[4]Equation (4) represents a more precise formulation of the relationship observed by L. Grodzins [Phys. Letters 2, 88 (1962)] between half-lives and energies of $2^+$ states of even-even nuclei and their mass numbers.

[5]There is an indication that for the heaviest deformed nuclei, $Q_{02}$ increases faster than Eq. (4) predicts (see Ref. 1, Fig. 9).

[6]Almost nothing is known about the behavior of $C$ on the neutron-rich side of the valley of stability.

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# MEASUREMENT OF THE REACTION $\pi^+ p \to K^+ \Sigma^+$ AT LARGE MOMENTUM TRANSFERS*

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Cross section and polarization in the reaction $\pi^+ p \to K^+ \Sigma^+$ have been measured at 3, 4, and 5 GeV/$c$ and for momentum transfers up to 3 (GeV/$c$)$^2$. Beyond the previously investigated forward peak the cross section shows a secondary maximum and a steep decrease towards large momentum transfers. The $\Sigma^+$ polarization is large and positive in this region.

The reaction $\pi^+ p \to K^+ \Sigma^+$ has been studied by our group in a previous experiment[1] which covered kaon laboratory angles between 3° and 17° and incident momenta from 3 to 7 GeV/$c$. The results from this experiment showed a diffractionlike forward peak and a dip or break at $-t \approx 0.5$ (GeV/$c$)$^2$ beyond which the cross section appeared to be rather flat. On the basis of these data it was not possible to decide whether the region of relatively slow variation in cross section indicated the presence of a secondary maximum followed by a steeper decrease or whether the cross section would continue its slow variation towards large momentum transfers. The present experiment was designed to answer this question and also to investigate whether there would be additional structure at larger momentum transfers which had been predicted by a Regge-pole fit[2] to previous data.

The present experiment covered kaon angles

between 13° and 27° and incident momenta of 3, 4, and 5 GeV/$c$. A description of the apparatus has already been given in a recent paper[3] on large-angle $\pi^+ p$ elastic scattering, so only a few characteristics of our setup will be mentioned. The measurements were performed at the Argonne zero-gradient synchrotron using a wire spark-chamber system connected on-line to an EMR-6050 computer. A positive beam with about $10^5$ pions per pulse interacted in a 12-in.-long liquid hydrogen target. Incoming pions were tagged by three threshold Cherenkov counters. The $K^+$ mesons were detected in a spectrometer consisting of two sets of counter hodoscopes, four sets of wire spark chambers, and a large-aperture bending magnet. A threshold Cherenkov counter rejected scattered pions. The protons from the decay mode $\Sigma^+ \to p\pi^0$ were detected by a second arm consisting of a scintillation counter and another set of wire chambers.

The identification of the $K^+\Sigma^+$ final state was based on a combination of missing-mass technique and recoil-particle measurement. From the measured $K^+$ angle and momentum the missing mass was calculated. Although at small angles the missing-mass spectrum calculated from the scattered $K$ meson alone showed a prominent peak at the $\Sigma$ mass, this was not the case at the large angles and correspondingly small cross sections of this experiment. There was only a small $\Sigma^+$ peak visible above a large background which was primarily due to protons counted in the $K$ spectrometer. A significant improvement was achieved by requiring a coincident proton track in the second arm within the geometric cone allowed by the kinematics of the decay $\Sigma^+ \to p\pi^0$. The recoil $\Sigma$ hyperons had momenta between 0.9 and 2.8 GeV/$c$ in the range of our measurements, and the protons from the decay $\Sigma^+ \to p\pi^0$ were restricted to a fairly narrow cone around the $\Sigma$ direction. There is no such kinematic restriction for $\pi^+$ mesons from the decay mode $\Sigma^+ \to n\pi^+$ and only a small percentage (6-9%) of the decay pions are within the proton cone.

