THE Σ^-p AND Σ^-d TOTAL CROSS SECTIONS AT 19 GeV

J. BADIER, R. BLAND *, A. ROMANA and R. VANDERHAGEN,
Ecole Polytechnique, Paris, France

J.C. CHOLLET, D. DÉCAMP, J.M. GAILLARD, J. LEFRANÇOIS,
B. MERKEL and J.P. REPELLIN
Laboratoire de l'Accélérateur Linéaire, Orsay, France

T. DEVLIN **, R. MEUNIER ‡ and G. SAUVAGE ‡‡
CERN, Geneva, Switzerland

Received 15 August 1972

The total cross sections of 18.7 GeV Σ^- hyperons on protons and deuterons have been measured to be 34.0 ± 1.1 mb and 61.3 + 1.4 mb, respectively. The derived Σ^--neutron cross section is 30.0 ± 1.2 mb.

The recent development of high-energy hyperon beams [1–3] exploiting the relativistic dilation of these particles' short lifetimes opens the door to a variety of new experiments. We describe here the second experiment done in our beam of negative hyperons, a measurement of the Σ^-p and Σ^-d total cross sections at 18.7 GeV. The results are compared with the predictions of the quark model sum rules.

Our experimental set-up at the CERN PS is shown in fig. 1. The beam, already described elsewhere [1], selected negative particles of 18.7 GeV/c with a momentum spread of ± 10%, parallel at the exit except for a momentum dispersion of 0.8 mrad/%. These particles traversed a DISC differential Čerenkov counter – set to select Σ^-'s – a target, and a second DISC. The beam was defined by 3 × 3 cm scintillators before and after each DISC ($T_1 - T_4$), and large anticounters (A_1 and A_2), with a central circular hole 3 cm in diameter, were placed before and after the first DISC to veto multiparticle triggers. Proportional wire chambers [4] before and after each DISC ($C_1 - C_4$) measured the particle position and direction before and after the target. These measurements permitted further limitations of the beam size in the subsequent analysis and, more important, permitted an extrapolation in scattering angle without a corresponding reduction in the solid angle accepted, as is necessary with the more common counter technique.

The decay $\Sigma^- \to n\pi^-$ after DISC 2 was used to improve the rejection of background. About 3 m (4 Σ^- decay lengths) after DISC 2 were placed two scintillators P_1 and P_2 (10 × 10 cm^2) and a neutron shower counter N, 17 × 17 cm^2 in cross section, with 1500 g/cm^2 of lead-scintillator sandwich. The anticoincidence $\overline{(P_1 P_2)}$ was used to reject background events including a stable charged particle along the beam direction (and also rejected about 12% of the Σ^-'s, where the decay π^- or the Σ^- itself passed through P_1 and P_2). The neutron counter, over 97% efficient, gave a further Σ^- signature.

The incident Σ^- signal was Strobe$_1$ × DISC 1, where Strobe$_1$ = $T_1 T_2 \overline{T}_{1H} \overline{T}_{2H} \overline{A}_1 \overline{A}_2$. $\overline{T}_{1H}$ and $\overline{T}_{2H}$ are vetoes of high pulses from T_1 and T_2, intended along with $\overline{A}_1$ and $\overline{A}_2$ to reject multiparticle showers which could trigger the DISC. A coincidence of all eight photomultipliers of the DISC was required, with an efficiency due to photon statistics of 95%. The diaphragms in the focal plane of the Čerenkov light were open to $\Delta\theta_C = \pm 5$ mrad ($\theta_C = 120$ mrad) for DISC 1, and to a much less restrictive opening $\Delta\theta_C = \pm 12$ mrad for DISC 2, still excluding however the π^-'s and K^-'s of the beam and the decay π^- from a Σ^- of 19 GeV. The transmitted Σ^- trigger was Σ_8 = Strobe$_1$ × DISC 1 × T_3 × T_4 × DISC 2. The coincidence $\Sigma_8 \times \overline{(P_1 P_2)} \times N$ was not included directly in the trigger, but was recorded on tape.

