than to $N\pi$. It should also be noticed that any possible contributions from t - and u -channel exchanges have also been neglected. The value of this coupling constant is given along with others in Table I.

TABLE I. Values of the coupling constants required for the estimation of the $pp \rightarrow pK^+K^-p$ and $pp \rightarrow pK^+\pi^0\Sigma^0$ cross sections. These have been estimated from the branching ratios quoted [1], though it should be noted that these are for all final charged states. As described in the text, the $\Lambda^*\bar{K}N$ coupling was obtained from the energy dependence of the $\Lambda(1405)$ width given by Eq. (11), and the $N^*\Lambda^*K$ coupling was derived from measurements of the $\pi^- p \rightarrow \Lambda(1405)K^0$ total cross section.

Vertex	Branching ratio	$g^2/4\pi$
$N^*N\pi$	0.45	0.038
$\Lambda^*\pi\Sigma$	1.00	0.064
$\Lambda^*\bar{K}N$	—	0.27
$N^*\Lambda^*K$	—	0.28

The full invariant amplitude for the $pp \rightarrow pK^+K^-p$ reaction is composed of four parts, corresponding to the diagrams shown in Fig. 1:

$$\mathcal{M} = \sum_{i=a,b,c,d} \eta_i \mathcal{M}_i. \quad (13)$$

To take account of the antisymmetry of the protons in the initial and final states, factors $\eta_a = \eta_d = 1$ and $\eta_b = \eta_c = -1$ are introduced. It is important to note that only \mathcal{M}_a and \mathcal{M}_b should be considered for the $pp \rightarrow pK^+\pi^0\Sigma^0$ reaction.

Each amplitude can be derived straightforwardly with the effective couplings given. We give as an example the form of the \mathcal{M}_a amplitude:

$$\begin{aligned} \mathcal{M}_a = & \frac{g_{\pi NN} g_{N^* N \pi} g_{N^* \Lambda^* K} g_{\Lambda^* \bar{K} N}}{m_K} F_{\pi}^{NN}(k_{\pi}^2) \\ & \times F_{\pi}^{N^* N}(k_{\pi}^2) F_{N^*}(q_1^2) F_{\Lambda^*}(q_2^2) G_{\pi}(k_{\pi}) \bar{u}(p_4, s_4) \\ & \times G_{\Lambda(1405)}(q_2) \gamma_5 \not{p}_5 G_{N^*(1535)}(q_1) u(p_1, s_1) \\ & \times \bar{u}(p_3, s_3) \gamma_5 u(p_2, s_2), \end{aligned} \quad (14)$$

where s_i ($i = 1, 2, 3, 4$) and p_i ($i = 1, 2, 3, 4$) represent the spin projections and four-momenta of the two initial and the two final protons, respectively. The q_1 and q_2 are the four-momenta of intermediate $N^*(1535)$ and $\Lambda(1405)$, while p_5 is the four-momentum of the final K^+ meson. The pion propagator is

$$G_{\pi}(k_{\pi}) = \frac{i}{k_{\pi}^2 - m_{\pi}^2}. \quad (15)$$

The final-state interaction (FSI) between the two emerging protons in the 1S_0 wave in the $pp \rightarrow ppK^+K^-$ case is taken into account using the Jost function formalism [39], with

$$J(q)^{-1} = \frac{k + i\beta}{k - i\alpha}, \quad (16)$$

where k is the internal momentum of the pp subsystem. The parameters $\alpha = -20.5$ MeV/ c and $\beta = 166.7$ MeV/ c [40] give a slightly stronger pp FSI in the near-threshold region than that used in the experimental article [29].

