On the $\Lambda$ to $\Sigma^0$ ratio from proton-proton collisions

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We compare the recent COSY data on the total $pp\to p\Lambda K^+$ and $pp\to p\Sigma^0 K^+$ cross sections with the predictions from two boson exchange models that either are based solely on $\pi$ and $K$ exchange or include $\pi$, $\eta$ and $\rho$ exchange as well as the virtual excitation of intermediate baryon resonances. Both models are found to reproduce the data after the inclusion of final state hyperon-nucleon interactions. Thus, within the experimental uncertainties, both models also roughly reproduce the strong dependence of the $\Lambda$ to $\Sigma^0$ ratio as a function of the excess energy near threshold, as well as at higher energies.

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Recently the total $pp\to p\Lambda K^+$ and $pp\to p\Sigma^0 K^+$ cross sections have been measured at the COoler SYnchrotron (COSY) at invariant collision energies $\sqrt{s}$ near the production threshold. It was observed that the ratio, $R$, of the cross sections for $\Lambda$ and $\Sigma$ production at the same excess energies, $\epsilon=\sqrt{s}-m_p-m_Y-m_K<13$ MeV, varies from about $20 - 30$ at threshold to $R\approx 2.5$ at high energies, $\epsilon\geq 1$ GeV. As a possible explanation it has been suggested that this large ratio close to threshold might arise from a strong $\Sigma\to\Lambda$ conversion by the final state interaction.

Very recently the $\Lambda$ to $\Sigma^0$ ratio from $pp$ collisions was studied in Ref. [5]. It was found that the experimentally observed suppression of the ratio of $\Sigma^0$ to $\Lambda$ hyperon production may be explained, at least in the region up to 15 MeV above threshold, by a destructive interference between the pion and kaon exchange.

To make a further investigation of these remarkable features, we consider here two types of boson exchange models, that have both been used quite often in the analysis of strangeness production in nucleon-nucleon interactions. To get more insight into the dynamics we compare the model calculations simultaneously with the $pp\to p\Lambda K^+$ and $pp\to p\Sigma^0 K^+$ cross sections as a function of the excess energy, $\epsilon$. Furthermore, to obtain a more decisive conclusion we perform the calculations with the model parameters as they were fixed some years ago in Refs. [6–8], rather than adjusting these parameters again. This also provides a crucial test of the predictive power of these models.

We recall that the $\pi+K$-exchange model leads to strangeness production through $\pi$ and $K$-meson exchanges, with the $\pi N\to Y K$ and $KN\to KN$ scattering amplitudes (cf. Fig. 1a) evaluated from the data [4]. The coupling constant and the form factor (FF) at the $NN\pi$ vertex were taken from the Bonn-Jülich model [7], while the parameters at the $NYK$ vertex were fitted to $pp\to NYK$ data at $\epsilon\geq 1$ GeV. Because of the lack of data, the interference between the $\pi$ and $K$-meson could not be unambiguously fixed and for simplicity was neglected. For further details of the model and its explicit expressions we refer the reader to Ref. [6].

The predictions of this model for the $pp\to p\Lambda K^+$ and $pp\to p\Sigma^0 K^+$ cross sections are shown by the dashed lines in Fig. 2 together with the data from Ref. [4](squares) and the recent data (circles) from COSY [1–3]. The calculations describe the experimental results reasonably well.
Figure 1. The diagrams for $pp \rightarrow N \Lambda K$ reactions in the $\pi + K$-exchange model (a) and within the resonance model (b).

Figure 2. The $pp \rightarrow p \Lambda K^+$ (a) and $pp \rightarrow p \Sigma^0 K^+$ (b) cross sections as a function of the excess energy $\epsilon$. The circles show the data from COSY [1–3] while the squares are from Ref. [4]. The lines show the calculations within the $\pi + K$-exchange model with (solid) and without (dashed) FSI.

The parameters of the $RYK$ and $RN\pi$ vertices in Fig. 1b were fixed [16] using the $\pi N \rightarrow \Lambda K$ and calculations including FSI. Clearly the calculation describes the $pK^+\Lambda$ channel remarkably well, while the $pK^+\Sigma^0$ cross section is slightly overestimated very close to threshold. This might also be attributed to an uncertainty in the $\Sigma^0p$ s-wave scattering parameters, $a_s$ and $r_s$.