The missing-mass spectra with the cone-angle requirement imposed show clear peaks at the $\Sigma$ mass. In Fig. 1 we present spectra at 5 GeV/$c$ without and with the cone-angle requirement imposed. The number of $K\Sigma$ events was obtained by fitting the missing-mass spectra with a Gaussian representing the $\Sigma$-mass peak, and a smooth background function. A correction was made for the $\Sigma^+$ branching ratio and the probability for detecting a decay $\Sigma^+ \to n\pi^+$.
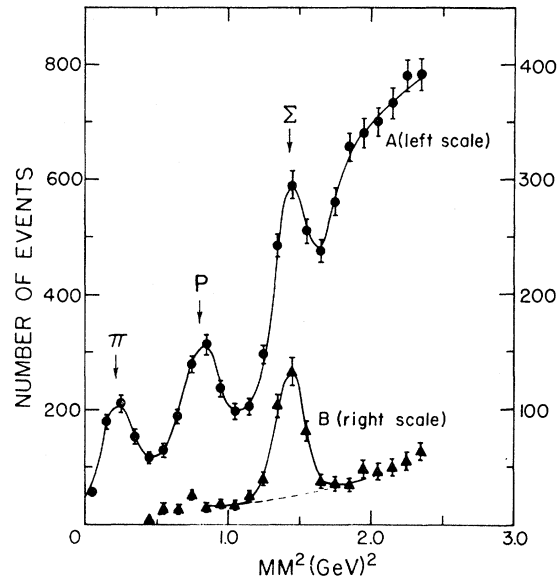


FIG. 1. Missing-mass spectra at 5 GeV/$c$, $1.3 < |t| < 1.6$ (GeV/$c$)$^2$. Spectrum $A$ is obtained by using the information from the scattered particle only. In spectrum $B$ the events are plotted which in addition fulfill the cone-angle requirement. Spectrum $A$ shows two peaks in addition to the $\Sigma^+$ peak. The one near $m_p^2$ (denoted "$p$") is due to $\pi^+ p$ elastic scattering in the forward hemisphere, where the pion is not rejected because of Cherenkov-counter inefficiency. The peak at small missing-mass squared (denoted "$\pi$") is due to $\pi^+ p$ scattering in the backward hemisphere, where the proton is scattered into the $K$ spectrometer. These peaks are shifted from their expected positions at $m_p^2$ or $m_\pi^2$ since the analysis program assumes that the scattered particle is a kaon.

The overall event-recognition efficiency was 45-60% because of nonideal chamber performance at high background rates and the simplicity of our track-fitting routine. To check the absolute normalization of the experiment, elastic $pp$ runs were interspersed with $K\Sigma$ runs. The cross section for $pp$ scattering is large in our angular region and has been well measured in counter experiments.[4] Since we used four gaps in every set of chambers, the system was sufficiently overdetermined that it was possible to calculate the chamber efficiencies from the actual data. The $pp$ cross sections obtained this way agree with the counter data within 5-10%. Because of this check on the normalization we are able to quote a ±10% systematic error. Further corrections were applied for $K$ decay, nuclear absorption, and $\mu$ contamination in the beam.

The differential cross sections are given in Table I and plotted in Fig. 2, together with the small-angle points of the previous experiment.

Table I. $d\sigma/dt$ in $\mu$b/(GeV/c)$^2$ for $\pi^+ p \to K^+\Sigma^+$.