The normalization is chosen such that the differential cross section is

$$\begin{aligned} d\sigma(pp \rightarrow pK^+pK^-) & \\ = & \frac{m_p^2}{F} \frac{1}{4} \sum_{s_i, s_f} |\mathcal{M}|^2 \frac{m_p d^3 p_3}{E_3} \frac{m_p d^3 p_4}{E_4} \frac{d^3 p_5}{2E_5} \frac{d^3 p_6}{2E_6} \\ & \times \frac{1}{2} \delta^4(p_1 + p_2 - p_3 - p_4 - p_5 - p_6), \end{aligned} \quad (17)$$

with the flux factor

$$F = (2\pi)^8 \sqrt{(p_1 p_2)^2 - m_p^4}. \quad (18)$$

The factor $\frac{1}{2}$ before the δ function in Eq. (17) results from having two final identical protons and must be omitted for the $pK^+\pi^0\Sigma^0$ final state.

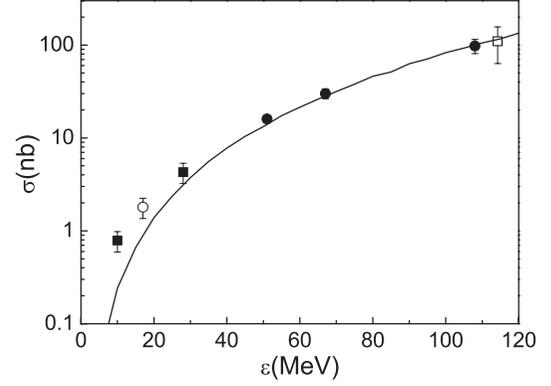


FIG. 4. The non- ϕ contribution to the $pp \rightarrow pK^+pK^-$ total cross section versus excess energy ϵ . The results of the present calculation are compared with experimental data from Refs. [29] (closed circles), [42] (open square), [43] (closed squares), and [44] (open circle).

III. NUMERICAL RESULTS AND DISCUSSION

The predictions for the variation of the $pp \rightarrow pK^+pK^-$ total cross section with excess energy ϵ , calculated using a Monte Carlo multiparticle phase-space integration program, are shown in Fig. 4. Although the general shape of the experimental data is described, nevertheless the results very close to threshold are underestimated. This may be due to the neglect of a K^+K^- FSI [41], which might be associated with the influence of the a_0 and f_0 scalar resonances [29].

The predicted K^-p invariant mass spectrum for the $pp \rightarrow pK^+\{K^-p\}$ reaction at $T_p = 2.83$ GeV ($\epsilon = 108$ MeV) is compared in Fig. 5 to the experimental data from the ANKE group [29]. The theoretical model reproduces well the shape of the data, being much more peaked to lower invariant masses than the four-body phase-space distribution, which is also shown. As already indicated in Fig. 4, the predicted 100 nb coincides with the experimental value of $(98 \pm 8 \pm 15)$ nb, where the first error is statistical and the second systematic [29].

The corresponding results for the $\pi^0\Sigma^0$ invariant mass distribution for the $pp \rightarrow pK^+\pi^0\Sigma^0$ reaction at the same beam energy, but excess energy $\epsilon = 212$ MeV, are shown in Fig. 6 together with the ANKE data [27]. Although the statistics are low, the shape of the spectrum is described correctly, with a rather asymmetric $\Lambda(1405)$ peak that is strongly influenced by the opening of the $\bar{K}N$ threshold, which is by the energy dependence of the $\Lambda(1405)$ width parametrized by Eq. (11). On the other hand, the overall normalization of the prediction is too high, giving a cross section of $4.0 \mu\text{b}$ compared to an experimental value of $(1.5 \pm 0.3 \pm 0.6) \mu\text{b}$ [27]. The predicted normalization could, of course, be reduced by considering the initial-state interaction, but that would then lower also the value for the $pp \rightarrow pK^+K^-p$ channel.

