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The measurement of the $pp \to K^+ n \Sigma^+$ reaction near threshold

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ABSTRACT

It is shown that a recent extraction of the total cross section for $pp \to K^+ n \Sigma^+$ from inclusive K^+ production data by the HIRES Collaboration [Phys. Lett. B 692 (2010) 10] is in conflict with experimental data on the exclusive $pp \to K^+ p \Lambda$ reaction. The HIRES result may be interpreted as an upper bound, which is not inconsistent with the much lower values that already exist in the literature.

Two recent measurements of the total cross sections for the $pp \to K^+ n \Sigma^+$ reaction close to threshold at COSY-ANKE [1,2] and COSY-HIRES [3] have given conflicting results. It is the purpose of this short Letter to suggest reasons for this discrepancy.

Following an initial study at the COSY-ANKE spectrometer at an excess energy of $\varepsilon = 129$ MeV [1], data on $pp \to K^+ n \Sigma^+$ were obtained at four energies closer to threshold [2]. This was achieved by measuring in parallel coincidence spectra from K^+-proton and $K^+\pi^+$ pairs, the latter being especially convincing because at low energies they can only arise from Σ^+ production. The results could be checked by studying the ratio of inclusive K^+ production in pp collisions just above to just below the Σ^+ threshold. The three methods gave consistent answers and showed production cross sections that were slightly smaller than those of $pp \to K^+ p \Sigma^0$, with $R(\Sigma^+/\Sigma^0) \approx 0.7 \pm 0.1$. The energy variation found was consistent with a phase-space dependence, with no evidence for a strong $\Sigma^+ n$ final state interaction (FSI).

In an alternative approach, the COSY-HIRES Collaboration [3] measured with high resolution the forward inclusive production of K^+ mesons in proton–proton collisions at a single beam momentum of $p = 2.870$ GeV/c, corresponding to an excess energy for Σ^+ production of $\varepsilon = 102.6$ MeV. Following a procedure developed earlier [4], they claimed that, after the subtraction of an assumed excitation function for the Λ channel, their results showed that $R(\Sigma^+/\Sigma^0) \approx 5 \pm 1$. However, the extraction of a $pp \to K^+ n \Sigma^+$ cross section from such data is not straightforward because, due to the mass difference, the available phase space is much larger for Λ production. Furthermore, even at the same excess energy the cross section for Σ^0 production is typically over an order of magnitude smaller than that of the Λ [5].

The above difficulties are compounded by the strong coupling between the ΣN and Λp channels, which can lead to a cusp in the Λp spectrum at the ΣN threshold. A spectacular example of this is seen in the $K^- d \to \pi^- \Lambda p$ reaction [6]. However, because such effects are sensitive to the interference between direct Λp production and that proceeding via the formation of a virtual ΣN pair, the form of the Λp spectrum can vary greatly from one reaction to another. This is illustrated by the comparison of pion photoproduction near the ηp threshold, with very contrasting structure being seen in the $\gamma p \to \pi^+ n$ and $\gamma p \to \pi^0 p$ cross sections [7]. It is the purpose of this Letter to point out that new exclusive data on $pp \to K^+ p \Lambda$, obtained at the COSY Time-of-Flight spectrometer (COSY-TOF) [8], show an anomalous behaviour near the ΣN threshold. The particular form of this undermines the assumptions inherent in the COSY-HIRES analysis [3] and suggests that their value for the $pp \to K^+ n \Sigma^+$ total cross section should be interpreted only as an upper limit.

Inclusive K^+ production in proton–proton collisions was studied with the SPES4 spectrometer at SATURNE at fixed non-zero laboratory angles [9]. Clear evidence was there obtained for a strong rise in the $pp \to K^+ X$ differential cross section in the vicinity of the ΣN threshold. These studies were taken up later at the Big Karl spectrometer, which was situated on an external beam line

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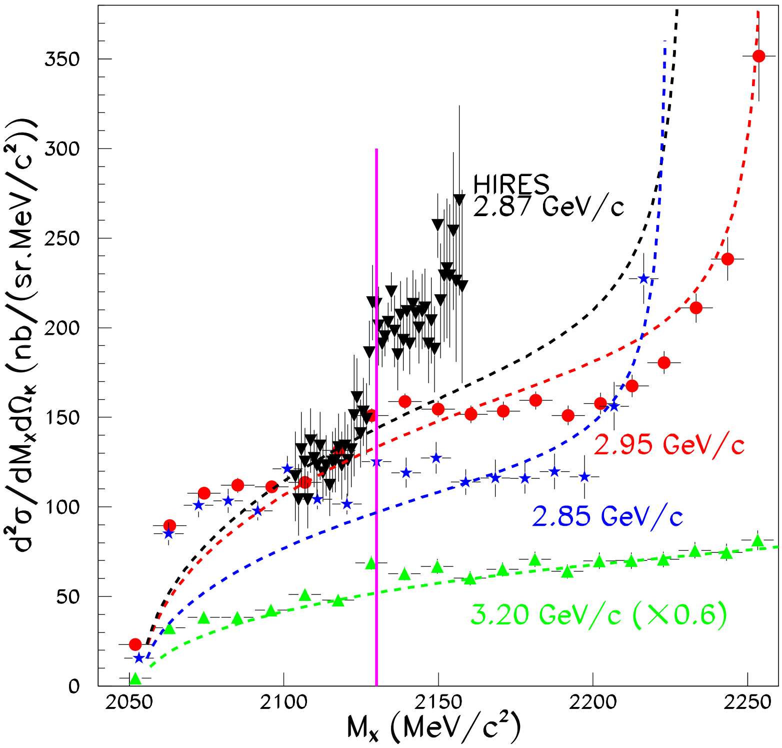

