Comparison of Λ and Σ^0 Production near Threshold 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. 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^{+6}_{-9} smaller than 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 in the Σ signal. This hypothesis is in line with other experimental evidence in the literature.

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The COSY–11 facility [1], at the Cooler Synchroton COSY [2], was designed for the study of meson production in proton-proton collisions near threshold. We report here experimental data on both the $pp \to pK^+\Lambda$ and $pp \to pK^+\Sigma^0$ reactions at excess energies $Q \leq$ 12.9 MeV. At intermediate energies, and especially in the threshold region, the physics of strange particle production is most appropriately described in terms of meson exchange. In such models both strange and nonstrange exchanges, with or without intermediate isobar excitation, may be present. Even considering just the π- and K-exchange contributions, see, e.g., Refs. [3–6], model predictions of Λ and Σ^0 production cross sections may differ enormously due to uncertainties in the coupling constants. For example, the ratio $g^2_{\Lambda NK}/g^2_{\Sigma NK}$, as extracted from different reactions involving hyperons, varies between 0.08 and 27 [4–13]. In addition, the exchange of heavier nonstrange and strange mesons and their interference effects might also have an influence on strangeness production [14]. Strong final state interactions (FSI), especially between the hyperon and proton, are also likely to be very significant.

The four-momenta of the proton and K^+ are measured in COSY-11 [1], leaving the neutral hyperon to be identified from the missing mass in the reaction. The two emerging positively charged particles from the $pp \to pK^+X$ reaction are momentum analyzed in a C-shaped COSY-dipole magnet, placed downstream of the internal hydrogen cluster target [15]. Two sets of drift chambers are placed close to the magnet gap such that the ejectiles of interest (p and K^+) cross them almost at right angles, allowing the positions and directions of the particle trajectories to be determined. The particle momenta can then be fixed by ray tracing through the known magnetic field back to the target. Particle identification is performed by measuring the time of flight (TOF) between start and stop scintillators.

The present investigation was designed to measure Σ^0 production and compare it with Λ production near threshold. Total cross sections for $pp \to pK^+\Sigma^0$ are presented at seven energies in the range $3.0 < Q <$ 12.9 MeV. Three extra Λ points at higher Q are added to our published set from $Q = 0.68$ to 6.68 MeV [16]. COSY was used in the "supercycle" mode, which allows the repetition of a sequence of spills with different beam momenta. In view of the large difference between the cross sections for the production of the two hyperons, 10 or 20 spills with momenta above the Σ^0 threshold were followed by one at the corresponding value of Q above the Λ threshold. The spill length was typically five minutes and the sequence repeated for a total running time of two to three days at each beam momentum. The supercycle mode compares similar processes under similar conditions, thus reducing possible errors due to shifts in accelerator and/or detector components.

To isolate the hyperon production channels in the offline analysis, all two-track events containing candidates for K^+ and p pairs were selected. After determining the three-momenta and times of flight for both particles, invariant mass spectra were extracted which showed clear signals for pions, kaons, and protons above a moderate background. For events with particle 1 identified as a

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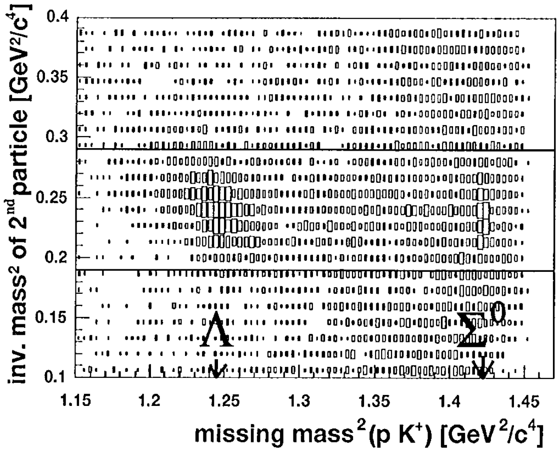

FIG. 1. Square of the mass of the second particle versus square of the missing mass, after identification of the first particle as being a proton. Data shown are at an excitation energy of $Q_{\Sigma^0} = 12.9$ MeV. The horizontal solid lines determine the $\pm 3\sigma$ limits of the assumed K^+ mass distribution.

