MEASUREMENTS OF THE TOTAL CROSS SECTIONS OF Σ^- AND Ξ^-
ON PROTONS AND DEUTERONS BETWEEN 74 AND 137 GeV/c

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ABSTRACT

The Σ^-p and Σ^-d total cross sections have been measured to a statistical accuracy of $\pm 1\%$ and $\pm 0.5\%$, respectively, at five momenta from 74.5 to 136.9 GeV/c, using the Hyperon Beam at the CERN SPS. The Ξ^-p and Ξ^-d total cross sections have also been measured to the same statistical accuracy at 101.5 and 133.8 GeV/c. The systematic uncertainty at each momentum is estimated to be of the order of $\pm 0.5\%$. The hyperon-nucleon cross sections are shown to be rising with energy, and the data are compared with various phenomenological models.

(Submitted to Nuclear Physics B)

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1. INTRODUCTION

We present results of measurements of the Σ^- and Ξ^- total cross sections on protons and deuterons made using the Hyperon Beam at the CERN SPS. The Σ^- cross sections have been determined at five momenta from 74.5 to 136.9 GeV/c, and the Ξ^- cross sections at 101.5 and 133.8 GeV/c. A statistical accuracy of $\pm 1\%$ has been obtained for the Σ^-p and Ξ^-p measurements and $\pm 0.5\%$ for those of Σ^-d and Ξ^-d , while the systematic uncertainty for each data point is estimated to be of the order of $\pm 0.5\%$. As an experimental check we have also measured the $\bar{p}p$ and $\bar{p}d$ total cross sections at 101.5 GeV/c, and find good agreement with the results of Carroll et al. [1] obtained at Fermilab.

No previous measurements have been made of the Ξ^- -nucleon total cross sections, and existing Σ^- -nucleon data are restricted to a single result at 18.7 GeV/c [2], having a statistical accuracy of $\sim \pm 3\%$. The most precise measurement of the Λp total cross section is that of Gjesdal et al. [3], who obtained a momentum averaged result of 34.6 ± 0.4 mb over the range 6 to 21 GeV/c. The present experiment thus provides the first good quantitative information on the strangeness dependence of high energy baryon-baryon cross sections.

In section 2 of this paper we describe the principle of the total cross section measurements, and in section 3 the details of experimental techniques. Section 4 deals with the analysis of the data and section 5 with the extrapolation of the partial cross sections to zero scattering angle. Data checks and corrections to the results are outlined in sections 6 and 7, and the cross sections are presented in section 8. In sections 9 and 10 we compare our results with various model predictions and summarize our conclusions.

2. THE PRINCIPLE OF THE MEASUREMENT

The total cross sections, σ_T , were measured using the transmission method, in which

$$\sigma_T = \frac{1}{n\ell} \lim_{\theta_i \rightarrow 0} \ln \left\{ \frac{E_{Ti}}{E_0} \times \frac{F_0}{F_{Ti}} \right\},$$

where, with an evacuated target, E_0 is the number of incident particles and E_{Ti} the number transmitted and detected within an angle θ_i of the incident beam. F_0 and F_{Ti} are the corresponding quantities for the target filled with liquid hydrogen or deuterium; n is the number of scattering centres per unit volume in the liquid and ℓ the target length.

The quantities E_{Ti} and F_{Ti} are obtained from the data for a series of values of θ_i , and the resulting partial cross sections are extrapolated to $\theta_i = 0$. The method is applicable for both stable and decaying beams, provided that the detection probability for unscattered particles is the same with the different targets. For our measurements, the incident particles were identified by means of a DISC Čerenkov counter, and, in the case of the hyperons, the transmitted particles were also identified downstream of the target by detecting the π^- from their decay:

$$\Sigma^- \rightarrow \pi^- + n, \quad \Xi^- \rightarrow \pi^- + \Lambda^0.$$

This latter identification has the advantage that the extrapolation to zero scattering angle for hyperons is performed only on elastically and quasi-elastically scattered particles. Also hyperons that decay before leaving the target do not enter into the data sample.

A schematic layout of the apparatus is shown in fig. 1. The incident hyperon direction was measured by means of the groups of multiwire proportional chambers (MWPCs) A1 and A2, and the transmitted direction by the groups B1 and B2. The fiducial region for the hyperon decay lay between B2 and D1 and was of length 480 cm. The trajectory of the decay pion and the kink that it formed with the hyperon trajectory were reconstructed from the MWPC groups C1, C2, D1, and D2. The magnet ($\int B \cdot d\ell = 2.6 \text{ T m}$) and downstream drift chambers (described in ref. [4]) allowed the decay pion momentum to be measured for a sample of events, in order to find the beam momentum and, in the case of Ξ 's, to monitor the purity of the DISC signal.

