

Formation of Strange Dibaryonic Resonance $X(2265)$ in $p + p \rightarrow K^+ + X$ reaction at $T_p = 2.5$ and 2.85 GeV

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Abstract. Analysis results of DISTO data on $pp \rightarrow p\Lambda K^+$ at $T_p = 2.50$ GeV are discussed in comparison with the previously reported $X(2265)$ resonance with $M_X = 2267$ MeV/ c^2 and $\Gamma_X = 118$ MeV found in the same reaction at 2.85 GeV. The yield at 2.5 GeV is found much less than that at 2.85 GeV (less than 10%). We discuss that this unexpectedly low yield is actually consistent with the nearly vanishing production yield of $\Lambda(1405)$ in the observed data and this can thus be indicating that $\Lambda(1405)$ plays an important role as a doorway state for the formation of $X(2265)$.

1 Introduction

1.1 Motivation

Hadronic systems with strange quarks, and in particular, attractive antikaon-nucleon interactions close to the threshold are very fruitful research fields to study antikaonic bound systems. The $\bar{K}N$ interaction is constrained mostly by the kaonic atom data, in particular by kaonic hydrogen x-ray measurements of the ground state level shift and width, and the kaon scattering data. $\Lambda(1405)$ is considered to be a K^-p bound state and gives another very important constraint. These constraints produce an attractive potential of the $\bar{K}N$ at below threshold, which subsequently leads to the prediction of kaonic nuclear bound states with anomalously high density [1].

The simplest kaonic nuclear bound system is a dibaryon system $(\bar{K}NN)_{S=0, I=1/2}$ often called K^-pp [2]. Several experimental searches have been performed [3–5]. It was predicted [6] that the K^-pp state could be populated substantially in a NN reaction due to a unique matching mechanism of a large momentum-transfer of the elementary process: $pp \rightarrow p\Lambda(1405)K^+$ with the high density nature of the K^-pp . This aspect is going to be discussed later in this report.

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1.2 The X(2265) resonance in the $pp \rightarrow p\Lambda K^+$ reaction at 2.85 GeV.

Recently we analyzed a set of the DISTO data for the exclusive reaction $pp \rightarrow p\Lambda K^+$ [7, 8] taken at an incident kinetic energy of $T_p = 2.85$ GeV, to search for a signature from a possible K^-pp state. We found [4] a broad resonance, which we call herein $X(2265)$, with a mass of $M_X = 2267$ MeV/ c^2 and a width of $\Gamma_X = 118$ MeV, in both the invariant-mass spectrum $M(p\Lambda)$ (Fig. 1) and in the missing mass spectrum $\Delta M(K^+)$, which are essentially equivalent provided that the events are purely exclusive.

The spectra are plotted in *DEV* unit, an efficiency-compensated presentation of the experimental data in which the ratio of *RAW/SIM* is evaluated bin by bin. Here the *SIM* represents event samples simulated for the $pK^+\Lambda$ final state according to a uniform phase-space distribution. The DISTO acceptance and the identical reconstruction and analysis procedures are applied to them. The *RAW* represents the experimental data without efficiency compensation.

This broad resonance is produced by a two-body process



which is followed by a decay of $X(2265)$ into $p + \Lambda$. This process is embedded in a more ordinary three-body process



It may be noted that indeed the "ordinary" reaction in Eq. 2 has the lowest threshold among strangeness production channels.

