Comparison of Λ and Σ^0 threshold production in proton-proton collisions

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Threshold measurements of the associated strangeness production reactions $pp \to pK^+\Lambda$ and $pp \to pK^+\Sigma^0$ are presented. Although slight differences in the shapes of the excitation functions are observed, the most remarkable feature of the data is that at the same excess energy the total cross section for the Σ^0 production appears to be **about** a factor of 28 smaller than the one for the Λ particle. It is concluded that strong $\Sigma^0 p$ final state interactions, and in particular the $\Sigma N \to \Lambda p$ conversion reaction, are the likely cause of the depletion for the yield in the Σ signal. This hypothesis is in line with other experimental evidence in the literature.

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At COSY - Jülich the "COSY-11" collaboration studies the production of strangeness in proton-proton scattering at threshold, using an internal cluster target facility [1]. Here we report on experimental data for the reactions: $pp \to pK^+\Lambda$ and $pp \to pK^+\Sigma^0$ at excess energies $Q = \sqrt{s} - m_p - m_{K^+} - m_{\Lambda(\Sigma)} \leq 12.9$ MeV. In this region low partial waves are expected to dominate.

In the non-perturbative domain of COSY energies, and especially in the threshold region, the physics of strangeness production is most appropriately described in terms of meson exchange. In such models both strange and non-strange exchanges with or without intermediate resonance excitation can occur. In addition to the commonly considered π and K exchange contributions, see e.g. Refs [2] - [5], the exchange of heavier non-strange and strange mesons [6] and their interference effects might have an influence on the strangeness production process. Effects of coupling constants, resonances and final state interaction (FSI) might become visible when comparing different final states like the ΛpK^+ and the $\Sigma^0 pK^+$ channels. For instance, the ratio of the coupling constants $g^2_{\Lambda NK}/g^2_{\Sigma NK}$, as extracted from different reactions involving hyperons, varies between 0.08 and 27 [3] - [5], [7] - [13]. As a consequence, model predictions of Λ and Σ^0 production cross sections differ significantly.

The COSY-11 facility, described in detail in Ref. [14], allows one to measure the four-momenta of the proton and K^+ directly, leaving the uncharged hyperon to be identified using the missing mass method. A regular COSY-dipole magnet, placed downstream of the target, separates the reaction products with momenta different from that of the circulating beam. Two drift chambers detect the directions of the particles and enable a momentum determination by ray tracing back through the known magnetic field into the target. Particle identification is then performed by measuring the time of flight between start and stop scintillators.

The main goal of the present investigation was to measure the Σ^0 production and to compare it with Λ production near threshold. Here we report on the measurement of the total cross section for $pp \to pK^+\Sigma^0$ at seven energies in the range $3.0 < Q < 12.9$ MeV. In the Λ case, we have already presented seven data points from $Q = 0.68$ to 6.68 MeV [15], and we here extend this range also to 12.9 MeV through the addition of three extra points. COSY was used in the "supercycle" mode, which allows a repetition of a sequence of spills with different parameters from spill to spill.

In view of the large cross section difference between the production of the two hyperons, 10 or 20 spills at beam momenta equivalent to excess energies $Q = 7.7$ MeV, 10.5 MeV, and 12.9 MeV above the Σ^0 threshold were followed by one spill at the equivalent Q-values above the Λ threshold. The spill length was five minutes and the sequence was repeated for a total running time of two to three days for each beam momentum. The supercycle mode compares two similar processes under similar conditions, thus reducing possible errors due to shifts in accelerator and/or detector components.

