

COMPARISON OF NEUTRAL PARTICLE PRODUCTION IN 100 GeV/c $\bar{p}p$ AND pp INTERACTIONS

D.R. WARD, R.E. ANSORGE, C.P. BUST, J.R. CARTER, W.W. NEALE and J.G. RUSHBROOKE
Cavendish Laboratory¹, Cambridge, England

C. MOORE, R. RAJA, L. VOYVODIC and R.J. WALKER
Fermi National Accelerator Laboratory², Batavia, Ill. 60510, USA

W. MORRIS³, B.Y. OH, D.L. PARKER⁴, G.A. SMITH and J. WHITMORE
Michigan State University⁵, E. Lansing, Michigan 48824, USA

Received 12 April 1976

We derive cross-sections for the inclusive production in $\bar{p}p$ interactions at 100 GeV/c of π^0 , K_s^0 and $\Lambda^0/\bar{\Lambda}^0$ of 91.5 ± 5.7 mb, 5.2 ± 0.4 mb and 4.8 ± 0.4 mb respectively, which are all higher than pp cross-sections at this energy. We find indications that these differences can be attributed to "annihilation" processes.

Introduction. We present results on the production of γ , K_s^0 , Λ^0 and $\bar{\Lambda}^0$ in $\bar{p}p$ interactions at 100 GeV/c. We also look for differences between pp and $\bar{p}p$ interactions, which could be ascribed to the effects of "annihilation" processes. Both the present experiment and pp experiments at this energy suffer from limited statistics, but we find that cross-sections for the production of neutral particles are in all cases somewhat higher in $\bar{p}p$ interactions than in pp interactions. In the case of $\Lambda^0/\bar{\Lambda}^0$ production (and possibly γ 's) the difference appears to arise mainly in the neighbourhood of $y^* = 0$, characteristic of a central production process.

The data to be described are the first on $\bar{p}p \rightarrow$ neutrals above 14.75 GeV/c, and come from a 100 000 picture exposure of the 30" hydrogen bubble chamber at Fermilab to a tagged beam of negative particles. Information on the $\bar{p}p$ charged multiplicity distribution

at 100 GeV/c [1] and on the difference between $\bar{p}p$ and pp topological cross-sections [2] has already been published. The efficiency for scanning for V^0 's was about 90% for singly scanned film, and after measurement and remeasurement 93% of events had been satisfactorily measured. After all cuts we have 1015 V^0 's associated to events inside our fiducial volume giving fits to Λ^0 , K_s^0 and $\bar{\Lambda}^0$ decays, or $\gamma \rightarrow e^+e^-$ conversion. Ambiguities (affecting about 9% of the events) were resolved by observing ionizations where possible, and otherwise by cuts on the transverse momentum of the decays and on the χ^2 probabilities of the fits.

The data were corrected for scanning and measuring losses, for losses of V^0 's decaying or converting outside the fiducial volume, or closer than 3 cm (2 cm in the case of K_s^0) to the production vertex, and for interactions of the strange particles. The pair production cross-section was taken from ref. [3], and the strange particle cross-sections were corrected for branching ratios taken from ref. [4]. A correction ($\sim 2-3\%$) was made for the loss of γ 's below 40 MeV/c using the symmetry of the reaction $\bar{p}p \rightarrow \gamma$ in the c.m. system.

Cross-sections and multiplicities. In table 1 we give cross-sections for $\Lambda^0/\bar{\Lambda}^0$, K_s^0 and π^0 production, the latter taken to be $\frac{1}{2} \sigma(\bar{p}p \rightarrow \gamma)$. We have used events in both forward and backward hemispheres in the c.m. system for the γ 's, since, apart from the loss of very slow γ 's, no forward/backward asymmetry was found

¹ Work supported by the Science Research Council, UK.

² Operated by the Universities Research Association, Inc., under Contract with the Energy Research and Development Administration, USA.

³ Presently at General Atomic Company, San Diego, CA 92138, USA.