Fig. 1. Forward inclusive cross section for $pp \to K^+X$ as a function of the missing mass M_X in the reaction. The HIRES data at a beam momentum of 2.87 GeV/c (inverted triangles) [3] were directly measured. The COSY-TOF data at 2.85 (stars), 2.95 (circles), and 3.20 GeV/c (triangles) were derived from exclusive $pp \to K^+p\Lambda$ measurements [13, 8] under the assumption that the distributions are isotropic in the K^+ c.m. angle. For clarity of presentation, the scale is limited to represent the full data set at 2.95 GeV/c, and the 3.20 GeV/c data have been reduced by a factors of 0.6. The vertical line indicates the position of the average Σ^+n/Σ^0p threshold. Also shown are three-body phase-space distributions (dashed lines) corresponding to the $pp \to K^+p\Lambda$ reaction, arbitrarily normalised at each momentum.

of the COSY accelerator. Working only in the forward direction, the HIRES Collaboration [3,10] obtained a better missing-mass M_X resolution than that of the SPES4 experiment. They could also determine quite accurately the absolute value of M_X and hence its relation to the ΣN threshold. The resulting forward differential cross sections are presented in Fig. 1 as a function of M_X.

The strong rise in the cross section in Fig. 1, which starts well below the ΣN threshold, must be associated with Λ production that is driven by coupled channel effects. The SPES4 data could be described in a phenomenological meson-exchange model by Laget [11], though the resultant structure in the threshold region is quite complex and his assignment of the production strength into different channels above the ΣN threshold is very model-dependent. There is also the possibility of fine structure, with a double cusp arising from the differences between the Σ^0p and Σ^+n thresholds [12].

Although these HIRES data are very detailed, their interpretation is contentious. It is assumed, without independent evidence, that the structure of the $pp \to K^+p\Lambda$ cusp contribution is a simple Breit–Wigner form with a full width of ≈ 6 MeV/c^2. It is further hypothesised that, away from the near-threshold region, the differential cross section for $pp \to K^+p\Lambda$ is essentially the same to the left and right of the ΣN threshold, in marked contrast even to the phase-space behaviour, shown by the dashed lines in Fig. 1. The inevitable consequence of these assumptions is that the excess of cross section to the right of the near-threshold region must be assigned to Σ production. However, since it is known that Σ^0 production through $pp \to K^+p\Sigma^0$ is relatively modest, this would have to be compensated by a large value for the $pp \to K^+n\Sigma^+$ cross section.

Fortunately, exclusive COSY-TOF data on the $pp \to K^+p\Lambda$ reaction allow us to test the hypothesis underpinning this analysis. Results on the Dalitz plots and $p\Lambda$ invariant masses have been provided at 2.75 and 2.85 GeV/c [13] and very recently at 2.95, 3.2 and 3.3 GeV/c [8]. The most prominent feature of the Dalitz plots is the band associated with the excitation of the $N^*(1650)$ [8,13]. In addition, though the data at 2.75 and 2.85 GeV/c [13] have relatively large fluctuations, both show structure at the ΣN threshold. However, the authors note that “the precision of the data is not sufficient to draw any conclusion on this”. On the other hand, the new results at 2.95, 3.20, and 3.30 GeV/c, confirm presence of the structure in the vicinity of the Σ production threshold [8]. The most pronounced effect is observed in the 2.95 GeV/c data set, which has the largest statistics.

Because the TOF spectrometer has a very large acceptance, the data obtained with it are spread over the whole of the three-body phase space and it is not meaningful to try to extract results with a small K^+ angular cut. However, after summing over all Λp invariant masses $M_{\Lambda p}$, it is found that globally the K^+ angular distribution is rather isotropic, whereas those in the proton and Λ show peaking towards the forward/backward directions [14]. The HIRES analysis [3] goes a little further than this in that it is there assumed that the cross section is independent of the K^+ c.m. angle for all values of M_X. This plausible assumption allows them to derive total cross sections from the values of the forward K^+ differential cross sections. By the same token, it allows us to estimate forward K^+ differential cross sections from the angle-integrated exclusive COSY-TOF data [8] and the results of doing this at 2.85, 2.95 and 3.20 GeV/c are shown in Fig. 1 [15].