On the other hand, the resonance model [8] generates strangeness production by $\pi$, $\eta$ and $\rho$-meson exchange with the excitation of intermediate baryon resonances, $R (N(1650), N(1710), N(1710)$ and $\Delta(1920))$ (cf. Fig. 1b), which can couple to the $\Lambda K$ and $\Sigma K$ states [13].
\(\pi N \rightarrow \Sigma K\) data from Ref. [4], which were available prior to the COSY data. The couplings and formfactors at the \(NN\pi\), \(NN\eta\), \(NN\rho\), \(RN\eta\) and \(RN\rho\) vertices were either taken from Ref. [10] or fitted [8] to the \(pp\rightarrow NYK\) data at high energies, \(\epsilon \geq 1\) GeV. Note again, that the baryonic resonance couplings are well controlled by the presently available resonance properties [15].

The resonance model calculations for the \(\Lambda\) and \(\Sigma^0\) channel without FSI are shown by the dashed lines in Fig. 3, while the solid lines show the resonance model results obtained with the same FSI [8] as in Fig. 2.

Keeping in mind that the parameters for both versions of the boson exchange models were not adjusted to the recent data [2] we conclude that the agreement between the model predictions [6–8] and the experimental results [1–3] is quite reasonable. It is important to note that both calculations reproduce simultaneously the data at low and high energies. Since both models were originally fixed at high energy, one might conclude that the cross sections at low energy are a strict consequence of the underlying reaction mechanism.

Figure 3. The \(pp\rightarrow p\Lambda K^+\) (a) and \(pp\rightarrow p\Sigma^0 K^+\) (b) cross sections as a function of the excess energy \(\epsilon\). The circles show the data from COSY [3] while the squares are from Ref. [4]. The lines show the calculations within the resonance model with (solid) and without (dashed) FSI.

Figure 4. The ratio of the \(pp\rightarrow p\Lambda K^+\) and \(pp\rightarrow p\Sigma^0 K^+\) cross sections as a function of the excess energy \(\epsilon\). The circles show the data from COSY [3], while the squares are from Ref. [4]. The lines show the results with (solid) and without (dashed) FSI calculated by the \(\pi+K\)-exchange (upper part) and the resonance model (lower part).

The parameters of the \(\pi+K\)-exchange model were fixed in 1995 [6], while the resonance model parameters were fixed in 1997 [8] – i.e., before the appearance of any near threshold COSY data [1–3].
Finally, the data on the $\epsilon$-dependence of the ratio of $pp \rightarrow p\Lambda K^+$ to $pp \rightarrow p\Sigma^0 K^+$ cross sections are shown in Fig. 4 together with the results from the $\pi + K$-exchange (upper part) and the resonance model (lower part). The dashed lines show the results obtained without FSI while the solid lines indicate the calculations with FSI. The comparison in Fig. 4 is given using a linear scale for $R$ and within about two experimental errors bars the agreement between data and calculations is reasonable. Apparently, by adjusting the coupling constants and cut-off parameters of the formfactors one can obtain a much better description of the data which, however, is not the aim of our present investigation.

Our results indicate that the strong variation of the ratio $R$ with the excess energy $\epsilon$ should not be considered as an extraordinary feature of the strangeness production process since the two different approaches, fixed some years ago at high energy, are obviously able to reproduce the data to better than a factor of 2. This finding also shows that the present data on the total cross sections are not sensitive to the details of the model and that it is still not possible to fix the explicit contribution from the kaon exchange channel, which is of fundamental interest.

We point out that a fully self-consistent model should include all available $\pi, \eta, \sigma, \rho, K$ and possibly $K^*$ and higher mass mesonic exchanges as well as the excitation of all available intermediate baryonic resonances and the direct kaon emission processes. The large number of parameters involved in such a model might be fixed using the $NN \rightarrow NY K$ data. However, this would require a larger number of experimental points than presently available.

In spite of these comments, the theoretical progress resulting from the new COSY data is significant. The role of FSI, as well as a direct experimental evaluation of the hyperon-nucleon interaction parameters from the data, can now be well understood phenomenologically. This is an important step for further theoretical and experimental analysis of differential cross section data on strangeness production in nucleon-nucleon collisions.

More detailed constraints on the theory can be obtained from differential cross section data at higher excess energies. It is crucial that the contribution from $K$-meson exchange may be directly investigated from polarization measurements as argued in Ref. [8], or by a partial wave decomposition of the Dalitz representation as advocated in Ref. [9]. The separation of the kaon exchange contribution would provide information on the $NY K$ coupling constants, which could be compared with the $SU(N)$ symmetry predictions and other experimental determinations.

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