⁴ Presently at Department of Physics, Iowa State University, Ames, Iowa, 50010, USA.

⁵ Work supported in part by the National Science Foundation, USA.

Table 1
Comparison of neutral particle cross-sections in $\bar{p}p$ and pp interactions at 100 GeV/c.

Charged Multiplicity n_{ch}	$\sigma(\bar{p}p \rightarrow \pi^0)$ mb	Smoothed $\sigma(pp \rightarrow \pi^0)$ mb	$\sigma(\bar{p}p \rightarrow K_s^0)$ mb	Smoothed $\sigma(pp \rightarrow K_s^0)$ mb	$\sigma(\bar{p}p \rightarrow \Lambda^0/\bar{\Lambda}^0)$ mb	$\sigma(pp \rightarrow \Lambda^0/\bar{\Lambda}^0)^c$ mb
0	0.65±0.32	—	—	—	0.02±0.02	—
2	4.8 ±0.8	7.2±1.5	0.26±0.11	0.31±0.07	0.48±0.12	0.36±0.14
4	15.4 ±1.6	14.5±1.0	0.97±0.15	0.77±0.15	1.14±0.18	1.32±0.24
6	22.8 ±2.8	22.8±4.0	1.27±0.17	1.1 ±0.15	1.24±0.20	0.80±0.18
8	23.0 ±2.0	20.3±2.2	1.39±0.18	0.8 ±0.1	1.00±0.20	0.64±0.18
10	11.6 ±1.5	10.9±1.0	0.71±0.14	0.65±0.1	0.62±0.14	0.46±0.16
12	6.9 ±1.0	6.3±1.0	0.46±0.11	0.3 ±0.07	0.14±0.06	0.04±0.04
14	5.4 ±1.2	2.5±1.5	0.10±0.05	0.07±0.07	0.16±0.08	—
16	0.2 ±0.2	1.0±0.4	0.03±0.03	0.04±0.04	—	—
18	0.6 ±0.4	0.5±0.5	—	0.02±0.02	—	—
Total ^a	91.5 ±5.7	86 ±6	5.2 ±0.4	4.1 ±0.3	4.8 ±0.4	3.6 ±0.4
$\langle n_{ch} \rangle$	7.45±0.15	7.17±0.19	7.25±0.22	7.05±0.24	6.48±0.24	5.79±0.29
$\langle n(V^0) \rangle$	2.64±0.16	2.70±0.19	0.15±0.01	0.13±0.01	0.14±0.01	0.11±0.01
Raw no. of $\bar{p}p$ events	628		230 (backward only)		157 (backward only)	
Average weight ^b	52.5		1.50		1.80	

^a The errors on the $\bar{p}p$ cross-sections here include a 5% systematic uncertainty in normalization.

^b Excluding scanning and measuring losses, and branching ratios. ^c Unsmoothed values from ref. [5], scaled up to allow for $\bar{\Lambda}^0$'s.

within errors. For the K_s^0 data, however, we have only used events in the backward hemisphere because of the low detection efficiency for fast V 's, but by C -invariance the cross-section in the two hemispheres must be equal. The $\Lambda^0/\bar{\Lambda}^0$ cross-section likewise uses only events in the backward hemisphere, but again C -invariance implies that Λ^0 and $\bar{\Lambda}^0$ distributions are related by a simple reflection about $y^* = 0$ in the c.m. Hence we lose no information on $\Lambda^0/\bar{\Lambda}^0$ by using only the backward hemisphere, and $\frac{1}{2} \sigma(\bar{p}p \rightarrow \Lambda^0/\bar{\Lambda}^0) = \sigma(\bar{p}p \rightarrow \Lambda^0) = \sigma(\bar{p}p \rightarrow \bar{\Lambda}^0)$. Table 1 gives cross-sections for different charged multiplicities at the primary vertex (corrected for undetected dalitz pairs and V^0 's). We also quote mean associated charged multiplicities for V^0 production and mean numbers of $\Lambda^0/\bar{\Lambda}^0$, K_s^0 and π^0 produced per inelastic collision. For comparison, the corresponding quantities are given for pp interactions. There are pp experiments at 102 GeV/c [5] and 100 GeV/c [6], and rather than simply averaging their values, we quote "smoothed" values for π^0 and K_s^0 cross-sections, taking account of pp data at other energies [7]. There are no data on the topological cross-