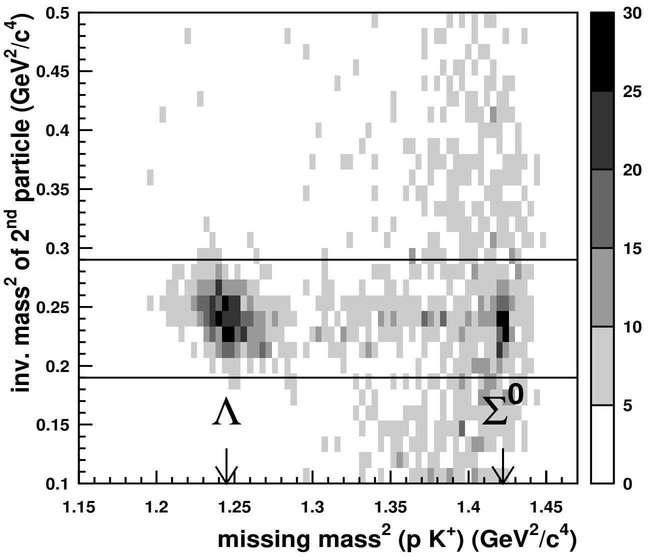

Figure 1: Square of the mass of the second particle *versus* square of the missing mass, after identification of the first particle as being a proton. Data shown are at an excitation energy of $Q_{\Sigma^0} = 12.9$ MeV. The horizontal solid lines indicate the limits of the K^+-band assumed. The much more populated π^+ and proton bands are off the figure.

To isolate hyperon production in the presence of a large background, all the two-track events, which are candidates for K^+ and p, were selected from the raw data. After the determination of the four-momentum vector $(E,\ \vec{p})$ of both particles, the missing mass was calculated. In Fig. 1,

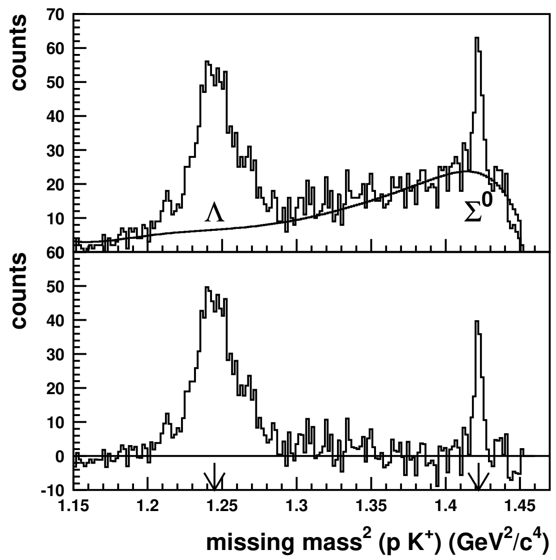

Figure 2: Top: Spectrum of missing mass squared for the reaction $pp \to pK^+X$ at a beam momentum equivalent to Q = 12.9 MeV with respect to the Σ^0 production threshold. The solid line indicates the smoothed background distribution obtained by projecting bands above and below the K^+-band of Fig. 1.
Bottom: Spectrum after background subtraction. Equivalent spectra for the measurements close to the Λ threshold can be seen in Ref. [15].

the square of the mass (m_{inv}) of the lighter particle is plotted *versus* the square of the missing mass. A clear K^+-band is apparent, with enhancements at the positions of the Λ and the Σ^0 -masses.

The projection onto the missing mass axis of the band between the two indicated lines is shown in the upper part of Fig. 2. The summed projection of adjacent bands in Fig. 1 (m^2_{inv} = 0.1 – 0.19 GeV^2/c^4 and m^2_{inv} = 0.29 – 0.34 GeV^2/c^4) is considered as representative of the background spectrum which, after normalising and smoothing to minimize statistical fluctuations, is shown as the solid curve in the figure. Subtracting this background from the missing mass spectrum results in the lower part of Figure 2, which shows clear Λ and Σ^0 peaks. The sharpness of the latter is a kinematic effect due to the proximity to the threshold and the same effect is seen in the corresponding spectra close to the Λ threshold [15].

nominal Excess energy Q (MeV)	extracted excess energy	$pp \to pK^+\Sigma^0$ cross section (nb)	extracted excess energy	$pp \to pK^+\Lambda$ cross section (nb)	$\frac{\sigma_T(pp\to pK^+\Lambda)}{\sigma_T(pp\to pK^+\Sigma^0)}$
3.0	2.8	1.6 ± 0.5			
5.0	5.5	5.7 ± 0.8			
7.0	7.5	8.6 ± 2.1			
7.7	8.0	9.7 ± 2.0	8.6	344 ± 41	35 ± 15
10.0	11.1	17.5 ± 3.8			
10.5	10.3	12.8 ± 2.4	10.9	385 ± 27	30 ± 9
12.9	13.0	20.1 ± 3.0	13.2	505 ± 33	25 ± 6

Table 1: Total cross sections for the $pp \to pK^+\Sigma^0$ and $pp \to pK^+\Lambda$ reactions. Uncertainties of the excess energies are discussed in the text.