Many effects cancel out in the estimation of the ratio of the $pp \rightarrow pK^+K^-p$ to $pp \rightarrow pK^+\pi\Sigma$ total cross sections. These include initial-state distortions and most of the parameters connected with the $N^*(1535)$. Combining the two experimental results one finds that, at a proton beam energy of

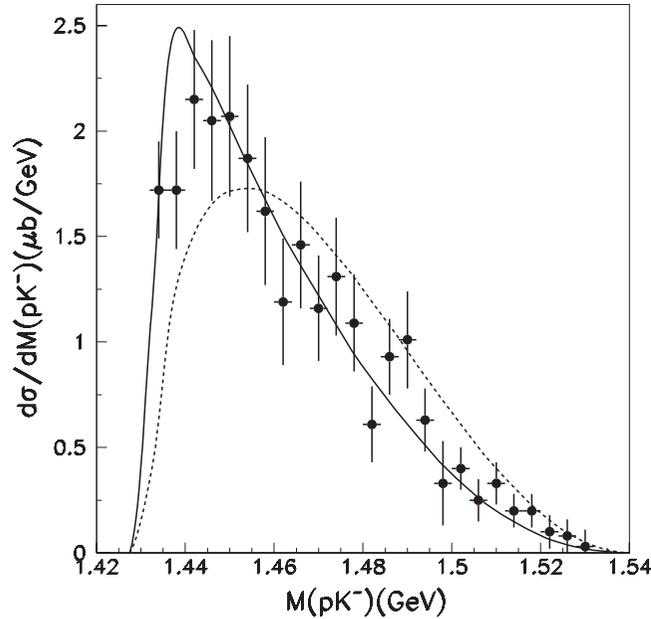


FIG. 5. Differential cross section for the $pp \rightarrow pK^+K^-p$ reaction at the excess energy $\varepsilon = 108$ MeV as a function of the K^-p invariant mass $M(pK^-)$. The ANKE data of Ref. [29] are compared to the predictions of the $N^*(1535)$ model (solid line), whereas the dashed line represents a normalized four-body phase-space distribution.

2.83 GeV,

$$R_{K\pi} = \frac{\sigma(pp \rightarrow pK^+K^-p)}{\sigma(pp \rightarrow pK^+\pi^0\Sigma^0)} = (65 \pm 24) \times 10^{-3}, \quad (19)$$

where only non- ϕ events have been considered. This is to be compared with a value of $R_{K\pi} \sim 25 \times 10^{-3}$ obtained within the framework of the present model. The theoretical uncertainties are hard to quantify because they reside to a large extent in the modeling of the low-energy $K^-p/\pi^0\Sigma^0$ system [37], which is based upon a limited experimental data set. In addition, there are possibly small contributions from $I = 1$ s -wave K^-p pairs or, for the higher masses, also some p -wave contributions. In view of the large experimental and theoretical uncertainties, the good agreement for the $R_{K\pi}$ ratio is very satisfactory.

IV. SUMMARY AND CONCLUSIONS

The total and differential cross sections for associated strangeness production in the $pp \rightarrow pK^+\{K^-p\}$ and $pp \rightarrow pK^+\{\pi^0\Sigma^0\}$ reactions have been studied in a unified approach using an effective Lagrangian model. The basic assumptions are that both the K^-p and $\pi^0\Sigma^0$ systems come from the decay of the $\Lambda(1405)$. This state itself results from the excitation of the $N^*(1535)$, for which there is strong evidence for the importance of hidden strangeness components. Although only pion exchange has been kept in the $pp \rightarrow pN^*(1535)$ reaction, our predictions are sensitive to the $N^*(1535)$ production rate, and pion exchange provides a reasonable description of this. Within the model, the energy dependence of the