* Present address: Dépt. of Natural Philosophy, The University, Glasgow, Scotland.

** Rutgers University Research Council Faculty Fellow, 1970–1971.

‡ Visitor from CEN, Saclay, France.

‡‡ CERN Fellow, on leave from LAL, Orsay, France.

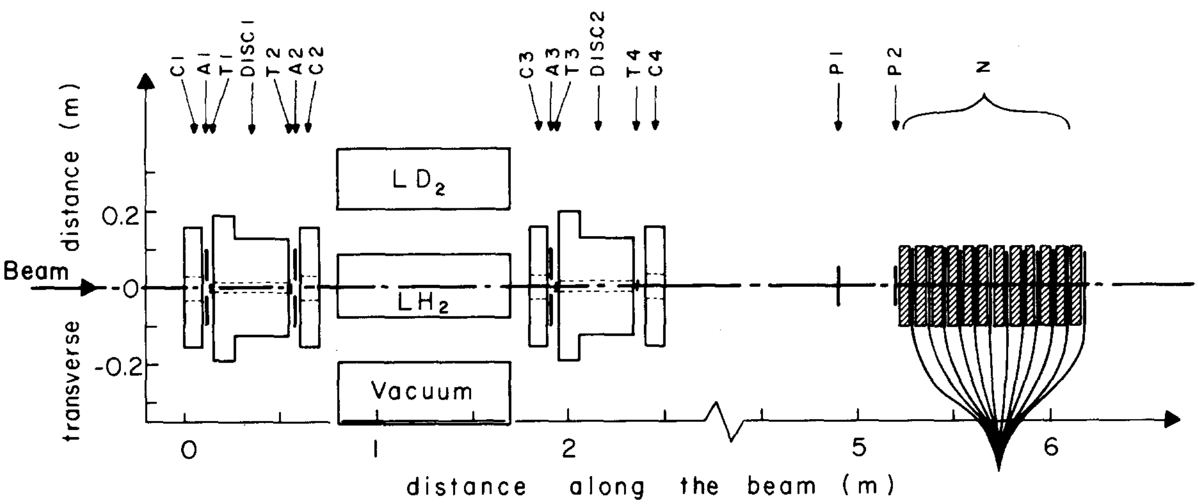

Fig. 1. Plan view of the experiment (note exaggerated transverse scale).

The target arrangement consisted of three identical cylindrical target vessels 92 cm long and 10 cm in diameter, each enclosed in a 2.5 cm cylindrical cooling jacket filled with liquid hydrogen at atmospheric pressure. One target was filled with liquid hydrogen, another with liquid deuterium, and the third was evacuated. The targets were cycled continually, with a run length of 1024 transmitted Σ^- triggers, corresponding to about 5 minutes of running, for vacuum and hydrogen, and 512 triggers for deuterium. All transmitted Σ^- triggers were recorded on magnetic tape by a Varian 621b computer. At every change of target a scaler record, including the number of incident Σ^-'s counted, was recorded.

The data were taken during two 15-day runs. About 2×10^{11} protons per pulse were incident on the production target, giving about 80 incident Σ^- counts and 6 transmitted Σ^- counts per burst, as well as about 10^5 π^-. We recorded 2.7×10^6 Σ^- triggers on magnetic tape. As a control experiment, we also measured the pp and pd total cross sections at 19.8 GeV. The experimental conditions for protons differed from those for Σ^-'s only in the following respects: the total beam flux was lower by a factor of 10; the beam was somewhat less divergent in angle; and, of course, the protons did not decay in the experimental apparatus. In a two-day run about 3×10^6 proton triggers were recorded.

The off-line analysis required the reconstruction of the incident and transmitted Σ^- tracks in the wire chambers. Events with no wires fired in one of the eight wire planes were lost. The fraction of such events, about 15%, was found to be largely target independent, giving an error of less than 0.5% in the cross section. About 50% of the events had more than one cluster of wires in at least one plane. In chambers 1 and 2 a quite restrictive recovery procedure was adopted: only one of the four wire planes could be recovered, and that one only by rejection of single isolated wires in favour of a multiwire cluster. Ten per cent of all events were not recoverable by this procedure.