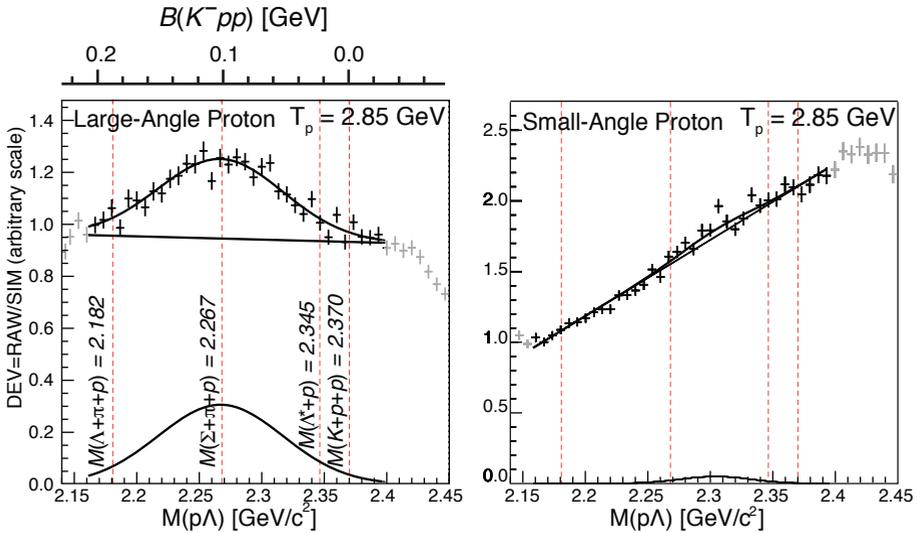


Figure 1. Invariant-mass spectra of the $pp \rightarrow p\Lambda K^+$ reaction at $T_p = 2.85$ GeV in an acceptance-compensated "Deviation" units with the Large-Angle-Proton cut (*LAP*, left) and the Small-Angle-Proton cut (*SAP*, right) [4, 9]. A broad resonance, $X(2265)$, that has a baryon number 2 and the strangeness -1 is seen with the *LAP* cut that suppresses the "ordinary" three body process.

A selection of events with protons emitted at large angle, i.e. $|\cos\theta_{cm}(p)| < 0.6 \equiv$ "*LAP*", efficiently enhances the two-body process, i.e. the $X(2265)$ formation. This is because protons in the

ordinary process which are dominating have the maximum momentum of p at 0.75 GeV/c and have a small transverse momentum ($P_T < 0.3$ GeV/c), whereas on the contrary protons in the two-body process involving the decay of X have a transverse momentum of about 0.4 GeV/c [4, 9].

Structureless flat distributions in $M(p\Lambda)$ with different slopes for LAP/SAP can be due to the three-body process (Eq. 2) following the calculation based on a simple reaction model as shown in Fig. 2 [10, 11].

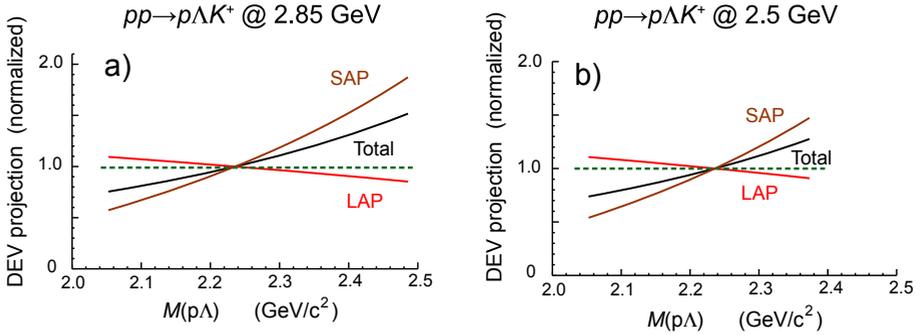


Figure 2. Calculated $M(p\Lambda)$ DEV spectra for the ordinary three-body process with two proton angle cuts (LAP/SAP) and without ($Total$) for the proton incident energy 2.85 GeV (left) and 2.5 GeV (right). The dashed lines are horizontal guide lines for phase space density. More detail of the calculation is found in Ref. [11].

2 Data at 2.5 GeV

In order to understand better the nature of $X(2265)$ we studied the entrance-channel behavior of the pp reaction by analyzing also the experimental data taken by DISTO at 2.5 GeV [11]. The same analysis criteria for the 2.85 GeV data are applied to evaluate the production of $X(2265)$ at 2.5 GeV. About 125k events were available at this beam energy whereas at 2.85 GeV about 177k events were analyzed. The data distributions are shown in Fig. 3. The invariant-mass spectra $M(p\Lambda)$ are flat for both proton angle cuts. The slopes are in agreement with the same theoretical calculation of the 2.85 case (Fig. 2 right). At this energy we therefore observed no clear sign of $X(2265)$ production.