proton, loose cuts on the measured invariant mass of particle 2 ($0.1 < m^2_{\text{inv}} < 0.4\ \text{GeV}^2/c^4$) excluded pions and protons. Taking this particle to be a K^+, the missing mass m_X of the unobserved particle in the event could be computed and in Fig. 1, the value of m^2_{inv} is plotted versus m^2_X. Clear K^+ enhancements are apparent at the positions of the Λ and Σ^0 masses. Monte Carlo simulations indicate that unphysical events in the figure arise from a variety of other reactions in addition to hyperon production, involving the rest gas in the scattering chamber, or secondary reactions in the beam pipe of elastically scattered protons. The false assumption, in the kinematic fit, that such tracks originate from the target leads to unphysical particle 2 masses with values of m_X pushed towards the kinematic limit. The same effect exists for the production of both hyperons near threshold, but it is far less important in the Λ case [16] because this signal is so much stronger. A weak but visible K^+ band shows up between the two peaks in Fig. 1. This is due to misidentifying protons from the Λ decay with primary reaction protons. The Monte Carlo calculations shown in Fig. 2 demonstrate that these additional K^+ events generally have $m^2_X < 1.4\ \text{GeV}^2/c^4$, so that they do not influence the Σ^0 peak region where the background was adjusted.

The projection onto the missing mass axis of the band $0.19 < m^2_{\text{inv}} < 0.29\ \text{GeV}^2/c^4$ is shown in the upper part of Fig. 3. Those from adjacent bands ($0.10 < m^2_{\text{inv}} < 0.19\ \text{GeV}^2/c^4$ and $0.29 < m^2_{\text{inv}} < 0.34\ \text{GeV}^2/c^4$) shown in the central part of Fig. 3 are considered as representative of nontarget events in the background spectrum. After smoothing to minimize statistical fluctuations and normalizing, this projection is shown as the solid curve which, when subtracted from the data, yields the lower part of Fig. 3. The resulting numbers of events in the clear Λ and Σ^0 peaks

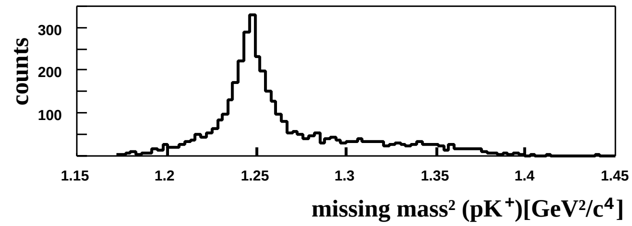

FIG. 2. Monte Carlo events for the $pp \to pK\Lambda$ reaction at $Q = 13$ MeV above the Σ^0 threshold, analyzed similarly to the experimental data. See text for discussion.

are not in practice different to those obtained by drawing smooth background curves by hand. The sharpness of the Σ^0 peak is a kinematic effect due to the proximity of the threshold; the same phenomenon is seen in the Λ peak close to its threshold [16].

The luminosity was determined by comparing counting rates of elastically scattered protons with data obtained by the EDDA Collaboration [17]. The COSY-11 acceptance was calculated using GEANT Monte Carlo simulations with a three-body phase-space generator and including the kaon lifetime. In the present Q range, the acceptance varies between 4.6% and 1.0% for Σ^0 production but is slightly smaller in the Λ case. The errors in the cross sections shown in Fig. 4 are purely statistical; the uncertainty in the Σ^0 yield arises mainly from the background contribution. There is also a total systematic uncertainty of $\leq 22\%$ (Λ) and $\leq 32\%$ (Σ^0), composed of luminosity ($\leq 13\%$), acceptance ($\pm 4\%$), and background subtraction ($\leq 5\%$ for Λ and $\leq 15\%$ for Σ^0). Direct measurement of the COSY momentum to $\pm 0.1\%$ would