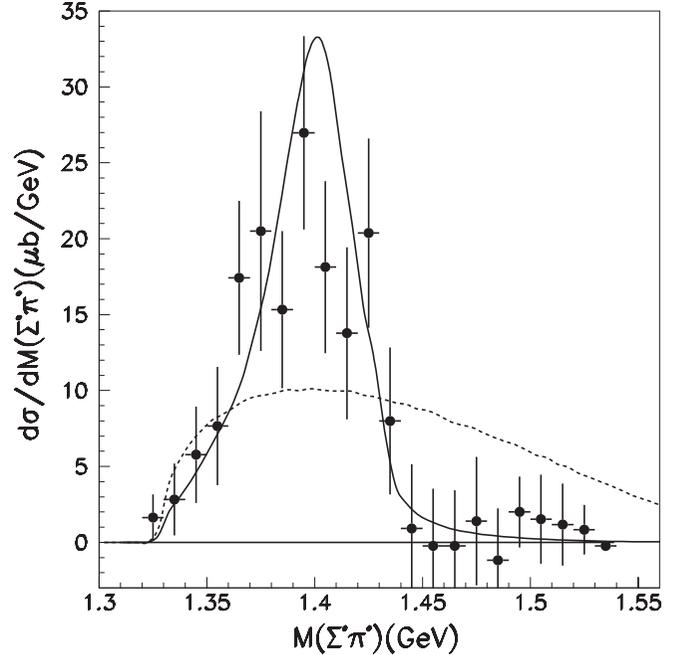


FIG. 6. Differential cross section for the $pp \rightarrow pK^+\pi^0\Sigma^0$ reaction at an excess energy of $\varepsilon = 212$ MeV. The predictions of the $N^*(1535)$ model (solid line) have been scaled down by a factor of about 1.5/4 before being compared to the ANKE data [27]. The fairly shapeless four-body phase-space distribution (dashed line) has also been normalized to the total number of experimental events.

$pp \rightarrow pK^+K^-p$ total cross section is well reproduced, as are the characteristic K^-p and $\pi^0\Sigma^0$ invariant mass distributions.

Of particular interest is the ratio $R_{K\pi}$ of the $pp \rightarrow pK^+K^-p$ and $pp \rightarrow pK^+\pi^0\Sigma^0$ total cross sections because in the estimation of $R_{K\pi}$ many unknowns drop out. Apart from initial-state distortion, which has been completely neglected in our work, the details of the $N^*(1535)$ doorway state are largely irrelevant provided that this state lies well below the $K^+\Lambda(1405)$ threshold. Thus the very satisfactory prediction for $R_{K\pi}$ would remain the same if one assumed that the processes were driven for example by the $N^*(1650)$. However, it is the absolute value of either cross section that depends upon the $N^*(1535)$ hypothesis, and it is the reasonable description here that gives further weight to the idea of large $s\bar{s}$ components in this isobar.

The link between K^-p and $\pi^0\Sigma^0$ production could be established through the use of much low-energy data, which led to the phenomenological separable potential description of the coupled $K^-p \rightleftharpoons \pi^0\Sigma^0$ systems [37]. Although this particular model gives rise to a single $\Lambda(1405)$ pole, it is merely a parametrization of measured scattering data, and we cannot rule out the possibility that similar results would be obtained if one used a chiral unitary description that requires two $\Lambda(1405)$ poles [28].

The production of $K\bar{K}$ resonances, such as the a_0/f_0 scalars [1], can clearly not contribute to the $pp \rightarrow pK^+\pi^0\Sigma^0$ reaction. Consequently, even if the model presented here is only qualitatively correct, it would suggest that non- ϕ K^+K^- production in $pp \rightarrow pK^+K^-p$ is driven dominantly through

the excitation of K^+ -hyperon pairs rather than nonstrange mesonic resonances.

Further experimental data are needed, and some should be available soon from the HADES Collaboration on the $pp \rightarrow pK^+\pi^0\Sigma^0$ reaction at the slightly higher energy of 3.5 GeV [45]. It would, however, be highly desirable to have data on kaon pair production at a similar energy to provide an independent check on the value of $R_{K\pi}$ and hence on the approach presented here.

ACKNOWLEDGMENTS

We thank Xu Cao, A. Gal, M. Hartmann, Feng-Kun Guo, J. Nieves, N. Shevchenko, and Bing-Song Zou for useful discussions and the CAS Theoretical Physics Center for Science Facilities for support and hospitality during the initiation of this work. This research was partially supported by the Ministerio de Educación “Estancias de movilidad de profesores e investigadores extranjeros en centros españoles,” Contract No. SB2009-0116.