3 Discussion

3.1 Relative $X(2265)$ yields

For a quantitative evaluation of the $X(2265)$ yield, here we introduce the quantity Y_X defined as the ratio of the area of the X signal and the $p\Lambda K^+$ background components in DEV units (Fig. 1,3),

$$Y_X(T_p) = \frac{\text{Peak}(= X) \text{ intensity in } DEV}{\text{BG}(= p\Lambda K^+) \text{ intensity in } DEV}. \quad (3)$$

The Y_X yield at each beam energy is estimated to be

$$Y_X(2.85) = 0.168 \pm 0.010, \quad (4)$$

$$Y_X(2.50) = 0.002 \pm 0.021. \quad (5)$$

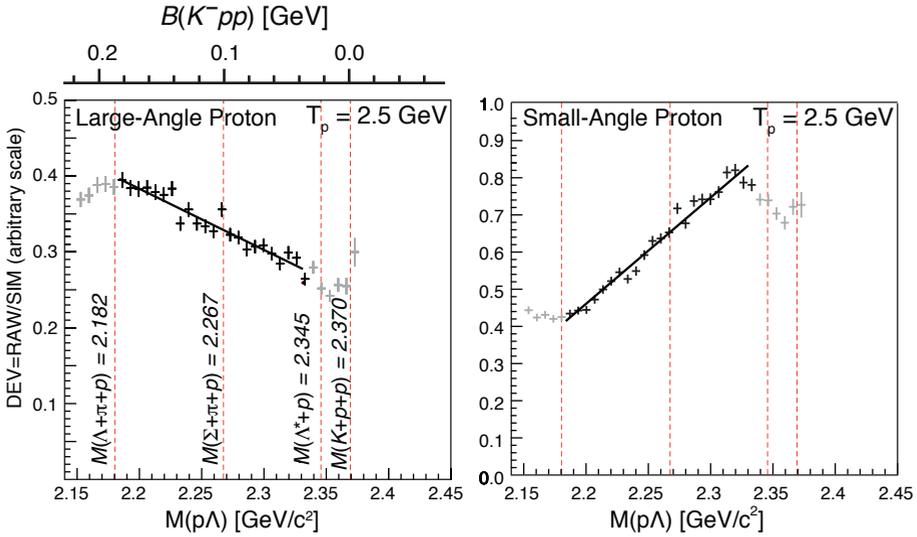


Figure 3. Invariant-mass spectra of $pp \rightarrow p\Lambda K^+$ reaction at $T_p = 2.5$ GeV in an acceptance-compensated "Deviation" units with the Large-Angle-Proton cut (left) and the Small-Angle-Proton cut (right) [4]. Contrarily to the data at 2.85 GeV we observed no clear sign of the production of $X(2265)$ for both proton angle cuts.

Thus the T_p dependence of Y is expressed by the ratio:

$$\frac{Y_X(2.50)}{Y_X(2.85)} = 0.012 \pm 0.125. \quad (6)$$

In order to obtain a yield ratio of X production at two energies, the above equation must be scaled by the cross section ratio of the BG process at the two energies. We estimated this ratio as described in the next section.

3.2 Energy dependence of the cross section for $pp \rightarrow pYK^+$ reactions

We consider now the energy dependence of the production cross sections of various strange particles in a $p + p$ reaction. Our goal here is to obtain *relative* cross section ratios of $T_p = 2.5$ GeV and 2.85 GeV, $\sigma(2.5)/\sigma(2.85)$. As our concern is the relative ratio, the issue is how to interpolate the excitation function between the threshold energy and 2.85 GeV. We refer to the semi-empirical universal formula of Sibirtsev [12] that is a function of the center-of-mass energy (\sqrt{s}) and to the single reaction threshold $\sqrt{s_0}$, expressed by

$$\sigma(s) = \sigma_0 \times \left(1 - \frac{s_0}{s}\right)^\alpha \times \left(\frac{s_0}{s}\right)^\beta \quad (7)$$

with two parameters, α and β , and a constant, σ_0 . This is basically consistent with what is expected from a simple phase-space dependence. Figure 4 shows this excitation functions with T_p in abscissa and with normalized ordinates, for the reactions $pp \rightarrow \Lambda p K^+$, $pp \rightarrow X(2265)K^+$, $pp \rightarrow \Lambda(1405)p K^+$. Those resonance states, $X(2265)$ and $\Lambda(1405)$, with finite widths are represented with masses $M = 2267$ MeV/ c^2 and 1405 MeV/ c^2 , respectively. The curves shown are for the best-fit parameters, $\alpha = 1.8$ and $\beta = 1.5$, which were found using the experimental data for Λ

(full circles) and Σ^0 (not shown in the figure) productions. The data points are taken from Landolt-Börnstein [13] for the data up to 1980's and new precise data come mainly from the COSY-TOF and COSY-11 experiments at COSY, FZ-Jülich [14–19].