Extracted cross sections for both reactions under discussion are listed in Table 1. The luminosity was determined by comparing the differential counting rates of elastically scattered protons with data obtained by the EDDA collaboration [16]. The acceptance of the COSY-11 apparatus was calculated using GEANT Monte-Carlo simulations [17] with a three-body phase-space generator. The errors in the cross sections are purely statistical, where the uncertainty in the Σ^0 yield is mainly due to the background contribution. In addition, there is a total systematic uncertainty of $\leq 22\%$ (Λ) and $\leq 32\%$ (Σ^0), made up of luminosity ($\leq 13\%$), acceptance ($\pm 4\%$), background subtraction ($\leq 15\%$ for Σ^0 and $\leq 5\%$ for Λ production). In view of the sharp energy variation of the cross sections, it is important to verify the beam momenta derived using the machine parameters. The estimated accuracy of the COSY momentum of 0.1% would result in an error of the excess energy of 0.87 MeV (0.80 MeV) at the $\Sigma^0(\Lambda)$-threshold, respectively. The value of the missing mass of the hyperons can be determined from the present data with an accuracy of the equivalent excess energy to be 0.4 MeV. By comparing this with the latest compilation [18] one can derive the true excess energy within 0.4 MeV.

The remarkable feature of the measurements is that at the same value of Q the ratio

$$R_{pp}(Q) = \frac{\sigma_T(pp \to pK^+\Lambda)}{\sigma_T(pp \to pK^+\Sigma^0)} \tag{1}$$

favours strongly Λ over Σ production, with an average value of approximately 28. At much higher energies [19] the available experimental data indicate this ratio to be about 2.5, suggesting a strong influence of threshold effects on the relative Λ - Σ^0 production cross section at low excess energies.

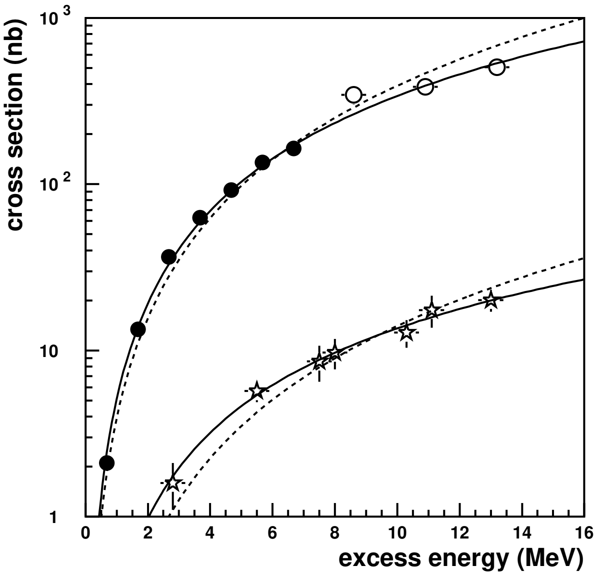

Figure 3: Cross sections for the reactions $pp \to pK^+\Lambda$ (circles) and $pp \to pK^+\Sigma^0$ (stars). Filled circles represent data published in [15]. Statistical error bars are given or are smaller than the symbol size. The horizontal error bars are discussed in the text. The curves represent phase-space fits with proton-hyperon final state interaction (solid curve) and without (dashed line); the latter corresponds to $\epsilon \to \infty$ in eq. (2).