The MWPCs are described further in section 3.3. Their arrangement in discrete groups, or modules, containing two planes per coordinate provided the very high

detection efficiency needed to ensure that the reconstruction probability of unscattered hyperons was the same for each target. Because of this the absolute chamber efficiency is not needed in the total cross section calculation, as it cancels between the full and empty targets. Equality of beam conditions and chamber performance between the data taken with the different targets was further improved by successive cycling of the targets into the beam. The movement took place in the 10 seconds between machine bursts, and a given target remained in the beam for 10 to 15 bursts at a time.

The statistical error on σ_T is given by the formula:

$$\delta\sigma_T = \frac{1}{n\lambda} \left\{ \frac{1}{E_T} - \frac{1}{E_0} + \frac{1}{F_T} - \frac{1}{F_0} \right\}^{\frac{1}{2}}.$$

The targets, detailed in section 3.2, gave attenuations due to nuclear scattering of about 25% for hydrogen and 50% for deuterium. However, the dominant attenuation of the hyperon beam arises from decay loss, and with the evacuated target the measured transmission ratio varied from 0.17 for 74.5 GeV/c Σ^- to 0.21 for 136.9 GeV/c Σ^- . Because of this, nearly as many triggers were needed with the evacuated as with the filled targets, the typical ratios of vacuum:hydrogen:deuterium being 1.0:1.2:1.1. Table 1 summarizes the total number of Σ^- and $\bar{\Sigma}^-$ triggers analysed in the experiment.

3. EXPERIMENTAL DETAILS

3.1 The charged hyperon beam

The CERN Hyperon Beam is described in detail elsewhere [4]. Secondary particles produced by a 250 GeV/c proton beam striking a BeO target pass through a magnetic channel approximately 10 m long, consisting of three bending magnets and two superconducting quadrupoles, Q1 and Q2. The DISC used to identify the hyperons (fig. 1) is also described in ref. [4]. It contained 250 cm of CO₂ as radiator and was designed for a Čerenkov angle of 40 mrad. The beam encountered 6% of a radiation length of material. The optical efficiency for the coincidence required between all eight DISC photomultipliers was $(90 \pm 2)\%$. This improvement over

the performance reported in ref. [4] resulted from a geometrical increase in the optical acceptance of the DISC mirror and from the use of specially selected photomultipliers of high quantum efficiency. The DISC diaphragm was adjusted so that the contamination of the Σ^- beam by E^- was less than 0.1% at all momenta. The measured $\bar{\Sigma}^+$ component of the beam [5] contributes a negligible error to the Σ^- total cross section ($< 0.01\%$). The ratio of Σ^- identified in the DISC to total beam varied from approximately 1:2000 at 74.5 GeV/c to 1:300 at 136.9 GeV/c, while the total incident beam rate was kept below a value of $\sim 1.2 \times 10^6$ particles per second to ensure good chamber performance (see section 6).

The E^- yield at the DISC was typically a factor of ten lower than that of Σ^- . Approximately 20% of the data at 101.5 GeV/c was taken with the DISC pressure set sufficiently far from the Σ^- peak to define a E^- beam with negligible impurity, but the instantaneous E^- counting rate was then only $\sim 100/s$. For the remainder of the E^- data a compromise was necessary between beam purity and acquisition rate. The DISC was adjusted to give $\sim 300 E^-$ triggers per second, and the Σ^- background in the defined beam was then approximately 3.5%. The correction due to this impurity is described in section 7.

The Σ^- and E^- data were taken with r.m.s. beam momentum bites that varied from $\pm 0.5\%$ to $\pm 2.1\%$, depending upon DISC settings. The beam is designed [4] such that at each momentum a dispersion relation of the form $p - p_0 = \alpha(\theta_x - \theta_0)$ can be found, where p is the momentum of a particle travelling at a horizontal angle θ_x , and p_0 and θ_0 are the central values of these quantities. We have determined the constants p_0 , θ_0 , and α for each data set (section 4.1.2) and hence have available an accurate value for the momentum of each incident beam particle.

3.2 The targets

Three identical target vessels, each 2 m long and 6 cm in diameter, were constructed with walls of 0.2 mm stainless steel and mylar end windows 0.2 mm thick. Each was contained within a copper heat shield with beam entry and exit apertures. The heat shields were cooled by the vapour returning to the liquefier

and the whole was surrounded by layers of superinsulation. A flow of N_2 gas was maintained across the end windows of the containing vacuum vessel to prevent water vapour permeating into the system and forming ice on the target windows.