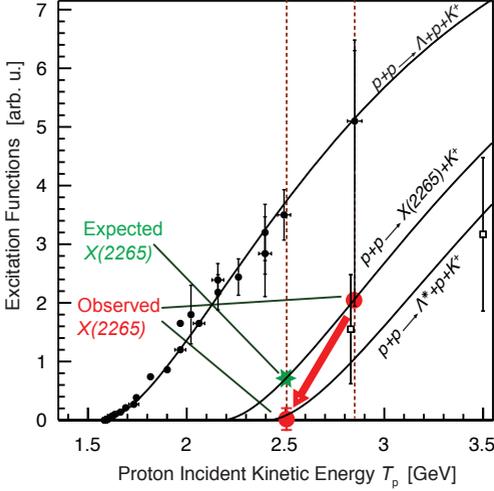


Figure 4. Normalized *relative* cross sections of the reactions $p + p \rightarrow p + \Lambda + K^+$, $p + p \rightarrow X(2265) + K^+$ and $p + p \rightarrow p + \Lambda(1405) + K^+$ as a function of the incident proton kinetic energy. The curves correspond to the universal formula (7) [12], on which known experimental points with error bars [13–19] are superimposed. The data for $\Lambda(1405)$ (open squares) production [20, 21] are also shown though their error bars are relatively large. The observed relative cross sections for $X(2265)$ at 2.50 and 2.85 GeV are shown by large red circles, and the expected one at 2.50 GeV is shown by a green star. This indicates that the present observation is significantly different from the prediction for the $X(2265)$ production by the universal curve.

Using these parameters we derive a cross section ratio of the BG reaction Eq. 2 as

$$\frac{\sigma_{pp \rightarrow p\Lambda K^+}(2.5)}{\sigma_{pp \rightarrow p\Lambda K^+}(2.85)} = 0.72. \quad (8)$$

The peak-to-background ratios, $Y_X(T_p)$, are then scaled by this cross section ratio. So the ratio of the cross section for $X(2265)$ at 2.50 and 2.85 GeV is obtained:

$$\begin{aligned} R_X^{\text{obs}} &= \frac{\sigma_X(2.50)}{\sigma_X(2.85)} = \frac{Y_X(2.50)}{Y_X(2.85)} \times \frac{\sigma_{p\Lambda K}(2.50)}{\sigma_{p\Lambda K}(2.85)} \\ &= 0.009 \pm 0.091. \end{aligned} \quad (9)$$

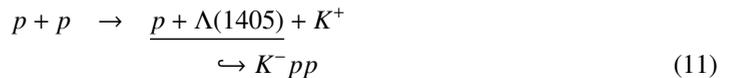
However, if we estimate the cross section ratio of the $X(2265)$ at 2.5 GeV and 2.85 GeV from Eq. 7 as shown in Fig. 4, we obtain

$$R_X^{\text{expected}} = \frac{\sigma_X(2.50)}{\sigma_X(2.85)} \approx 0.33 \quad (10)$$

and this is clearly not consistent with the observed value. To be consistent with the error bar, we consider an upper limit including one standard deviation, that is, $R_X^{\text{obs}} < 0.10$. Note that, the peak yield, $Y_X(T_p)$, inferred from a *DEV* spectrum, is already acceptance corrected.

3.3 Production of $\Lambda(1405)$ at 2.85 GeV and 2.5 GeV

One possibility to explain the discrepancy between the observed (Eq. 9) and expected (Eq. 10) $X(2265)$ production cross section ratios at two energies is suggested in Ref. [6]. They discuss a production mechanism of the $K^- pp$ state in the $p + p$ collision through



and point out the role of the $\Lambda(1405)$ as a doorway state, which would mean a very high $\Lambda(1405)p \rightarrow K^-pp$ sticking probability despite a large Q-value of the reaction, on the order of ~ 1.6 GeV/c. The distance of $\Lambda(1405)$ to p would be short when it is created in a short-range pp interaction and the relative momentum would be large. It is said that this is the desired condition for the $\Lambda(1405)$ and p to coalesce and form the K^-pp bound state if the K^-pp is small-sized and has high density as anticipated.

