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Exclusive production of hyperon-antihyperon pairs

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Abstract

A review is presented on the exclusive production of hyperon-antihyperon pairs that has been pursued over the past years using proton-antiproton annihilations at LEAR. The physics motivation for these studies is given, and selected experimental results on cross-sections as well as spin observables are presented which have been obtained at energies ranging from the $\bar{\Lambda}\Lambda$ threshold to those of $\bar{\Sigma}\Sigma$ and above. Recent theoretical ideas are summarised, and future directions in this area of research are outlined.

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1 PHYSICS INTRODUCTION

1.1 Strange particles in proton–antiproton interactions

The entirety of hadronic proton–antiproton interactions at low or intermediate energies can be categorised in terms of elastic scattering $\bar{p}p \rightarrow \bar{p}p$, charge exchange $\bar{p}p \rightarrow \bar{n}n$, meson production $\bar{p}p \rightarrow \bar{p}p + [\text{mesons}]$, and a variety of annihilation processes such as $\bar{p}p \rightarrow [\text{mesons}]$ or $\bar{p}p \rightarrow [\text{baryons}]$. At an antiproton momentum $p_{\bar{p}} = 2 \text{ GeV}/c$, which corresponds to an invariant mass $\sqrt{s} = 2.43 \text{ GeV}$ of the $\bar{p}p$ system, the total cross-section is $\sigma_{\text{tot}}(\bar{p}p) \approx 90 \text{ mb}$. Nearly 40 % of this is due to elastic scattering, and the charge-exchange reaction amounts to about 5 %. More than one half of all $\bar{p}p$ interactions can be classified as annihilations. Here we use “annihilation” for a hadronic $\bar{p}p$ reaction that does not fall into any of the previous two categories.

Additive quantum numbers constraining the possible final states in $\bar{p}p$ annihilation processes are: the total electric charge, $Q = 0$; the total isospin, $(I, I_3) = (0, 0)$ or $(1, 0)$; the total strangeness, $S = 0$; and the total baryon number, $B = 0$. One class of examples for $\bar{p}p$ annihilations are exclusive two-body processes such as:

- $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$, $\bar{p}p \rightarrow \bar{\Lambda}\Sigma^0 + c.c.$, $\bar{p}p \rightarrow \bar{\Sigma}^{\pm}\Sigma^{\pm}$;
- $\bar{p}p \rightarrow \pi^+\pi^-$, $\bar{p}p \rightarrow \pi^0\eta$, $\bar{p}p \rightarrow \omega\phi$, $\bar{p}p \rightarrow \phi\phi$, $\bar{p}p \rightarrow \bar{K}K$, $\bar{p}p \rightarrow \bar{K}K^* + c.c.$.

Another class of examples is given by the production of three or more final-state particles in a suitable combination:

- $\bar{p}p \rightarrow \pi^0\bar{\Lambda}\Lambda$;
- $\bar{p}p \rightarrow [\pi, \eta, \eta', \rho, \omega, \phi, K, K^*, \dots]$.

The reaction that will be discussed in some detail below is $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$. Its production cross-section constitutes a fraction 10^{-3} to 10^{-5} of all $\bar{p}p$ interactions, depending on the energy chosen. Therefore, when selectively studying such a process, it is not the aim to extract information on the gross features of the proton–antiproton interaction as a whole. But the aim is to examine specific properties of the interaction, which may be particularly sensitive to the choices made in theoretical descriptions. The $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ reaction is a prototype process of “quark-flavour production”, which is characterised by the annihilation of a light and the creation of a strange quark–antiquark pair [1].

1.2 Experimental studies close to the reaction threshold

Since hyperons are heavier than nucleons, there is a kinematical threshold for reactions such as $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ or $\bar{p}p \rightarrow \bar{\Lambda}\Sigma^0 + c.c.$ to be overcome. As a consequence, a relatively large momentum transfer is required between the initial- and final-state particles. At the threshold of $\bar{\Lambda}\Lambda$ production, for instance, this is $600 \text{ MeV}/c \simeq 3 \text{ fm}^{-1}$.

The reaction threshold is defined by the condition that the two produced particles be at rest with respect to the $\bar{p}p$ centre-of-mass system. In such a case the final-state orbital angular momentum must be $L = 0$. As the antiproton beam momentum increases, the relative kinetic energy of the produced particles increases as well. Values $L > 0$ may then contribute to the reaction. It is quite clear, however, that the number of partial waves is

restricted to only a few in the region close to threshold. This can substantially simplify the interpretation of experimental data.

With a non-polarised beam incident on a non-polarised target, the measurement of $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ and similar reactions can provide the following items of information:

- the production cross-section σ ;
- the differential cross-section $d\sigma/d\Omega$;
- the Λ and $\bar{\Lambda}$ polarisations P ;
- the Λ - $\bar{\Lambda}$ spin-correlation matrix $(C_{ij})_{i,j=x,y,z}$, and from its diagonal elements the spin-1 or spin-0 production probabilities.