One target was evacuated, one contained liquid hydrogen at a temperature of 20.48 K, and the third liquid deuterium at 22.86 K. These temperatures were continuously monitored during the experiment using carbon glass and silicon diode detectors, distributed in pairs in the liquids at the entrance, exit, and mid-point of each target. Each detector was accurate to better than 0.02 K and the mean target temperature was known to ± 0.02 K for hydrogen and ± 0.03 K for deuterium, these limits being determined from the variation in temperature found along the target lengths. The molar volumes were calculated from the temperatures using the data of refs. [6] and [7], with final uncertainties of $\pm 0.03\%$ for hydrogen and $\pm 0.05\%$ for deuterium. The target lengths were measured cold to an accuracy of better than $\pm 0.02\%$.

The purity of the liquid deuterium was estimated from mass-spectrometer and gas-chromatography measurements. No hydrogen in the form of H_2 molecules was detected, and the molar fraction $HD:D_2$ was found to be $\leq 0.5\%$. This translates into an uncertainty of $\leq 0.16\%$ in the deuterium total cross sections.

It was confirmed that the scattering properties of the three target vessels were identical by measuring the three transmission ratios for an 86 GeV/c anti-proton beam with the targets emptied of liquid. No statistical differences were observed, and the limits of the measurements correspond to uncertainties in the total cross sections of $\pm 0.2\%$ for hydrogen and $\pm 0.1\%$ for deuterium.

An antiproton beam was also used to check that no ice had formed on the ends of the hydrogen and deuterium targets during the course of the experiment. The $\bar{p}p$ and $\bar{p}d$ total cross sections were measured to a statistical accuracy of the order of $\pm 0.3\%$ soon after the targets were filled with liquid, and again after the maximum interval of five weeks during which the targets were cold. The second measurements gave cross sections for both protons and deuterons that were smaller by just over one standard deviation, thus confirming that no ice was present on the targets.

3.3 The multiwire proportional chambers

The groups of MWPCs used in the experiment, A1, A2, B1, B2, C1, C2, D1, and D2 are shown in fig. 1, and their properties are outlined in table 2. The separation between a pair of x planes or y planes within a group was 10 cm for the A and B chambers and 6.8 cm for the C and D chambers. For the A chambers, no inclined (u/v) planes were required, since only events with a single beam track were selected. The $\frac{1}{2}$ mm wire spacing in chambers A and B was needed to achieve high accuracy on the scattering angle ($\sim \pm 0.1$ mrad, section 4.1), while minimizing the separation of the chamber groups and hence the hyperon decay losses. The 1 mm wire spacing of the C and D chambers allowed the hyperon decay angle to be measured to ± 0.2 mrad, and the z coordinate of the decay to ± 8 cm. All chambers were specially developed for the experiment, and are described in refs. [8] and [9]. The chamber system had a 100% geometrical acceptance for scattering and decay up to a scattering angle of 7 mrad at all incident momenta, although in fact only data below 2.5 mrad were used in the extrapolation.

The individual chamber efficiencies were monitored at frequent intervals throughout the data taking, and were maintained at typically 99% for the A and B chambers and 98% for the C and D chambers.

3.4 Data acquisition

The scintillators used are shown in fig. 1. Each beam trigger constituted an event and was defined by $T1 \cdot T2 \cdot \overline{V1} \cdot (DISC)$, where T1 and T2 were 30×30 mm² counters, and V1 a surrounding halo veto counter. A beam rationer ensured that only single beam track events were triggered, by requiring that no other particles passed through T1 or T2 within a time interval extending from 100 ns before to 50 ns after the counted one.

No on-line data cuts were made, and for each event the information from the 44 MWPC planes was read into a DEC VAX 11/780 computer and written to magnetic tape. The T2 pulse height and any hits in the muon background wing counters W1, W2, the halo counter V2 and the 20×20 mm² counters S1 and S2, were among

additional information recorded for each event by ADCs and pattern units for use in subsequent off-line tests. For every Ξ^- event and every tenth Σ^- event the drift-chamber information was also written to tape to allow magnetic analysis of hyperon decays.

The data at each momentum were divided into some 50 runs of typically 1.2×10^5 events per run. Every run contained events from each of the three targets, and typically there were seven complete target cycles in a run lasting one hour.