Also shown in the figure are $pp \to K^+p\Lambda$ phase-space distributions corresponding to the HIRES and the three COSY-TOF momenta, each being arbitrarily normalised. For clarity, the presentation is optimised for the 2.95 GeV/c data, while the data collected at 3.20 GeV/c has been scaled by a factor of 0.6. It is very important to note that, for kinematic reasons, the phase-space distributions increase strongly with M_X. The effect of this in the ΣN threshold region becomes more marked as the beam momentum is reduced and the maximum missing mass gets closer. The rapidly varying phase space changes the peak seen in the 2.95 GeV/c COSY-TOF angle-integrated cross section [8] into a smeared step function in the forward laboratory cross section of Fig. 1.

The statistics of the COSY-TOF data and the inherent resolution lead to a much wider binning than that used for the HIRES results but a rise in the cross section around the ΣN threshold is clear in their most extensive data set at 2.95 GeV/c. In addition to the kinematic effect discussed above, this might be influenced by the overlap of the $N^*(1650)$ with the ΣN threshold region then representing a large fraction of the Dalitz plot. The situation for the 2.85 GeV/c data in Fig. 1 is less clear due to the much lower statistics and hence the larger fluctuations.

The HIRES data at 2.87 GeV/c show a lot of similarities to the COSY-TOF results at 2.95 GeV/c and some of the residual differences might be due to the 80 MeV/c offset in beam momentum and the normalisation uncertainties, as well as the K^+ isotropy assumption. In both cases the sharp rise in the cross section starts at about 10 MeV/c^2 below the ΣN threshold and the cross sections stay high well to the right of the threshold. To quantify this, let us consider the change in the cross sections in the stable regions from the left to the right of the threshold. The increase for the HIRES inclusive data is ≈60% whereas for the COSY-TOF exclusive results at 2.95 GeV/c the change is closer to ≈40%. However, it should be noted that a 40% rise in the forward $pp \to K^+p\Lambda$ cross section from 2110 to 2160 MeV/c^2 is not very different from that which is predicted at 2.95 GeV/c on the basis of phase space, as shown in Fig. 1. The channel coupling seems merely to sharpen up the steady phase-space rise in this representation.

Although the HIRES 2.87 GeV/c and the COSY-TOF 2.95 GeV/c data themselves look somewhat similar, the interpretation offered is starkly different. The HIRES group assumed that the differential cross section for $pp \to K^+p\Lambda$ is essentially the same on the left and right of the ΣN threshold. This is in flat contradiction to the COSY-TOF *exclusive* $pp \to K^+p\Lambda$ data which show, at a close beam momentum, that Λ production does not drop to the pre-existing level once the ΣN threshold has been passed. As a consequence, a large fraction of what the HIRES Collaboration has ascribed to Σ production might be Λ production, whose shape does not resemble phase space.

The COSY-TOF data at 2.85 GeV/c [13] are much closer in momentum to the HIRES results at 2.87 GeV/c but, unfortunately, they are subject to much larger fluctuations. Whereas simulations based on the HIRES ansatz show moderate consistency away from the regions of the $p\Lambda$ final-state interaction and Σ production threshold [10], this approach fails badly for the high statistics data set at 2.95 GeV/c collected later by the same experimental group [8].

Without a clear understanding of the coupled-channel effects or detailed experimental data on $pp \to K^+p\Lambda$ at the HIRES beam momentum, it is not possible to deduce a model-independent cross section for Σ production from inclusive K^+ data, even if one accepts that this is isotropic in the c.m. system. Any uncertainty in the Λ production cross section is reflected directly as a systematic error in the Σ cross section. The HIRES analysis [3] assumes that, away from a narrow region around the ΣN threshold, the laboratory cross section for Λ production in Fig. 1 is constant over their range of missing masses. However, the COSY-TOF data [8] show that Λ production generally increases over this region and that the rise through the ΣN threshold is even sharper than phase space. As a consequence the HIRES analysis probably provides an upper bound on the cross sections for ΣN production, i.e. $R(\Sigma^+/\Sigma^0) < 5 \pm 1$. Although this is sufficient to rule out the early results of the COSY-11 group [16] by a large factor, it is of limited value because the already published COSY-ANKE paper presented the much lower figure of $R(\Sigma^+/\Sigma^0) = 0.7 \pm 0.1$ by using three different experimental techniques at several energies [2].

To show the sensitivity of the HIRES analysis to the assumed threshold behaviour, if the excess to the right of the ΣN threshold in Fig. 1 were reduced from 60% to 20% to take account of the $pp \to K^+p\Lambda$ jump found in the COSY-TOF data [8], one would conclude that the total cross sections for $pp \to K^+n\Sigma^+$ and $pp \to K^+p\Sigma^0$ would be broadly similar. This would not be inconsistent with the COSY-ANKE findings [2].

In conclusion, we have demonstrated that the methodology used in the HIRES analysis to deduce a cross section for Σ^+ production in proton–proton collisions is not robust. Without further information, it is impossible to quantify the error associated with the assumption regarding the behaviour of the forward laboratory cross section for Λ production. Reliable results can only be achieved through measurements that are more exclusive.

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