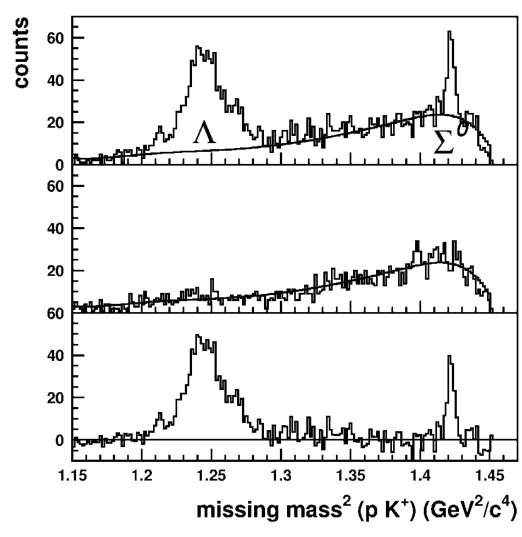

FIG. 3. Top: Spectrum of missing mass squared for the reaction $pp \to pK^+X$ at $Q = 12.9$ MeV. The solid line indicates the smoothed background derived by projecting bands above and below the K^+ band of Fig. 1. Center: Background spectrum extracted as described in the text with the smoothed solid line. Bottom: Spectrum after background subtraction. Similar spectra for measurements close to the Λ threshold can be seen in Ref. [16].

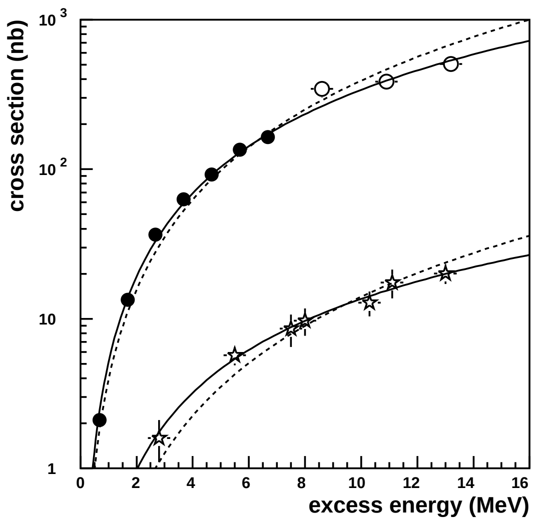

FIG. 4. Cross sections for the reactions $pp \to pK^+\Lambda$ (circles) and $pp \to pK^+\Sigma^0$ (stars). Filled circles represent data published in [16]. The curves represent phase-space fits with proton-hyperon FSI (solid curve) and without (dashed line); the latter corresponds to $\epsilon \to \infty$ in Eq. (2).

result in an error in Q of 0.87(0.80) MeV at the $\Sigma^0(\Lambda)$ threshold. However, by comparing our measured values of the Σ^0 and Λ missing masses with compilations [18], the excess energy could be determined to ± 0.4 MeV.

The excitation functions for the two reactions in the threshold region are compared in Fig. 4; numerical values can be found in Refs. [16,19]. The most remarkable feature of the data is that, at the same value of Q, the ratio

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

favors strongly Λ over Σ production, by about a factor of 28^{+6}_{-9}. At much higher energies, experiments show a ratio of about 2.5 [20], suggesting that there must be some strong threshold effect in the relative Λ-Σ^0 production cross section at low excess energies.

The high momentum transfers mean that the reaction is sensitive primarily to short range effects and the energy variation should be determined by phase space modified by any final state interaction. Taking into account only the elastic hyperon-nucleon FSI's, it is expected that [3]

$$\sigma_T = CQ^2 \times (1 + \sqrt{1 + Q/\epsilon})^{-2}, \qquad (2)$$

where ϵ represents the energy of a nearby virtual state. The best fit to the data, shown in Fig. 4, corresponds to

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

showing that $R_{pp}(Q)$ varies from about 20 to 30 over our Q range.

A quantitative explanation of the relatively low Σ^0 production rate observed in pp collisions near threshold must await detailed theoretical investigation, but already a qualitative discussion can be presented. Both π^0 and K^+ t-channel exchanges can contribute to the production of neutral hyperons in pp collisions. For pure one-kaon exchange and ignoring the hyperon-nucleon FSI, the Λ/Σ^0 production ratio is given essentially by the ratio of the coupling constants $g^2_{\Lambda NK}/g^2_{\Sigma NK}$, about which there is considerable uncertainty [4–13]. Perhaps fortuitously, the SU(6) prediction of 27/1 for the ratio [21] would then reproduce our observed Λ/Σ^0 production ratio.