4. ANALYSIS PROCEDURES

4.1 Σ^- and Ξ^- data

4.1.1 MWPC analysis

A good event from the MWPC data, that is, one in which an unscattered or elastically/quasi-elastically scattered hyperon decayed in the allowed fiducial region, required all of the following:

- a) A single reconstructed beam track with 3 or 4 A chamber coordinates on a line in both x and y, and a good χ^2 . The percentage of triggers giving such a track varied from 69% at the lowest momentum to 82% at the highest. The loss was due to those hyperons decaying between the A chamber modules, after identification in the DISC, and was independent of the scattering target.
- b) One and only one track associated with the beam, defining the hyperon scattering angle, reconstructed in the B1 and B2 modules.
- c) A single decay kink in the fiducial region between B2 and D1 ($6.885 \text{ m} < z < 11.685 \text{ m}$) with a hyperon-pion laboratory decay angle greater than 3 mrad. This was established by finding the tracks defined by the D1 and D2 modules and continuing them as far as possible upstream into the C chambers, while still maintaining an acceptable χ^2 for a straight line fit. The B chamber track was similarly extended downstream if possible into the C chambers and a good closest distance of approach between these B and D chamber lines was required for a decay kink.

For tracks downstream of the target, one coordinate in x and one in y was sufficient from a given chamber module, so that the reconstruction efficiency was very high, and hence insensitive to the scattering target. (For example, some 95% of B1-B2 chamber tracks have, as expected, the maximum possible number of four coordinates in both x and y , corresponding to a single plane efficiency of $\sim 99.4\%$).

In fig. 2 we compare measured decay-angle distributions with Monte Carlo predictions for a selection of our data, and the very good agreement in each case illustrates that we are correctly identifying the hyperon decays. The z distribution of the decay vertex shows similar agreement with the Monte Carlo data.

The resolution obtained on the projected scattering angle is shown in fig. 3a for Σ^- vacuum target data at 74.5 GeV/c. The fitted Gaussian has zero mean and a standard deviation of 0.125 mrad. The latter is smaller at higher momenta because of reduced multiple scattering in the DISC, and is less than 0.1 mrad at 136.9 GeV/c. In fig. 3b the Gaussian curve of fig. 3a is incorporated with the theoretical multiple scattering distribution in the 2 m long deuterium target, and the resulting Gaussian with $\sigma = 0.162$ mrad is seen to fit well to the experimental data.

4.1.2 Magnetic analysis

For those accepted events having associated drift-chamber data, the pion from the hyperon decay was reconstructed downstream of the magnet (fig. 1), and hence its momentum was found. The hyperon momentum or mass could then be calculated, and the distributions of the latter are shown in fig. 4 for both Σ^- and Ξ^- . The data were used to determine the mean beam momenta to an accuracy of $\sim \pm 0.1$ GeV/c and also, from the reconstructed masses, the contamination of Σ^- in the Ξ^- beam (section 7).

4.2 The antiproton data

$\bar{p}p$ and $\bar{p}d$ total cross sections were measured for comparison with Fermilab data [1], and to allow rapid high statistics checks of the properties of the scattering targets (section 3.2), and of the experimental procedures. Like the

hyperons, the antiprotons identified in the DISC constitute a small proportion (~ 1 in 400) of the negative beam.

Good events were defined from the MWPC data as having:

- a) A single beam track, as in the hyperon analysis.
- b) A single straight line track reconstructed in the B, C, and D chambers, associated with the beam, and having at least one coordinate in both x and y fitting on the line from each of the six downstream chamber modules.

Because all downstream chambers were available to define the scattering angle, the measurement accuracy is better than for hyperons. The standard deviation of the projected angle is 0.06 mrad at 101.5 GeV/c for the vacuum target.

4.3 Data consistency checks

Careful run by run consistency checks were carried out at all momenta, comparing the number of events identified at each stage of the analysis procedure, the chamber performance, the beam characteristics, and the measured transmission ratios. Those runs in which there were known chamber faults were rejected, but the remainder were all found to be statistically consistent with one another.

5. THE EXTRAPOLATION OF PARTIAL CROSS SECTIONS TO ZERO SCATTERING ANGLE

A selection of extrapolations for Σ^- , E^- , and $\bar{p}$ data is shown in fig. 5. Partial cross sections were obtained as a weighted average of those from each run, and the values of t were computed on the assumption of elastic scattering. The results have been corrected for single Coulomb scattering and Coulomb-nuclear interference effects. The real parts of the forward scattering amplitude were taken from the model predictions of Lipkin [10], which have been found to agree satisfactorily with experiment for a variety of incident particles between 70 and 200 GeV/c [11]. The combined effects of the Coulomb and Coulomb-nuclear interference corrections were always small in the t range used, the maximum value being 0.2% for 101.5 GeV/c E^- .