sections for $pp \rightarrow \bar{\Lambda}^0$, but this is a small contribution, so we have taken the same topological dependence as for $pp \rightarrow \Lambda^0$. Fig. 1 (a-c) shows the cross-sections with data at lower energies [8], and we also show the energy dependence of the pp channels, for comparison.

The cross-section for $\bar{p}p \rightarrow \pi^0$ is higher by ~ 5.5 mb than in pp interactions, though this is less than one standard deviation. Fig. 1(d) shows that $\langle n(\pi^0) \rangle$ as a function of n_{ch} is virtually identical to pp interactions, implying that the degree of correlation between charged and neutral pions is the same in both cases, and has not been significantly affected by any annihilation component, in contrast to the behaviour found at 14.75 GeV/c [8]. This is also indicated by the correlation parameters $f_2^{-0} = \langle n_0 n_- \rangle - \langle n_0 \rangle \langle n_- \rangle$, which has the value at 100 GeV/c of 0.94 ± 0.24 for $\bar{p}p$, compared to 1.10 ± 0.26 for pp interactions.

Fig. 1(e) shows the variation of $\langle n(K_s^0) \rangle$ with n_{ch} for $\bar{p}p$ and pp interactions, and likewise fig. 1(f) for $\Lambda^0/\bar{\Lambda}^0$. Again there is no clear difference between $\bar{p}p$ and pp , indicating that correlations between charged particles and neutrals are similar in the two cases. We