| $-t$ | $d\sigma/dt$ 3 GeV/$c$ | $-t$ | $d\sigma/dt$ 4 GeV/$c$ | $-t$ | $d\sigma/dt$ 5 GeV/$c$ |
|---|---|---|---|---|---|
| 0.625 | 44.3 ±5.3 | 0.9 | 22.6 ±1.7 | 1.15 | 9.17 ±0.94 |
| 0.775 | 41.7 ±4.3 | 1.1 | 22.0 ±1.7 | 1.25 | 8.15 ±0.89 |
| 0.925 | 36.7 ±4.5 | 1.3 | 14.4 ±1.6 | 1.45 | 5.99 ±0.63 |
| 1.075 | 30.5 ±4.4 | 1.5 | 12.4 ±1.5 | 1.75 | 3.18 ±0.46 |
| 1.225 | 21.4 ±4.2 | 1.7 | 6.2 ±1.2 | 2.05 | 1.65 ±0.38 |
| | | 1.9 | 4.4 ±1.0 | 2.35 | 0.81 ±0.24 |
| | | 2.2 | 2.0 ±0.7 | 2.65 | 0.27 ±0.15 |
| | | | | 2.95 | 0.16 ±0.15 |
| | | | | 3.30 | 0.17 ±0.09 |

The error bars include the background-subtraction uncertainty but not the ±10% systematic uncertainty mentioned above.

The measurement of the $\Sigma$ polarization is based on the fact that the parity-nonconserving decay $\Sigma^+ \to p\pi^0$ has a large absolute value of the asymmetry parameter, $\alpha = -0.98^{+0.05}_{-0.02}$.[5] The angular distribution of the proton in the $\Sigma$ rest frame is given by $\frac{1}{2}(1 + \alpha \cos\theta)$, where $\theta$ is measured with respect to the $\Sigma$ spin. Since parity conservation in the strong process $\pi^+ p \to K^+\Sigma^+$ allows only a $\Sigma$ polarization perpendicular to the reaction plane, a nonzero $\Sigma$ polarization manifests



FIG. 2. Differential cross section for $\pi^+ p \to K^+\Sigma^+$. The lines are drawn to guide the eye and to indicate the behavior in the forward peak region where data points have been omitted.

itself in an up-down asymmetry of the decay protons with respect to the reaction plane. The polarization $P$ of the $\Sigma$ hyperons is given in terms of the asymmetry $A$ by

$$P = (2/\alpha)A, \text{ where } A = (N_U - N_D)/(N_U + N_D).$$

$N_U$ ($N_D$) is the number of protons going "up" ("down"). We define "up" as the direction of the vector cross product $\vec{p}_\pi \times \vec{p}_K$. The number of $K\Sigma$ events with a recoil particle going "up" or "down" was determined by fitting the corresponding missing-mass spectra in the way described earlier. A correction was made for the fraction of $\Sigma^+ \to n\pi^+$ decays seen because the asymmetry parameter for this decay is close to zero.

The correct relative alignment of the $K$ spectrometer and the second arm was determined from the elastic $pp$ runs. By this method a slight vertical displacement of the incoming beam and possible alignment errors of the chambers were eliminated. The background under the $\Sigma$ missing-mass peak as determined by the fitting procedure was found to have only a slight asymmetry, $A_{\text{background}} \approx +0.04 \pm 0.03$.

Our polarization data are plotted in Fig. 3 together with the previous small-angle data.[1] The error bars include background subtraction uncertainties.