Chambers 3 and 4 were treated differently. Being after the target, a target-dependent effect could bias the recovery procedure, as in the case of forward δ-rays produced in the target and passing through the chambers. We therefore recovered *all* multicluster events, by taking the cluster closest to the projection of the track defined by chambers 1 and 2. This procedure chose the wrong cluster for less than 0.05% of the events.

Several geometrical cuts were then made on the data, using only the coordinates in chambers 1 and 2 so as to preclude target-dependent effects. The DISCs have an unobstructed circular aperture of 30 mm. The incident track was therefore limited in chamber 1 to an ellipse with a horizontal axis of 16 mm and a vertical axis of 26 mm centered on DISC 1, and the projection of the incident track onto the entrance of DISC 2 was limited to a central 23 mm circle. The tails of the θ_x and θ_y distributions for the incident particles were cut at ± 4 mrad and ± 2.5 mrad, respectively.

Finally, the sample was limited to events giving a $\Sigma_8 \times \overline{(P_1 P_2)} \times N$ coincidence. About 25% of the transmitted Σ^- triggers survived all the cuts.

These events were used to calculate the cross section, from the formula

$$\sigma^{\mathrm{H}}_{\mathrm{tot}} = \sigma^{\mathrm{H}}_0 \ln \left[(N^{\mathrm{V}}/M^{\mathrm{V}})/(N^{\mathrm{H}}/M^{\mathrm{H}})\right].$$

Here V and H refer to the vacuum and hydrogen targets, with a similar formula holding for the deuterium data; N is the number of transmitted Σ^-'s; M(monitor) is the number of incident Σ^-'s; and $\sigma_0^{(\mathrm{H,D})} = A/N_{\mathrm{A}}\rho L$, where N_{A} is Avagadro's number, A is the atomic weight of the target material, L is the target length (L = 91.73 ± 0.05 and 91.60 ± 0.05 cm for H and D, respectively), and ρ is the density of the target material (ρ = 0.0707 ± 0.0005 and 0.1703 ± 0.0009 g/cm^3 for H and D respectively). It was checked that the deuterium included less than 1.5% of hydrogen.

This cross section is implicitly a function of a maximum scattering angle θ_{max}. For any finite value of θ_{max} we have to correct for forward scattering counted as transmitted events, and for the widening of the angular distribution due to Coulomb scattering in the full targets. The Coulomb scattering is treated by folding into the empty-target angular distribution a Gaussian multiple Coulomb scattering. The magnitude of this scattering, determined by fitting the angular distribution for V, H, and D between θ = 0 and 1.6 mrad, is $\theta_{\mathrm{rms-Coul}}$ = 0.292 ± 0.005 mrad for hydrogen, 0.324 ± 0.0057 mrad for deuterium.

The forward scattering correction is calculated a priori, assuming that Σ^-p scattering is similar to pp scattering. The elastic scattering is the sum of three terms: Coulomb single scattering, nuclear scattering, and scattering by the strong-electromagnetic interference. To account for inelastic scattering giving a secondary within the acceptance of DISC 2, we multiply the nuclear scattering term by a factor $K > 1$. The parameters of pp elastic scattering at 19 GeV are well known [5,6]:

$$\alpha \equiv \mathrm{Re} f(0)/\,\mathrm{Im} f(0) = -0.21 \pm 0.02\,,$$

where the slope of the dσ/dt distribution

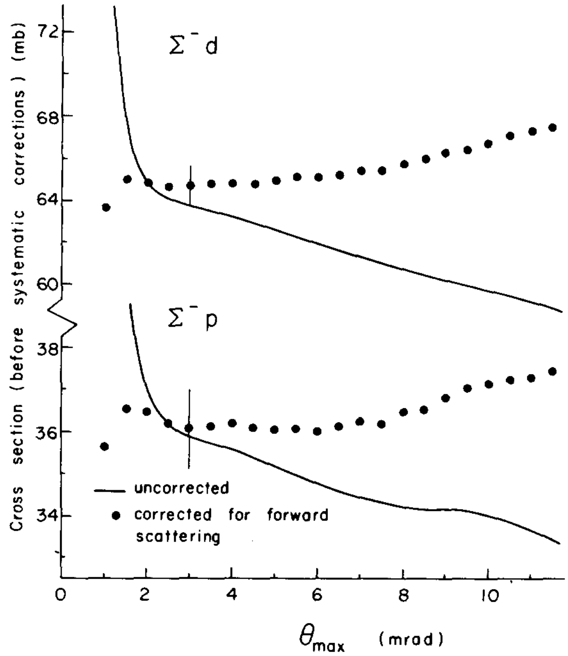

Fig. 2. Cross section as a function of cut-off angle θ_{max}. The solid lines are calculated without any corrections, and the circles are corrected for forward scattering. The error bars are purely statistical, and systematic corrections have not yet been applied (see table 1).

$$B = 10 \pm 1\,(\mathrm{GeV}/c)^{-2}\,.$$

Using these parameters, we determine K from a fit to our pp data: K_{proton} = 1.70 ± 0.05. For the Σ^-p elastic scattering we take the pp parameters, correcting for the difference in total cross section (anticipating our result) according to scaling suggested by the optical model:

$$\alpha = -0.23 \pm 0.25, \quad B = 8.8 \pm 1.0\,(\mathrm{GeV}/c)^{-2},$$

$$K = 1.7 \pm 0.2\,.$$

The forward-scattering correction for deuterium is rather complicated; we follow Bellettini et al. [7] (pd at 19 GeV), except that again we multiply the direct nuclear scattering term by the factor K. For Σ^-n we take

$$\alpha = -0.25 \pm 0.25, \quad B = 7.6 \pm 1.0\,(\mathrm{GeV}/c)^{-2}$$

$$K = 1.7 \pm 0.2\,.$$

Table 1
Our results, compared with previous measurements, for the proton data, and with quark model predictions, for the Σ^- data, using the sum rules given in the text.

	$\sigma_{tot}(\Sigma^- p)$	$\sigma_{tot}(\Sigma^- d)$	$\sigma_{tot}(\Sigma^- n)$	$\sigma_{tot}(pp)$	$\sigma_{tot}(pd)$	$\sigma_{tot}(pn)$
Uncorrected, $\theta < 3$ mrad	35.80 ± 0.93	63.70 ± 0.96		39.29 ± 0.55	73.53 ± 0.55	
Forward scattering	0.23 ± 0.4	0.94 ± 0.6		− 0.10 ± 0.10	0.78 ± 0.35	
Dead-time	− 1.67 ± 0.5	− 2.88 ± 0.9		− 0.6 ± 0.2	− 0.8 ± 0.4	
Decays	− 0.4	− 0.5				
$\sigma_{tot}(d) - \sigma_{tot}(p)$			27.30 ± 1.14			34.92 ± 0.67
Glauber correction			2.71 ± 0.5			3.82 ± 0.4
Final result	34.0 ± 1.1	61.3 ± 1.4	30.0 ± 1.3	38.6 ± 0.6	73.5 ± 0.8	38.7 ± 0.8
Other experiments				39.10 ± 0.12 (ref. [10])	74.1 ± 0.7 (ref. [11])	38.9 ± 0.7 (ref. [11])
Quark model	35.0 ± 0.9	66.8 ± 0.9	34.4 ± 0.25			

Sum rules	This expt.	Quark model
$\sigma_{tot}(pp) - \sigma_{tot}(\Sigma^- p)$	5.1 ± 1.1	4.1 ± 0.9
$\sigma_{tot}(pd) - \sigma_{tot}(\Sigma^- d)$	12.8 ± 1.5	
$\sigma_{tot}(pn) - \sigma_{tot}(\Sigma^- n)$	8.9 ± 1.4	
$\sigma_{tot}(\Sigma^- p) - \sigma_{tot}(\Sigma^- n)$	4.0 ± 1.3	0.6 ± 0.8
$\sigma_{tot}(\Sigma^- p) + \sigma_{tot}(\Sigma^- n)$	64.0 ± 1.5	69.2 ± 0.8