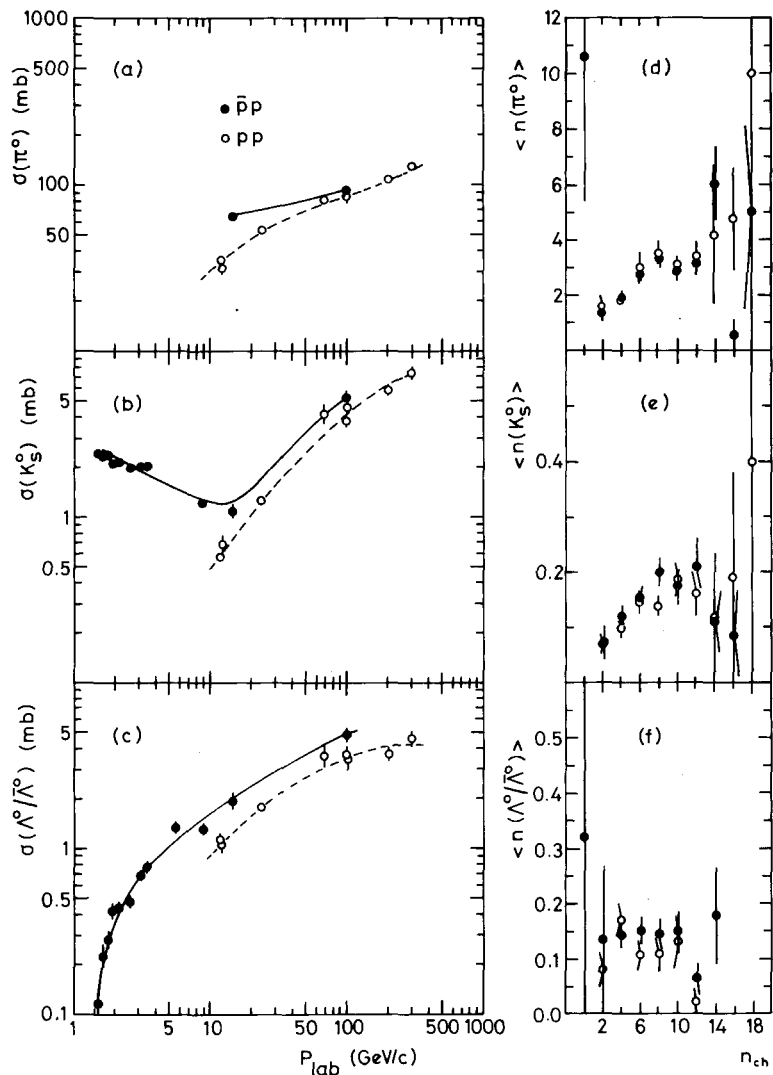


Fig. 1. (a) Cross-section for $\bar{p}p \rightarrow \pi^0$ as a function of laboratory momentum, with pp data for comparison. (b) Likewise for K_S^0 . (c) Likewise for $\Lambda^0/\bar{\Lambda}^0$. (d) $\langle n(\pi^0) \rangle$ as a function of charged multiplicity, for 100 GeV/c $\bar{p}p$ and pp interactions. (e) likewise for K_S^0 . (f) Likewise for $\Lambda^0/\bar{\Lambda}^0$. The curves merely guide the eye.