-
- [1] C. Amsler *et al.*, *Phys. Lett. B* **667**, 1 (2008).
 [2] C. Garcia-Recio, M. F. M. Lutz, and J. Nieves, *Phys. Lett. B* **582**, 49 (2004).
 [3] B. C. Liu and B. S. Zou, *Phys. Rev. Lett.* **96**, 042002 (2006); **98**, 039102 (2007); *Commun. Theor. Phys.* **46**, 501 (2006).
 [4] L. S. Geng, E. Oset, B. S. Zou, and M. Döring, *Phys. Rev. C* **79**, 025203 (2009).
 [5] J. Z. Bai *et al.*, *Phys. Lett. B* **510**, 75 (2001); H. X. Yang *et al.*, *Int. J. Mod. Phys. A* **20**, 1985 (2005).
 [6] P. Kowina *et al.*, *Eur. Phys. J. A* **22**, 293 (2004).
 [7] G. Penner and U. Mosel, *Phys. Rev. C* **66**, 055211 (2002); **66**, 055212 (2002); V. Shklyar, H. Lenske, and U. Mosel, *ibid.* **72**, 015210 (2005).
 [8] B. Julia-Diaz, B. Saghai, T.-S. H. Lee, and F. Tabakin, *Phys. Rev. C* **73**, 055204 (2006).
 [9] M. Q. Tran *et al.*, *Phys. Lett. B* **445**, 20 (1998); K. H. Glander *et al.*, *Eur. Phys. J. A* **19**, 251 (2004).
 [10] R. Nasseripour *et al.*, *Phys. Rev. C* **77**, 065208 (2008).
 [11] N. Kaiser, T. Waas, and W. Weise, *Nucl. Phys. A* **612**, 297 (1997).
 [12] T. Inoue, E. Oset, and M. J. Vicente Vacas, *Phys. Rev. C* **65**, 035204 (2002).
 [13] J. Nieves and E. Ruiz Arriola, *Phys. Rev. D* **64**, 116008 (2001).
 [14] M. Döring and K. Nakayama, *Eur. Phys. J. A* **43**, 83 (2010).
 [15] M. Dugger *et al.*, *Phys. Rev. Lett.* **96**, 062001 (2006); **96**, 169905 (2006).
 [16] Xu Cao and X. G. Lee, *Phys. Rev. C* **78**, 035207 (2008).
 [17] M. Döring, E. Oset, and B. S. Zou, *Phys. Rev. C* **78**, 025207 (2008).
 [18] J. J. Xie, B. S. Zou, and H. C. Chiang, *Phys. Rev. C* **77**, 015206 (2008).
 [19] Xu Cao, J. J. Xie, B. S. Zou, and H. S. Xu, *Phys. Rev. C* **80**, 025203 (2009).
 [20] B. S. Zou, *Nucl. Phys. A* **835**, 199 (2010).
 [21] A. Zhang *et al.*, *High Energy Phys. Nucl. Phys.* **29**, 250 (2005).
 [22] C. S. An and B. S. Zou, *Eur. Phys. J. A* **39**, 195 (2009).
 [23] N. Isgur and G. Karl, *Phys. Rev. D* **18**, 4187 (1978).
 [24] R. H. Dalitz and S. F. Tuan, *Ann. Phys. (NY)* **10**, 307 (1960).
 [25] T. Inoue, *Nucl. Phys. A* **790**, 530 (2007).
 [26] E. Oset and A. Ramos, *Nucl. Phys. A* **635**, 99 (1998); E. Oset, A. Ramos, and C. Bennhold, *Phys. Lett. B* **527**, 99 (2002); J. A. Oller and U.-G. Meißner, *ibid.* **500**, 263 (2001); D. Jido, J. A. Oller, E. Oset, and U.-G. Meißner, *Nucl. Phys. A* **725**, 181 (2003); C. Garcia-Recio, J. Nieves, E. Ruiz Arriola, and M. J. Vicente Vacas, *Phys. Rev. D* **67**, 076009 (2003); T. Hyodo, S. I. Nam, D. Jido, and A. Hosaka, *Phys. Rev. C* **68**, 018201 (2003).