A comparison of the excitation functions for the two reactions in the threshold region is shown in Figure 3. If the production is of short range, the energy variation should be determined by phase-space modified by any final state interaction (FSI). Taking into account only the dominant hyperon-nucleon FSI, it is expected [2] that

$$\sigma_T = C\,\frac{Q^2}{\left(1+\sqrt{1+Q/\epsilon}\right)^2}\,, \tag{2}$$

where ϵ represents the energy of a nearby virtual state. A best fit to the data is shown in Fig. 3 and gives:

$$\begin{aligned} C(\Lambda) &= (21.7 \pm 1.0)\ \mathrm{nb/MeV}^2 \qquad & \epsilon(\Lambda) &= (7.5 \pm 1.4)\ \mathrm{MeV}\,, \\ C(\Sigma^0) &= (1.3 \pm 0.6)\ \mathrm{nb/MeV}^2 \qquad & \epsilon(\Sigma^0) &= (3.1 \pm 3.2)\ \mathrm{MeV}\,. \end{aligned} \tag{3}$$

This parametrization shows again that the Σ^0 production yield is much less than the Λ one, with a ratio of the normalisation factors being $C(\Lambda)/C(\Sigma^0) \approx 17$. It is however important to note that the structure in the $\Sigma^0 p$ FSI is much sharper than for Λp.

A quantitative explanation of the relatively low Σ^0 production cross section observed in pp collisions at threshold has to wait for detailed theoretical investigations, but already a qualitative discussion can be presented.

Both π^0 and K^+ exchange diagrams in the t-channel can contribute to the production of neutral hyperons in pp collisions. If we consider the one-kaon-exchange contribution alone (and ignore effects from the hyperon-nucleon final state interaction) then the Λ/Σ^0 production ratio is essentially given by the ratio of the coupling constants $g^2_{\Lambda NK}/g^2_{\Sigma NK}$. There is considerable uncertainty in the values of the $K^+p\Lambda(\Sigma^0)$ coupling constants [3] - [5], [7] - [13] but, with a suitable choice, it would be possible to reproduce the observed large Λ/Σ^0 production ratio in a pure kaon-exchange model. It is perhaps fortuitous that the measured ratio happens to coincide almost exactly with the value of the SU(6) prediction [20] for the coupling constant ratio, which is 27/1.

At the higher beam energy of 2.3 GeV, corresponding to $Q = 170$ MeV with respect to the Σ^0 channel, there has been a detailed inclusive measurement of K^+ production in the $pp \to K^+X$ reaction [12]. Significant enhancements are observed at both the Λp and ΣN thresholds with similar magnitudes. Since only the K^+ was detected, there is no way of knowing whether the second rise is due to true Σ production or whether virtually produced Σ's are captured on the nucleon and emerge rather as Λ's through a strong $\Sigma N \to \Lambda p$ final state interaction. Such effects are well documented in the literature in, for example, K^- absorption in deuterium [27, 28, 29]. Data for fully constrained $K^- d \to \pi^- \Lambda p$ events with stopping kaons show a steep rise from threshold with evidence for a strong Λp FSI [27]. The most remarkable feature, however, is the sharp peak at an effective mass of $m(\Lambda p) = 2129$ MeV/c^2, *i.e.* at the $\Sigma^0 p$ threshold, with a FWHM of about 8 MeV/c^2. This is to be associated with the two-step process $K^- d \to \pi^-(\Sigma N \to \Lambda p)$. Such a very large effect in deuterium, where the average proton-neutron separation is about 4 fm, requires the ΣN scattering length to have an imaginary part of about 1.4 fm [30]. This must lead to much bigger effects in the proton-proton production studied here, since the large momentum transfers favour short distances and this in turn will enhance the $\Sigma^0 \to \Lambda$ conversion rate. Unless the basic physics changes radically between threshold and the energy of the Saclay measurement, the obvious way to reconcile the two results is to assume that at COSY-11 many Σ's are produced but that most of them are converted to Λ's in the interaction. In this case one needs a production mechanism which offers a larger yield than predicted by the K^+ exchange with SU(6) coupling constants.

In the one-pion-exchange contribution to the threshold $pp \to pK^+\Lambda(\Sigma^0)$ amplitudes, the driving terms are proportional to the $\pi^0 p \to K^+\Lambda(\Sigma^0)$ amplitudes. There are measurements of the $\pi^- p \to K^0\Lambda(\Sigma^0)$ [21] and $\pi^+ p \to K^+\Sigma^+$ [22] cross sections near and somewhat above threshold. Assuming isospin $I = \frac{1}{2}$ dominance due to the presence of the $N^*(1650)$, the data of Ref. [21] suggest that near threshold

$$R_{\pi p}(Q) = \frac{|f(\pi^- p \to K^0\Lambda)|^2}{|f(\pi^- p \to K^0\Sigma^0)|^2} = \frac{|f(\pi^0 p \to K^+\Lambda)|^2}{|f(\pi^0 p \to K^+\Sigma^0)|^2} \approx 0.4\,. \tag{4}$$

Neglecting the effects of the hyperon-nucleon final state interactions in a one-pion-exchange model, one would naively expect $R_{\pi p}(0) \approx R_{pp}(0)$, which leads to a discrepancy with respect to the present data of about two orders of magnitude.