The minimum value of $|t|$ used in the extrapolation was determined from multiple scattering and resolution. The difference in widths of, for example, the data in figs. 3a and 3b causes the apparent rise in partial cross sections near $t = 0$ in fig. 5b. We have chosen not to apply large multiple-scattering corrections, but rather to start the extrapolation from t values where the effects are negligible. These range from $-t = 0.005 \text{ (GeV/c)}^2$ at 74.5 GeV/c to $-t = 0.009 \text{ (GeV/c)}^2$ at 136.9 GeV/c for Σ^- and Ξ^- and $-t = 0.0055 \text{ (GeV/c)}^2$ for $\bar{p}$ data. It should be noted that the high resolution of the MWPCs has allowed us to use partial cross sections closer to $t = 0$ than can be achieved with scintillation counters in transmission experiments ($|t_{\min}| = 0.016 \text{ (GeV/c)}^2$ in the Fermilab data of ref. [1]). Our extrapolation procedure is correspondingly more reliable, as can be seen from fig. 5.

The total cross section σ_T is determined by extrapolating the value of the partial cross section σ_m at the minimum usable $|t|$ value, t_m , to $t = 0$. This has been done using the analytic forms:

$$\sigma_T = \sigma_m - \sum_{j=1}^n \alpha_j t_m^j$$

and

$$\ln \sigma_T = \ln \sigma_m - \sum_{j=1}^n \beta_j t_m^j ,$$

with $n = 2$ or 3 and the values of α_j and β_j found by fitting the differences in partial cross sections, or their logarithms, between adjacent t bins, to minimize correlations. The χ^2 per degree of freedom of these fits is satisfactory at all data points, and the two forms give identical answers for the t ranges used in this experiment. The values of σ_T were found to be stable to sensible variations of t_m , the bin size in t , the range of t used, and the value of n . The estimated error in σ_T due to the extrapolation is typically $\pm 0.15\%$ for hydrogen and $\pm 0.10\%$ for deuterium, and in the quoted results it has been added in quadrature to the statistical error.

6. DATA QUALITY CHECKS

6.1 Tests for rate dependence of the measured total cross sections

As shown in table 1, Σ^- data were taken at 119.8 GeV/c at two different beam rates. The higher rate ($T1 \cdot T2 \sim 10^6/s$) was typical of normal data taking, and the second was lower by a factor of two. Antiproton data at 101.5 GeV/c were also taken at two $T1 \cdot T2$ rates of $10^6/s$ and $0.5 \times 10^6/s$. The differences in measured cross sections are given in table 3, and it is seen that no systematic rate-dependent effects were observed.

6.2 The effects of cuts on the data

The data at each momentum were subjected to some 15 separate cuts and the total cross section results compared with the original sample. Examples of such cuts were a reduction in the length of the decay region, an increase in the minimum kink angle accepted from 3 to 5.5 mrad, cuts on beam wing and halo veto counters (section 3.4) and on the beam size and angle. For Ξ^- , comparison was also made with the subset of data in which the decay $\Lambda \rightarrow p\pi^-$ was detected in the MWPCs. No systematic effects were observed as a result of any of these cuts.

7. CORRECTIONS TO THE MEASURED TOTAL CROSS SECTIONS

The following three effects were taken into account where necessary:

7.1 Ξ^- beam contamination

The Σ^- contamination in the Ξ^- beam was found by two separate methods:

- i) From the hyperon mass distribution reconstructed using the magnetic spectrometer data (section 4.1.2).
- ii) From the hyperon decay angle distribution. For a given incident momentum the maximum hyperon-pion decay angle is greater in Σ^- than Ξ^- decays (see figs. 2c and d). Σ^- decaying above the Ξ^- cut-off can thus be counted, and the number scaled up using the known decay angular distribution to find the total contamination.

The results from the two methods were in good agreement, and the Σ^- contamination in the Ξ^- data sample was 3.0% at 101.5 GeV/c and 3.5% at 133.8 GeV/c. Using the measured $\Sigma^- - \Xi^-$ total cross section differences, the correction applied to the Ξ^- results varied from -0.4% to -0.5%, with uncertainties of typically $\pm 0.15\%$.

7.2 Delta-ray production

A delta-ray produced in the full target and passing through the B chambers would cause an event to be rejected. The maximum correction for this effect was 0.1%.

7.3 Energy-loss effects

Beam energy loss in the full target slightly alters the probability of detecting a hyperon decay in the decay region. The maximum correction was -0.2% at 74.5 GeV/c.

8. THE TOTAL CROSS SECTION RESULTS

The results for the total cross sections are presented in table 4, where the quoted errors include both statistical and extrapolation uncertainties. We estimate an additional systematic error of $\pm 0.5\%$ based upon internal consistency checks and the reproducibility of the data.

In fig. 6 our $\bar{p}p$ and $\bar{p}d$ results are compared with those of the Fermilab experiment of Carroll et al. [1]. The present $\bar{p}p$ measurement lies $0.5 \pm 0.3\%$ above the smooth curve through the Fermilab data points, and our $\bar{p}d$ measurement is higher by $0.5 \pm 0.2\%$. The momentum-independent scale error of the Fermilab data is $\pm 0.4\%$ for $\bar{p}p$ and $\pm 0.5\%$ for $\bar{p}d$. Taking this and our systematic error of $\pm 0.5\%$ into account, the agreement between the two experiments is very good.