We therefore examine the production of $\Lambda(1405)$ at 2.5 GeV as following. First we can obtain the expected ratio using the Eq. 7 and Fig. 4 that leads

$$R_{\Lambda(1405)} = \frac{\sigma_{\Lambda(1405)}(2.50)}{\sigma_{\Lambda(1405)}(2.85)} \approx 0.1, \quad (12)$$

though here the finite width of $\Lambda(1405)$ is not taken into account. We can confirm nonetheless the very low production rate of $\Lambda(1405)$ with the real data. Fig. 5 shows the missing-mass spectra $\Delta M(pK^+)$ at $T_p = 2.85$ and 2.50 GeV. The $\Delta M(pK^+)$ spectrum at 2.85 GeV shows peaks at masses of Λ , Σ^0 , and an unresolved peak of $\Sigma^0(1385) + \Lambda(1405)$. The $\Delta M(pK^+)$ spectrum at 2.50 GeV is overlaid with the 2.85 GeV spectrum with its scale normalized with the height of the Λ peak. One can see clearly the higher-mass Σ^0 hyperon is less populated at 2.5 GeV compared with the one at 2.85 GeV. This tendency is more pronounced, i.e. less produced, for the excited hyperons. It is to be noted that the tail of the combo peak of $\Delta M(pK^+)$ does not exceed 1.4 GeV/c². The momentum distributions of the two particles, p and Λ , are then examined to prove that the momentum acceptance for $\Delta M(pK^+)$ is flat at both incident energies. Thus, the cut-off of the missing-mass spectrum $\Delta M(pK^+)$ at 1.4 GeV/c² for $T_p = 2.50$ GeV is not to be due to the momentum acceptance of the p and K^+ . Since there is an ambiguity in decomposing these excited hyperon peaks, we cannot give a quantitative estimation here, however, we could confirm that the $\Lambda(1405)$ production rate is considerably small at 2.5 GeV.

If we follow this scenario that $\Lambda(1405)$ plays a key role as a doorway to produce the K^-pp state, and if the $X(2265)$ resonance is to be identified as K^-pp , then the non-observation of the $X(2265)$ resonance despite what is expected from a kinematical consideration can be justified and can therefore suggest that $X(2265) \equiv K^-pp$ is a dense compact system.

4 Summary

In summary, we studied the incident beam energy T_p dependence of $X(2265)$ production in $p + p \rightarrow X(2265) + K^+$ reaction and found that the formation cross section at 2.50 GeV is much less than at 2.85 GeV. This result is inconsistent with the expectation from a simple kinematical consideration treating the $X(2265)$ as any other object created in a pp collision. On the other hand, since the formation of the $\Lambda(1405)$ resonance drops down at 2.50 GeV, if this particle is really a doorway to produce the kaonic nuclear bound states [2, 6] and the formation of $X(2265)$ is also suppressed at 2.50 GeV.

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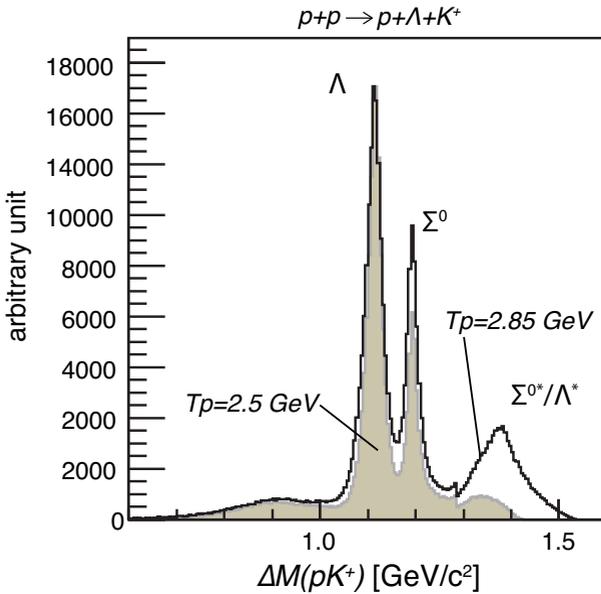


Figure 5. Comparison of missing-mass $\Delta M(pK^+)$ spectra of the $pp \rightarrow p\Lambda K^+$ reaction at $T_p = 2.85$ GeV (solid histogram) and 2.50 GeV (shaded) normalized to the numbers of observed Λ 's.

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