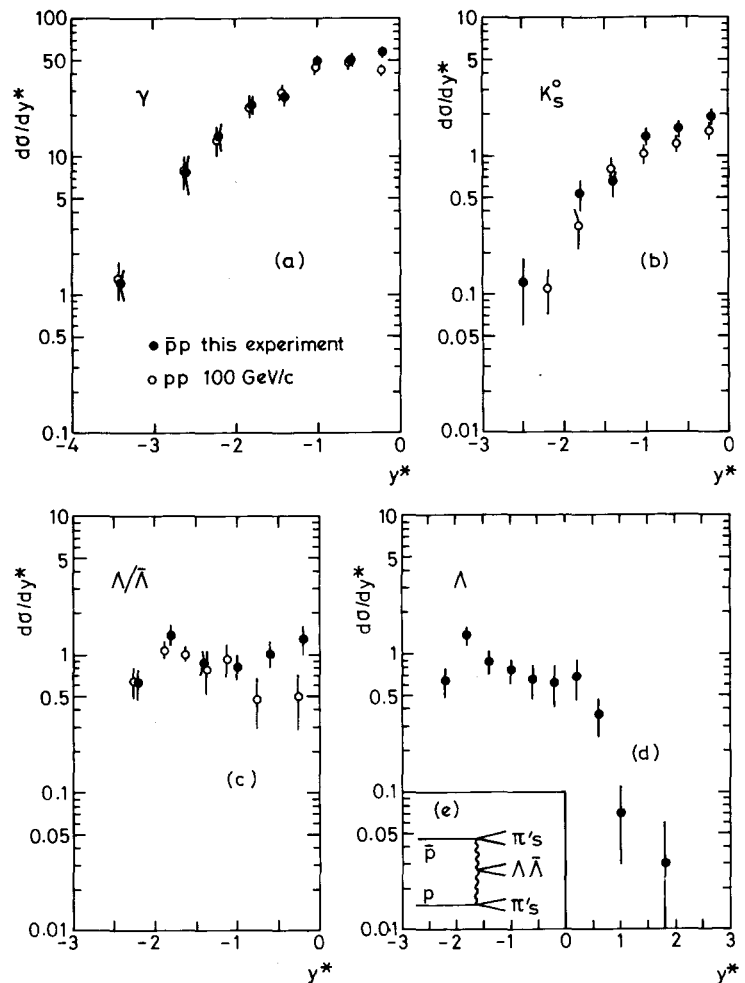


Fig. 2. (a) $d\sigma/dy^*$ vs y^* for $\bar{p}p \rightarrow \gamma$ at 100 GeV/c, with pp data (averaged using data of refs. [5, 6]) for comparison. Data from both hemispheres are averaged. (b) $d\sigma/dy^*$ for $\bar{p}p \rightarrow K_S^0$, compared with pp data at 100 GeV/c. Only backward hemisphere data is used. (c) $d\sigma/dy^*$ for $\bar{p}p \rightarrow \Lambda^0/\bar{\Lambda}^0$ at 100 GeV/c compared with pp data [5]. (d) $d\sigma/dy^*$ for $\bar{p}p \rightarrow \Lambda^0$ at 100 GeV/c; backward hemisphere Λ^0 , and $\bar{\Lambda}^0$ reflected into the forward hemisphere to represent the full Λ^0 distribution. (e) Diagram which could contribute an excess of $\Lambda^0/\bar{\Lambda}^0$ in the central region in $\bar{p}p$ interactions.

can make an estimate of the “annihilation” component in $\bar{p}p \rightarrow K_s^0$ and $\bar{p}p \rightarrow \Lambda^0/\bar{\Lambda}^0$ from the differences $(\bar{p}p - pp)$, subtracting the cross-sections given in table 1. The mean charged multiplicities calculated from these differences are 8.0 ± 1.3 and 8.4 ± 1.6 respectively which are probably both somewhat higher than for the overall samples of K_s^0 and $\Lambda^0/\bar{\Lambda}^0$ events. Such an effect was also seen in the $(\bar{p}p - pp)$ multiplicity distribution of all events [2], where a mean charged multiplicity 9.06 ± 0.56 was found; hence we are encouraged to associate the difference in cross-sections with “annihilations”, an interpretation which receives some support from the single particle distributions presented in the next section. The mean charged multiplicity for $(\bar{p}p - pp) \rightarrow \pi^0$ is also high, ~ 10 , though with large errors.

Single particle distributions. We now try to localise these cross-section differences in terms of single particle distributions. We find the most useful of these to be the centre-of-mass rapidity, y^* . Fig. 2(a–c) shows $d\sigma/dy^*$ for our γ , K_s^0 and $\Lambda^0/\bar{\Lambda}^0$ data, folded about $y^* = 0$ and halved in the former case, compared with pp data from refs. [5, 6]. Fig. 2(d) shows the $\bar{p}p \rightarrow \Lambda^0$ and $\bar{p}p \rightarrow \bar{\Lambda}^0$ data separately (the latter reflected into the forward hemisphere).

The $d\sigma/dy^*$ distribution for the γ 's, fig. 2(a), has the best statistics, and indicates that any difference between $\bar{p}p$ and pp cross-sections is mostly coming from the region $|y^*| \leq 1.0$. For $|y^*| > 1$ the agreement is really rather close. For the K_s^0 , fig. 2(b), the difference in cross-sections appears to be spread fairly uniformly over the range of y^* , though our statistics do not permit us to say whether the K 's are really behaving differently from the γ 's. Fig. 2(c) shows the rapidity distribution for combined $\Lambda^0/\bar{\Lambda}^0$ production (the small $pp \rightarrow \bar{\Lambda}^0$ contribution was estimated by scaling the distribution at 200 GeV/c [9] to the 100 GeV/c cross-section). Here there is good agreement between $\bar{p}p$ and pp in the proton fragmentation region, $y^* < -1$, but a substantial excess in $\bar{p}p$ in the central region, $y^* > -1$. This observation invites interpretation in terms of processes like $\bar{p}p \rightarrow (\Lambda\bar{\Lambda}) + \pi$'s, which cannot occur in pp interactions, and insofar as there are no leading baryons, may be akin to annihilation processes, (see fig. 2(e)), and yield central hyperons and antihyperons^{†1}.