In fig. 7 we show the Σ^-p , Ξ^-p , Σ^-d , and Ξ^-d total cross sections. These are all increasing with momentum, and the slopes of the straight line fits to the Σ^-p and Σ^-d data are $0.015 \pm 0.005 \text{ mb (GeV/c)}^{-1}$ and $0.020 \pm 0.006 \text{ mb (GeV/c)}^{-1}$, with a χ^2 per degree of freedom of 0.7 and 1.1, respectively. Figure 8 includes the 18.7 GeV/c Σ^- cross sections of Badier et al. [2] and also previous proton

and K^+ measurements [1, 12] to illustrate the variation of σ_T amongst these exotic channels.

The neutron cross sections given in table 4 have been derived using conventional Glauber theory [13]. Furthermore, for consistency of presentation, we have taken $\langle r^{-2} \rangle = 0.035 \text{ mb}^{-1}$, the same as the value used by Carroll et al. [1]. The estimated uncertainty in $\langle r^{-2} \rangle$ of $\pm 0.004 \text{ mb}^{-1}$ contributes an additional systematic error of $\pm 0.35 \text{ mb}$ to $\Sigma^- n$ and $\pm 0.27 \text{ mb}$ to $\Xi^- n$. The neutron and proton cross sections are compared in fig. 9; the slope of the straight line fit to $\Sigma^- n$ is $0.008 \pm 0.007 \text{ mb (GeV/c)}^{-1}$ with a χ^2 per degree of freedom of 0.6.

9. A COMPARISON WITH σ_T MODELS

Various predictions have been published for the magnitudes of $\Sigma^- N$ and $\Xi^- N$ total cross sections. The simple additive quark model [14] implies an equal spacing rule:

$$\begin{aligned}\sigma_T(\Sigma^- p) &= \sigma_T(pp) - \Delta \\ \sigma_T(\Xi^- p) &= \sigma_T(pp) - 2\Delta.\end{aligned}\tag{1}$$

This idea is tested in fig. 10a, where the appropriate values of $\sigma_T(pp)$ have been interpolated from the data of ref. [1]. The measurements at our two Ξ^- momenta indicate that relation (1) is qualitatively correct, and quantitatively the different estimates of Δ vary by $\leq \pm 10\%$ about a mean value of 4.7 mb. In principle, a better test of equal spacing can be made by using the difference of the sums of cross sections from proton and neutron targets, as possible isospin-dependent effects are then removed. These differences, shown in fig. 10b, have been estimated by adding the Glauber screening correction to our deuterium data, and to the pd data of ref. [1]. A clear departure from equal spacing is seen. It should be noted that this conclusion is insensitive to reasonable variations in the value of the Glauber parameter $\langle r^{-2} \rangle$, provided that the latter is still taken to be the same for pd, $\Sigma^- d$, and $\Xi^- d$.

The additive quark model gives a value of Δ from the relation:

$$\Delta = \sigma_T(\pi^- p) - \sigma_T(K^- p) ,$$

and using again the data of ref. [1], the resulting cross section predictions for $\Sigma^- p$ and $\Xi^- p$ are shown in figs. 11a and b to be in poor agreement with experiment.

The two-component Pomeron model of Lipkin [15] predicts an equal spacing between the sum of the cross sections from neutron and proton targets, which, as already shown, is not accurately satisfied experimentally. However, with the further assumption that $\sigma_T(pp) = \sigma_T(pn)$ ^{*)}, the model also leads to relation (1). In this form, Lipkin has fitted all previously existing high-energy total cross section data to his model, and hence predicts from the Pomeron terms:

$$\sigma_T(\Sigma^- p) = 19.5 \left(\frac{p}{20} \right)^{0.13} + 13.2 \left(\frac{p}{20} \right)^{-0.2}$$

$$\sigma_T(\Xi^- p) = 19.5 \left(\frac{p}{20} \right)^{0.13} + 6.6 \left(\frac{p}{20} \right)^{-0.2} ,$$

where p is the hyperon laboratory momentum, and cross sections are in millibarns. The parametrized prediction for Δ is then:

$$\Delta = 6.6 \left(\frac{p}{20} \right)^{-0.2} .$$

Within the constraints of relation (1), the curves shown in figs. 11a and b fit very well to the data. However, it should be noted that Δ can be evaluated directly in this model from

$$\Delta = \frac{3}{2} \left\{ \sigma_T(\pi^- p) - \sigma_T(K^- p) \right\} = \frac{1}{2} \sigma_T(pp) - \frac{3}{4} \sigma_T(K^+ p) .$$

The two estimates of Δ given by this relation are both larger than the value derived from the parametrized form. They give better agreement with the $\Sigma^- p$ cross sections, but lead to significant (up to ~ 1 mb) discrepancies with $\Xi^- p$ cross sections.