 [27] I. Zychor *et al.*, *Phys. Lett. B* **660**, 167 (2008).
 [28] L. S. Geng and E. Oset, *Eur. Phys. J. A* **34**, 405 (2007).
 [29] Y. Maeda *et al.*, *Phys. Rev. C* **77**, 015204 (2008).
 [30] C. Wilkin, *Acta Phys. Polon. Suppl.* **2**, 89 (2009).
 [31] J.-F. Germond and C. Wilkin, *Nucl. Phys. A* **518**, 308 (1990); J. M. Laget, F. Wellers, and J. F. Lecomte, *Phys. Lett. B* **257**, 258 (1991); T. Vetter, A. Engel, T. Biró, and U. Mosel, *ibid.* **263**, 153 (1991); E. Gedalin, A. Moalem, and L. Razzdolskaja, *Nucl. Phys. A* **650**, 471 (1999); M. Batinić, A. Švarc, and T.-S. H. Lee, *Phys. Scr.* **56**, 321 (1997); V. Bernard, N. Kaiser, and U.-G. Meißner, *Eur. Phys. J. A* **4**, 259 (1999); M. T. Peña, H. Garcilazo, and D. O. Riska, *Nucl. Phys. A* **683**, 322 (2001); G. Fäldt and C. Wilkin, *Phys. Scr.* **64**, 427 (2001); K. Nakayama, Y. Oh, and H. Haberzettl, *arXiv:0803.3169*.
 [32] R. Machleidt, K. Holinde, and C. Elster, *Phys. Rep.* **149**, 1 (1987).
 [33] K. Tsushima, S. W. Huang, and A. Faessler, *Phys. Lett. B* **337**, 245 (1994); K. Tsushima, A. Sibirtsev, and A. W. Thomas, *ibid.* **390**, 29 (1997).
 [34] B. S. Zou and F. Hussain, *Phys. Rev. C* **67**, 015204 (2003).
 [35] T. Feuster and U. Mosel, *Phys. Rev. C* **58**, 457 (1998); **59**, 460 (1999).
 [36] W. H. Liang *et al.*, *J. Phys. G* **28**, 333 (2002).
 [37] N. V. Shevchenko, A. Gal, and J. Mareš, *Phys. Rev. Lett.* **98**, 082301 (2007); N. V. Shevchenko, A. Gal, J. Mareš, and J. Révai, *Phys. Rev. C* **76**, 044004 (2007).
 [38] A. Baldini, V. Flaminio, W. G. Moorhead, and D. R. O. Morrison, *Landolt-Börnstein: Numerical Data and Functional Relationships in Science and Technology*, edited by H. Schopper (Springer-Verlag, Berlin/New York, 1988), Vol. 12.
 [39] J. Gillespie, *Final-State Interactions* (Holden Day, San Francisco, 1964).
 [40] A. Sibirtsev, J. Haidenbauer, and U.-G. Meißner, *Eur. Phys. J. A* **27**, 263 (2006).
 [41] A. Dzyuba *et al.*, *Phys. Lett. B* **668**, 315 (2008).
 [42] F. Balestra *et al.*, *Phys. Rev. C* **63**, 024004 (2001).
 [43] P. Winter *et al.*, *Phys. Lett. B* **635**, 23 (2006).
 [44] C. Quentmeier *et al.*, *Phys. Lett. B* **515**, 276 (2001).
 [45] L. Fabbietti and E. Eppele, *Nucl. Phys. A* **835**, 333 (2010).