The results of applying these corrections is shown in fig. 2. The solid line represents the data without any correction. The circles have been corrected according to the following algorithm: (1) fold in the multiple Coulomb scattering and recalculate the cross section ($\Delta\sigma = -0.2$ mb for Σ^-p and Σ^-d, $\theta_{max} = 3$ mrad); (2) add the cross section for forward *nuclear* scattering at $\theta < \theta_{max}$ ($\Delta\sigma = 0.3$ and 0.8 mb for Σ^-p and Σ^-d); and (3) subtract the cross section for single Coulomb scattering and for scattering due to the Coulomb-nuclear interference for $\theta > \theta_{max}$ ($\Delta\sigma_{Coul} = -0.2$ mb, $\Delta\sigma_{interference} = +0.35$ and $+0.55$ mb for Σ^-p and Σ^-d). The algorithm is expected to be valid for $\theta_{max} \gg \theta_{rms-Coul}$, where the effects of single and multiple Coulomb scattering can be separated, and for angles small enough that DISC 2 is efficient over the entire angular spread of the beam. We see from fig. 2 that there is a good "extrapolation plateau", for $2 < \theta_{max} < 7$ mrad for hydrogen, $2 < \theta_{max} < 6$ mrad for deuterium. We use the values for $\theta_{max} = 3$ mrad, where the errors due to uncertainties in the slope B and the inelasticity parameter K are negligible (less than 0.1 mb). The results are given in table 1. The error on the forward scattering correction is that due to an uncertainty in α of $\Delta\alpha = \pm 0.25$. This uncertainty is our guess at the validity of the assumption that Σ^-p elastic scattering is "like" pp elastic scattering. A weak experimental confirmation of this assumption can be obtained by fitting our Σ^-p angular distribution. With K constrained to be 1.7 ± 0.2, we find $\alpha = -0.3 \pm 0.4$. [The slope B was fixed at the value given previously, as it has little effect at such small angles; for $\theta = 7$ mrad, $t \approx -0.02$ (GeV/c)^2.]

We have made an extensive study of possible experimental biases. They can be divided into three sorts: variable Σ^- detection efficiency as a function of target position, effects of non-Σ^- background in the beam, and incorrect target positioning or density.

Variable Σ^- detection efficiency: The singles counting rates of all counters downstream of the target, monitored continuously throughout the experiment, are variable with target positions, due to the interaction of the π^- beam in the target. Most of the counters are protected against random coincidence and dead-time effects by the rejection in chambers 1 and 2 of multitrack events. This is not true of the photomultipliers of DISC 2, which, because of their low threshold, count at a very high singles rate, due to particles not in the centre of the beam. The resulting deadtime, about 15% on the average, varied slightly with target position, giving rise to the correction given in table 1.

The slight widening of the beam due to multiple Coulomb scattering in the target should have no effect, since a well-collimated beam is selected using the coordinates in chambers 1 and 2. The energy loss in the full targets, about 20 MeV, has a light effect by changing the decay length of the Σ^-'s; the corresponding correction is given in table 1.

Possibles biases due to the recovery of multicluster events in chambers 3 and 4 have been investigated, and the effect is negligible.

Non-Σ^- background: We have tried to understand the background by studying the events rejected by the Σ^- signature $\overline{(P_1\, P_2)} \times N$. These events include some good Σ^-'s (12% of all events), π^-'s of ~ 2 GeV/c and K^-'s of ~ 7 GeV/c (~ 8% of all events), protons of ~ 14 GeV/c ($\lesssim 5$% of all events), and a remaining background (~ 5% of all events). All of these backgrounds should be strongly rejected by the anticoincidence $\overline{(P_1 P_2)}$. As a final test, we have made much more rigorous cuts on the entrance angles and position, discriminating selectively against the poorly-focused π's, K^-'s, and protons. The cross section does not change, whitin statistical errors.