*) $\sigma_T(pn) - \sigma_T(pp) = 0.5 \pm 0.5$ mb in the energy region of this experiment [1], where the error is due to uncertainties in the Glauber correction.

Another two-component Pomeron model giving equal cross section spacing is that of Joynson and Nicolescu [16], with

$$\Delta = \frac{2}{3} \left\{ \sigma_T(\pi^- p) - \sigma_T(K^- p) \right\} = \frac{1}{4} \sigma_T(pp) - \frac{3}{8} \sigma_T(K^+ p) .$$

This is seen in fig. 11 to be incompatible with our results.

The two-component Pomeron model of Yoshida [17], which predicts equal cross sections for $\Sigma^- p$ and $\Xi^- p$ (fig. 11), is also clearly ruled out by the data.

Finally, we show in fig. 11 the predictions of the f-coupled Pomeron model of Carlitz, Green and Zee [18]:

$$\sigma_T(\Sigma^- p) = \sigma_T(pp) \left\{ \frac{2 + r(1 - \epsilon)}{3 - \epsilon} \right\}$$

$$\sigma_T(\Xi^- p) = \sigma_T(pp) \left\{ \frac{1 - \epsilon + 2r}{3 - \epsilon} \right\}$$

evaluated with $r = 0.6$ and the D/F ratio $\epsilon = -1/3$. Good agreement is found with the $\Xi^- p$ cross sections, but the $\Sigma^- p$ prediction falls systematically below the data.

10. SUMMARY

We have presented the results of $\Sigma^- p$, $\Sigma^- d$, $\Xi^- p$, and $\Xi^- d$ total cross section measurements in the momentum range 74.5 to 136.9 GeV/c. The statistical accuracy is $\pm 1\%$ for proton target data and $\pm 0.5\%$ for deuteron target data, and the systematic uncertainty is estimated as $\pm 0.5\%$. The $\bar{p}p$ and $\bar{p}d$ total cross sections measured at 101.5 GeV/c agree well with the data of Carroll et al. [1].

We have compared our results with five different phenomenological models and find that the most successful predictions come from the two-component Pomeron model of Lipkin [15], although its physical basis is not well understood. Nevertheless our new experimental information on the strangeness dependence of hadronic total cross sections demonstrates the inadequacies of all existing theories when tested at the 1% level.

Acknowledgements

We wish to thank R. Hand and B. Charles for their work on the data-acquisition programmes, and R. Schillsott and J. Zimmer for their technical support.

We are very grateful to L. Mazzone and the CERN cryogenic target group for the construction and operation of the scattering targets. The support we have received from members of the engineering and technical groups in our laboratories is also gratefully acknowledged, as is the contribution of R. Tavano in the early stages of the experiment. We are indebted to the Rutherford Laboratory for providing the computing facilities required for the analysis of the experiment.

This work was supported in part by the Bundesministerium für Forschung und Technologie, Fed. Rep. Germany, the UK Science Research Council and the Swiss National Foundation for Scientific Research. AJB and DPS thank the SRC for financial support.

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Table 1

Beam momenta and event totals

Incident particle	Momentum (GeV/c)	Total DISC triggers analysed
Σ^-	74.5	7.9×10^6
Σ^-	86.1	8.2×10^6
Σ^-	101.3	5.9×10^6
Σ^-	119.8 ^{a)}	5.6×10^6
Σ^-	119.8 ^{b)}	5.8×10^6
Σ^-	136.9	5.2×10^6
Ξ^-	101.5	9.2×10^6
Ξ^-	133.8	5.3×10^6

a) Data taken with low-intensity beam

b) Data taken with higher intensity beam (section 6.1)

Table 2

The MWPC chamber groups

Chamber group	Wire spacing (mm)	Active area (mm ²)	z coordinate of centre (m)
A1	0.5	32 × 32	0
A2	0.5	32 × 32	2.897
B1	0.5	64 × 64	5.452
B2	0.5	80 × 80	6.687
C1	1.0	160 × 160	8.585
C2	1.0	224 × 224	10.086
D1	1.0	352 × 352	11.989
D2	1.0	416 × 416	13.883

Table 3

σ_T measurements at different beam rates

Incident particle	Momentum (GeV/c)	$\Delta\sigma_T$ (mb) low-high beam rate	
		H ₂ target	D ₂ target
Σ^-	119.8	0.25 ± 0.45	-0.30 ± 0.47
$\bar{p}$	101.5	0.32 ± 0.20	0.0 ± 0.28