The differential cross section of the reaction $\pi^+ p \to K^+\Sigma^+$ shows some similarity to that of $\pi p$ elastic scattering. The cross section has a diffractionlike forward peak followed by a break at $-t \approx 0.5$ (GeV/$c$)$^2$ and a secondary maximum, beyond which it falls rather steeply towards large momentum transfers. The secondary maximum is fairly clear at 4 and 5 GeV/$c$ but at 7 GeV/$c$ the data show only a change in curvature. The higher-energy data of Bashian et al.[6] also reveal only this change in curvature. A similar energy-dependent variation of the secondary maximum
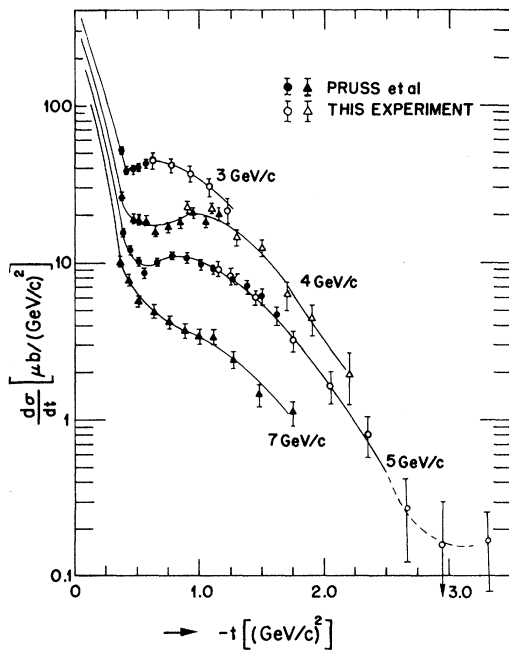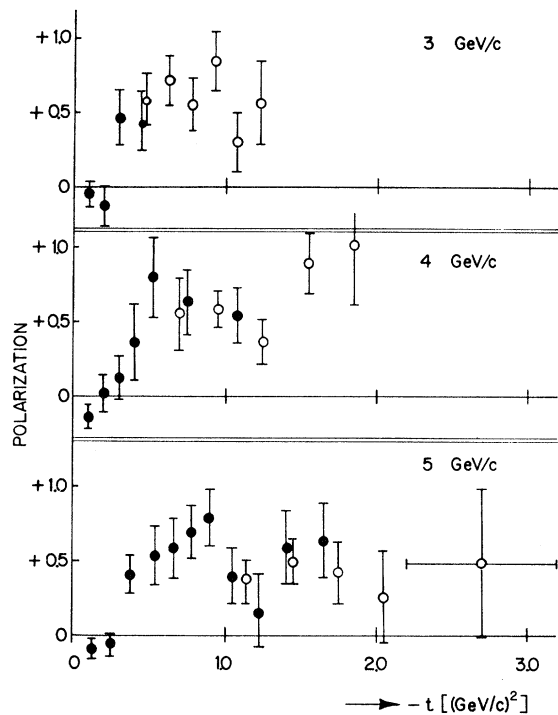
FIG. 3. Polarization of the $\Sigma^+$. Closed circles, Pruss et al., Ref. 1; open circles, this experiment.

is observed in $\pi p$ elastic scattering, but there the secondary maximum vanishes above 3 or 3.5 GeV/$c$.[7] The structures in the $\pi^+ p \to K^+ \Sigma^+$ cross section and polarization are closely related. The polarization is small in the forward peak region but becomes large where the break or dip in the cross section occurs. It stays positive out to large momentum transfers, although our errors are too large to make a more detailed statement. The three highest momentum-transfer points at 5 GeV/$c$ indicate that the cross section might level off at $-t \approx 3$ (GeV/$c$).[2] It is interesting to speculate whether in the $K^+\Sigma^+$ reaction there is a dip at $-t \approx 2.8$ (GeV/$c$)$^2$ similar to the one observed in $\pi^+ p$ elastic scattering.[3] The large error bars on these points are not due to limited counting rate—the $K\Sigma$ cross section is of the same magnitude as the $\pi^+ p$ elastic cross section in this region—but rather to background in the missing-mass spectrum. Only an experiment

with significantly better background rejection could resolve this question.

Reeder and Sarma[2] have proposed a Regge model for $\pi^+ p \to K^+ \Sigma^+$ which is based on nondegenerate $K^*(890)$ and $K^{**}(1420)$ exchanges. Their model reproduces the general features of the differential cross section and polarization out to momentum transfers of about 1 to 1.5 (GeV/$c$)$^2$. They predict a deep dip in the cross section and a change of sign in the polarization at $-t \approx 1.8$ (GeV/$c$)$^2$ that we do not observe. In the model this is due to the passing of the $K^{**}$ trajectory through $-1$, and by modifying the residue function or the shape of the trajectory it might be possible to avoid these difficulties.

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