In reality one expects that both π and K exchange will contribute to the production of hyperons. In case of Λ threshold production the ratio of K^+ to π^0 exchange contributions is roughly given by the ratio of $|f(K^+p \to K^+p)|^2$ to $|f(\pi^0 p \to K^+\Lambda)|^2$. Based upon the K^+p S-wave scattering length [23] and the $\pi N \to K\Lambda$ data of Ref. [21] this ratio can be estimated to be about 9:1, where the main uncertainty is due to the off-shell extrapolations. This suggests that the K exchange should be the dominant Λ production mechanism. For Σ^0 threshold production, however, the situation is reversed. Here the K exchange will be strongly suppressed if one assumes the SU(6) ratio for the pertinent coupling constants, whereas the pion-exchange contribution will be somewhat enhanced according to eq. (4). Therefore the Λ/Σ^0 production ratio will be given essentially by the ratio of the K-exchange in Λ production to π-exchange in Σ^0 production which – combining the numbers given above – amounts to $R_{pp}(0) \approx 9 \times 0.4 \approx 4$. Clearly there is still a discrepancy of a factor of about 7 between this estimation and the empirical ratio.

A large value of $R_{pp}(Q)$ could be obtained if the low energy ΛN interaction were attractive and the ΣN repulsive. However, in addition to being at variance with other data, the smallness of the value of $\epsilon(\Sigma^0 p)$ given in eq. (3) can only be understood for an attractive interaction.

The COSY-11 acceptance for $pp \to pK^+\Lambda$ near the Σ threshold is poor in the region expected to be strongly affected by the extra two-step contribution *via* the Σ hyperon. However, the TOF collaboration at COSY has measured the exclusive $pp \to pK^+\Lambda$ production at beam momenta of 2.50 GeV/c and 2.75 GeV/c [31], and the $pK^+\Sigma^0$ threshold lies between these two values. The distribution of Λp masses from the higher momentum data shows clear evidence for an attractive final state interaction but, in addition, at an invariant mass $M(\Lambda p) = (2129 \pm 2)$ MeV/c^2, there is an isolated point which is high compared to the phase-space distribution. Since $m(\Sigma) + m(N) \approx$ 2130 MeV/c^2, we suggest that this is evidence for $\Sigma N \to \Lambda p$ conversion in this reaction. Given that the TOF binning was about 8 MeV/c^2, the observation of an excess in a single bin is completely consistent with the K^--deuterium data [27]. It seems likely that the TOF peak is a genuine effect but the $pK^+\Lambda$ production cross section should be remeasured just above the $pK\Sigma$ threshold with high precision and good statistics. Combining this with the COSY-11 results would allow one to deduce $\Sigma N \to \Lambda p$ transition parameters.

In conclusion, the experimental data of the near threshold production in the associated strangeness process favour the Λ over the Σ^0 cross section by a factor of about 28. A pure kaon exchange could reproduce the presented measurements of the $\sigma_T(pK^+\Lambda)/\sigma_T(pK^+\Sigma^0)$ ratio provided that the SU(6) value is taken for the ratio of the ΛNK^+ and ΣNK^+ coupling constants. However, any reasonable contribution from pion exchange destroys this agreement and other explanations must be sought. There is much experimental evidence to suggest that the effect is due to the produced Σ's being converted into Λ's through a $\Sigma N \to \Lambda p$ transition in the final state. This would give at least one natural explanation of the observed ratio. Further experimental data which allow one to decouple both spin and isospin observables are essentially needed. A quantitative understanding of the phenomenon is very important since it is precisely in this coupling that existing nucleon-hyperon models [8, 13] deviate most strongly.

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