The statistical significance of these effects is shown by making a direct subtraction of the data of refs. [5, 6] from our $\bar{p}p$ cross-sections. In the regions $|y^*| > 1$ and $|y^*| < 1$ we obtain for $\sigma(\bar{p}p - pp \rightarrow \gamma)$: -1.1 ± 7.5 mb

and 12.1 ± 11.2 mb respectively, for $\sigma(\bar{p}p - pp \rightarrow K_s^0)$: 0.50 ± 0.28 mb and 0.60 ± 0.37 mb, and for $\sigma(\bar{p}p - pp \rightarrow \Lambda^0/\bar{\Lambda}^0)$: 0.16 ± 0.36 mb and 1.16 ± 0.42 mb. It is clear that both $\bar{p}p$ and pp experiments with much better statistics are required in order to observe these effects in any greater detail.

The transverse momentum distributions of $\Lambda^0/\bar{\Lambda}^0$, K_s^0 and γ have been examined, and show no convincing differences from pp data in their shape, essentially just differing in normalization. The mean transverse momenta of γ , K_s^0 and $\Lambda^0/\bar{\Lambda}^0$ are 0.16 ± 0.01 , 0.46 ± 0.03 and 0.52 ± 0.04 GeV/c respectively, compared to mean values in pp interactions at 102 GeV/c [5]: 0.175 ± 0.020 , 0.42 ± 0.04 and 0.54 ± 0.06 GeV/c^{†2}.

Summary. We have derived cross-sections for the production of γ , K_s^0 and $\Lambda^0/\bar{\Lambda}^0$ in $\bar{p}p$ interactions at 100 GeV/c. In all cases the cross-sections are higher than in pp experiments at this energy. The difference in cross-sections tends to be associated with higher charged multiplicities, which inclines us to identify the differences with annihilation processes. In γ and $\Lambda^0/\bar{\Lambda}^0$ production the differences are probably concentrated near $y^* = 0$, while for K_s^0 there may be a difference at larger $|y^*|$ as well.

^{†1} In this connection it may be worth noting that we have five events containing both Λ^0 and $\bar{\Lambda}^0$, corresponding to a cross-section ~ 0.6 mb, compared with the inclusive $pp \rightarrow \bar{\Lambda}^0$ cross-section, ~ 0.2 mb. Further, in four out of these five events the $\Lambda\bar{\Lambda}$ effective mass is small; less than 3.5 GeV/c².

^{†2} This value is $\langle p_T \rangle$ for Λ^0 alone, and could be slightly affected by the inclusion of $\bar{\Lambda}^0$'s.

- [1] R.E. Ansorge et al., Phys. Lett. 59B (1975) 299.
- [2] J.G. Rushbrooke et al., Phys. Lett. 59B (1975) 303.
- [3] T.M. Knael, DESY report 70/3 (1970) unpublished.
- [4] Particle Data Group, Phys. Lett. 50B (1974) 1.
- [5] J.W. Chapman et al., Phys. Lett. 47B (1973) 465.
- [6] M. Alston-Garnjost et al., Phys. Rev. Lett. 35 (1975) 142.
- [7] V. Blobel et al., Nucl. Phys. B69 (1974) 454. [12,24 GeV/c];
K. Jaeger et al., Phys. Rev. D11 (1975) 1756 [12.4 GeV/c];
H. Blumenfeld et al., Phys. Lett. 45B (1973) 525, 528 [69 GeV/c];
K. Jaeger et al., Phys. Rev. D11 (1975) 2405 [205 GeV/c];
A. Sheng et al., Phys. Rev. D11 (1975) 1733 [303 GeV/c];
- [8] F.T. Dao et al., Phys. Lett. 51B (1974) 505 [14.75 GeV/c];
B.Y. Oh et al., Nucl. Phys. B51 (1973) 57 [1.51–3.45 GeV/c];
S.N. Ganguli & B. Sadoulet, Nucl. Phys. B53 (1973) 458 [5.7 GeV/c];
R. Carlsson et al., Nucl. Phys. B99 (1975) 451 [9 GeV/c].
- [9] S.J. Barish et al., Phys. Rev. D12 (1975) 1260.