Incorrect target positioning or density: The identity of the target was determined by two separate data registers, and was in addition verified by counting rates recorded in the scaler record which varied according to the density of the target in the beam.

The density given above for the hydrogen and deuterium assumed thermal equilibrium between the targets and their cooling jackets. The agreement of our values of σ_{tot}(pp) and σ_{tot}(pd) with published results supports these values. Their ratio is in addition verified by the ratio of the multiple Coulomb scattering in the hydrogen and deuterium targets (given above). The attenuation of the π^- beam in the targets, monitored continuously during the experiment, shows no variation in target density as a function of time. In particular, assuming that the density of the hydrogen did not change, the ratio of the deuterium density for the two runs was $\rho_{D_2}(\text{run }2)/\rho_{D_2}(\text{run }1) = 0.996 \pm 0.015$.

Our final results, including all corrections, are given in table 1. The agreement between our incident proton results and results already published is excellent. For comparison with the quark model [8], we have used the following sum rules:

$$\sigma_{tot}(pp) - \sigma_{tot}(\Sigma^- p) = \sigma_{tot}(\pi^- p) - \sigma_{tot}(K^- p) + 2[\sigma_{tot}(K^+ p) - \sigma_{tot}(K^+ n)]\,,$$

$$\sigma_{tot}(pp) - \sigma_{tot}(\Sigma^- n) = \sigma_{tot}(\pi^- p) - \sigma_{tot}(K^- p)\,,$$

$$\sigma_{tot}(pd) - \sigma_{tot}(\Sigma^- d) = \sigma_{tot}(\pi^- d) - \sigma_{tot}(K^- d)\,,$$

$$\sigma_{tot}(\Sigma^- p) + \sigma_{tot}(\Sigma^- n) = 2\sigma_{tot}(\Lambda^0 p)\,.$$

Here we assume additivity of the quark–quark elastic scattering amplitude and isotopic-spin invariance for the quark–quark interaction. [Nucleon–nucleon and meson–nucleon cross sections, evaluated respectively at 19 and 12.3 GeV, are taken from standard data compilations [6, 9]. For the Λ^0p total cross section we use the recently published value of Gjesdal et al. [3] 34.6 ± 0.4 mb.] From table 1 it is evident that, while our Σ^-p total cross section agrees with the quark model, our Σ^-d total cross section and the derived Σ^-n total cross section are in substantial disagreement with the quark model.

We would like to thank Professors R.E. Mischke, W. Cleland and W. Wales for permission to use the target assembly, and Messrs. L. Mazzone and R. Brandt for preparing and operating the target for our experiment.

References

[1] J. Badier et al., Phys. Lett. 39B (1972) 414.
[2] W.J. Willis, The AGS hyperon beam as a facility, HEDG Minutes, June 9, 1971.

[3] S. Gjesdal et al., Phys. Lett. 40B (1972) 152.
[4] B. Merkel, Nuclear Instrum. Methods 94 (1971) 573.
[5] K.J. Foley et al., Phys. Rev. Lett. 19 (1967) 857.
[6] O. Benary, L.R. Price and G. Alexander, NN and ND interactions (above 0.5 GeV/c) – A compilation, Lawrence Radiation Laboratory Report UCRL – 20000 NN (1970).
[7] G. Bellettini et al., Phys. Lett. 19 (1965) 341.
[8] See, for example, J.J.J. Kokkedee, The quark model (Benjamin, New York, 1969).
[9] E. Flaminio et al., Compilation of cross sections, Vols. I, III, VI, CERN/HERA 70–2, 70–4, 70–7 (1970). L. Price et al., A compilation of K^+N reactions, Lawrence Radiation Laboratory Report UCRL–20000 K^+N (1969).
[10] K.J. Foley et al., Phys. Rev. Lett. 19 (1967) 857.
[11] G. Bellettini et al., Phys. Lett. 19 (1965) 341.