At the higher beam energy of 2.3 GeV, corresponding to $Q(\Sigma N) \approx 170$ MeV, there has been a detailed inclusive measurement of K^+ production in the $pp \to K^+X$ reaction [12]. Significant enhancements of similar magnitude are observed at the Λp *and* ΣN thresholds. Since only the K^+ was detected, the second rise could be due to true Σ production or to virtually produced Σ's being captured on the nucleon and emerging rather as Λ's through a strong $\Sigma N \to \Lambda p$ FSI. Such effects are well documented in the literature in, for example, K^- absorption in deuterium [22–24]. 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 [22]. The most remarkable feature is the sharp peak at an effective mass of $m(\Lambda p) = 2129$ MeV/c^2, i.e., at the ΣN 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 a large imaginary part, about 1.4 fm [25]. This must lead to much bigger effects in our experiment since the large momentum transfers favor short distances which enhances the $\Sigma^0 p \to \Lambda p$ conversion. Unless the physics changes radically between threshold and the energy of the Saclay measurement [12], the obvious way to reconcile the two results is to assume that at COSY-11 many Σ's are produced but that most are converted to Λ's through an FSI. One would then need a larger Σ yield than that of K^+ exchange with SU(6) coupling constants.

The driving terms in the one-pion-exchange contribution to the $pp \to pK^+\Lambda(\Sigma^0)$ amplitudes are proportional to those of $\pi^0 p \to K^+\Lambda(\Sigma^0)$. There are measurements of $\pi^-p \to K^0\Lambda(\Sigma^0)$ [26] and $\pi^+p \to K^+\Sigma^+$ [27] cross sections near and somewhat above threshold. Assuming $I = \frac{1}{2}$ dominance, due to the presence of the $N^*(1650)$, the data of Ref. [26] suggest that near threshold

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

In a one-pion-exchange model without FSI's, one naively expects $R_{\pi p}(0) \approx R_{pp}(0)$, leading to a discrepancy with the present data of about 2 orders of magnitude.

In reality both π and K exchanges will contribute to hyperon production. In the Λ case, the ratio of K^+ to π^0 exchange is given roughly by $|f(K^+p \to K^+p)|^2/|f(\pi^0 p \to K^+\Lambda)|^2 \approx 9$, again after ignoring the FSI. The main uncertainty comes from the off-shell extrapolation of the measured on-shell amplitudes [26,28]. Thus K exchange should dominate Λ production, but the situation is reversed for the Σ^0. K exchange is strongly suppressed if SU(6) coupling constants are assumed, whereas pion exchange is enhanced according to Eq. (4). The Λ/Σ^0 production ratio will then be given essentially by the ratio of K exchange in Λ production to π exchange in Σ^0 production. Combining the above numbers, this leads to $R_{pp}(0) \approx 9 \times 0.4 \approx 3.6$, which is about a factor of 8 below our measurement.

A large value of $R_{pp}(Q)$ would follow 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 $\epsilon(\Sigma^0 p)$ in Eq. (3) can be understood only for an attractive interaction.

The COSY-TOF Collaboration [29] has measured the exclusive $pp \to pK^+\Lambda$ reaction at 2.50 and 2.75 GeV/c, and the $pK^+\Sigma^0$ threshold lies between these two momenta. The distribution in Λp invariant masses from the higher momentum data shows an isolated point at $M(\Lambda p) = (2129 \pm 2)$ MeV/c^2 which is high compared to its neighbors. 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 [22]. To confirm the TOF peak, the $pK^+\Lambda$ production cross section should be remeasured above the $pK\Sigma$ threshold with high precision and good statistics in order to deduce information on $\Sigma N \to \Lambda p$ transition parameters.

In conclusion, we have shown that the near-threshold Λ production cross section is 20–30 times larger than that for Σ^0. Pure kaon exchange can reproduce this ratio provided that the SU(6) value is taken for the ratio of the ΛNK^+ and ΣNK^+ coupling constants but any plausible contribution from pion exchange destroys the agreement. There is much experimental evidence to suggest that the ratio is mainly affected by the produced Σ's being converted into Λ's in the final state. Further experimental data which would allow one to deduce both the spin and isospin dependence of the effect are essential. 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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