Table 4

The measured total cross sections in millibarns

	Momentum (GeV/c)						
	74.5	86.1	101.3	101.5	119.8	133.8	136.9
Σ^-p	33.08 ± 0.31	33.21 ± 0.27	33.33 ± 0.31		33.29 ± 0.33		34.14 ± 0.30
Σ^-d	62.49 ± 0.30	63.13 ± 0.30	62.67 ± 0.32		63.44 ± 0.33		63.94 ± 0.30
Σ^-n	32.40 ± 0.43	32.94 ± 0.45	32.39 ± 0.45		33.24 ± 0.47		32.93 ± 0.42
Ξ^-p				29.19 ± 0.29		29.35 ± 0.31	
Ξ^-d				55.38 ± 0.29		56.27 ± 0.34	
Ξ^-n				28.51 ± 0.41		29.32 ± 0.46	
$\bar{p}p$				42.33 ± 0.14			
$\bar{p}d$				80.02 ± 0.18			

The errors quoted cover both statistics and uncertainties in the extrapolation procedure. See text for neutron cross section evaluation.

Figure captions

- Fig. 1 : A schematic plan view of the apparatus. The quadrupole Q2 is the last element of the Hyperon Beam line. The modules A1, A2, B1, B2, C1, C2, D1, and D2 denote the collection of proportional chambers detailed above them.
- Fig. 2 : Measured hyperon-pion laboratory decay angular distributions, compared with normalized Monte Carlo predictions (solid curves).
- Fig. 3 : The distribution of the projected scattering angle of 74.5 GeV/c Σ^- :
a) with the vacuum target; the curve is a fitted Gaussian with zero mean and $\sigma = 0.125$ mrad;
b) with the deuterium target; the Gaussian curve, $\sigma = 0.162$ mrad, is the prediction of multiple scattering in the target combined with the angular resolution of a). (Less than 0.6% of these data have undergone nuclear scattering.)
- Fig. 4 : Reconstructed hyperon mass distributions. The standard deviations are:
a) 3.2 MeV/c² for Σ^- at 86.1 GeV/c,
b) 2.2 MeV/c² for Ξ^- at 101.5 GeV/c.
- Fig. 5 : A selection of extrapolations in the logarithm of the transmission ratio $[(1/n\ell) \times \text{partial cross section}]$. The dashed curves show the fit to the data, the maximum $|-t|$ used, and the extrapolation to $t = 0$ (see text), where the statistical error is indicated.
- Fig. 6 : The total cross sections of Carroll et al. [1] compared with this experiment at 101.5 GeV/c, a) for $\bar{p}p$ and b) for $\bar{p}d$. The curves are our smooth interpolations to their data.
- Fig. 7 : a) The Σ^-p and Ξ^-p total cross sections. b) The Σ^-d and Ξ^-d total cross sections. The best straight-line fits to the Σ^- data are shown (see text).

Fig. 8 : A selection of total cross section data:

■ This experiment, • Carroll et al. [1], ○ Allaby et al. [12],
 × Badier et al. [2] (Σ^-N).

Fig. 9 : A comparison of the total cross sections from protons and neutrons.
 The best straight line fits to the Σ^- data are shown. (See text for details of neutron cross section evaluation.)

Fig. 10 : Differences between proton and hyperon total cross sections:

a) + $[\sigma_T(pp) - \sigma_T(\Sigma^-p)]$, • $\frac{1}{2}[\sigma_T(pp) - \sigma_T(\Xi^-p)]$,
 ○ $[\sigma_T(\Sigma^-p) - \sigma_T(\Xi^-p)]$.
 b) + $[\sigma_T(pp + pn) - \sigma_T(\Sigma^-p + \Sigma^-n)]$,
 • $\frac{1}{2}[\sigma_T(pp + pn) - \sigma_T(\Xi^-p + \Xi^-n)]$,
 ○ $[\sigma_T(\Sigma^-p + \Sigma^-n) - \sigma_T(\Xi^-p + \Xi^-n)]$.

These cross sections are derived from deuterium data, as described in the text. The errors shown are statistical only. The pp and pd data are from ref. [1].

Fig. 11 : A comparison of various model predictions with a) Σ^-p , b) Ξ^-p total cross sections. The curves represent the following models:

(1) Lipkin [15], (2) Joynson and Nicolescu [16], (3) Additive quark model [14], (4) Carlitz et al. [18], (5) Yoshida [17].

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 5 (cont.)

Fig. 6

Fig. 7

Fig. 8

| Fig. 9

Fig. 10

Fig. 11