From cross-sections one can determine orbital angular momenta L in the final state, and spin variables contain information on the final-state spin angular momenta S . With the help of selection rules deduced from general invariances, the quantum numbers $^{2S+1}L_J$ in the $\bar{\Lambda}\Lambda$ system can then be determined. This is important in particular in view of conclusions to be drawn about possible reaction mechanisms.

For the following consideration about $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ near threshold we make the simple albeit somewhat questionable assumption, that the transition-matrix element as well as the initial- and final-state interactions are energy-independent over some energy interval. For a partial wave with orbital angular momentum L , the differential cross-section is given in terms of the scattering amplitude $f(\theta)$ and the particles' centre-of-mass momenta by

$$\frac{d\sigma}{d\Omega} \propto \frac{p_\Lambda}{p_p} |f(\theta)|^2 \propto \frac{(p_\Lambda)^{2L+1}}{p_p} . \quad (1)$$

The “excess energy” ϵ is the relative kinetic energy in the $\bar{\Lambda}\Lambda$ system as determined by the total invariant mass $\sqrt{s}$,

$$\epsilon = 2 T_\Lambda = \sqrt{s} - 2 m_\Lambda . \quad (2)$$

Close to the reaction threshold, where $\epsilon \ll 4 m_\Lambda$, one finds $p_\Lambda \propto \sqrt{\epsilon}$. Therefore, if in such case of “phase-space type” behaviour only undisturbed S-, P- or D-waves contribute to the reaction near threshold, the production cross-section would be given by

$$\sigma = b_0 \sqrt{\epsilon} + b_1 \sqrt{\epsilon^3} + b_2 \sqrt{\epsilon^5} . \quad (3)$$

There has been much discussion about the possible existence of more or less narrow baryon-antibaryon states, which are called “baryonia”. These may show up in $\bar{p}p$, in $\bar{\Lambda}\Lambda$, or in any other baryon-antibaryon channel at small relative energies. Should they exist and have sizeable strengths, one would expect to detect them at some level in the energy-dependence of the $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ production cross-section. Such a resonance, if not too broad, would thus be visible as a well-defined structure on top of the phase-space type excitation function as given above. We shall come back to this point in the discussion of experimental results.

Very close to threshold one expects in any case deviations from the phase-space behaviour [2]. The $\bar{\Lambda}\Lambda$ particles moving closely together, final-state interactions can lead to the population of other related channels. The preferred channels are those that have certain structural and dynamical features in common. In principle, a reduced $\bar{\Lambda}\Lambda$ strength

could be observed in such a case, but in practice this is difficult because the cross-section is anyhow very small near threshold. An experimentally less difficult way to observe such “cusp effects” is to measure the excitation function of one reaction channel across the threshold of another one. For instance, $\bar{p}p \rightarrow \bar{K}K$ or $\bar{p}p \rightarrow \bar{K}^*K^*$ would be measured across the $\bar{\Lambda}\Lambda$ threshold, or $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ would be scanned over the $\bar{\Lambda}\Sigma^0 + \text{c.c.}$ and $\bar{\Sigma}^\pm\Sigma^\pm$ thresholds.

1.3 Quark model and selection rules

In the Constituent Quark Model the lightest hyperon is described as a combination $\Lambda = [(ud)s]$, where the relative orbital momentum between any two quarks is zero. The light “diquark” (ud) couples to spin- and isospin-0, hence $J^P = 1/2^+$. The Λ spin should thus be entirely determined by the spin of its constituent s-quark. The Σ^0 hyperon is based on the same flavour configuration, but in this case the light diquark couples to spin- and isospin-1. Consequently, the s-quark spin should contribute with a fraction $-1/3$ to the Σ^0 spin.

Clearly, such a simple static quark model must be used with caution, since it only sums up quantum numbers of the quarks. Dynamical quark models contain important features, such as a confining quark–gluon interaction, a spin-dependent interaction added to it, an s-quark mass larger than the u- and d-quark masses, and a mechanism for mixing different quark–antiquark configurations. Finally, the role of “sea” $\bar{s}s$ pairs in the nucleon may be non-negligible even at relatively low energies of typical $\bar{p}p$ annihilations.

The quantum numbers of the proton are $I(J^P) = 1/2(1/2^+)$. For the $\bar{p}p$ initial state we have therefore: the isospin $(I, I_3) = (0, 0)$ or $(1, 0)$; the spin $s = 0$ or 1 ; the parity $P = (-1)^{l+1}$; the charge-conjugation $C = (-1)^{l+s}$; and the G-parity $G = (-1)^l C$.

The Λ hyperon has quantum numbers $I(J^P) = 0(1/2^+)$. In the $\bar{\Lambda}\Lambda$ final state one has: the isospin $(I, I_3) = (0, 0)$; the spin $S = 0$ or 1 ; the parity $P = (-1)^{L+1}$; and the charge-conjugation and G-parity $C = G = (-1)^{L+s}$. From the conservation of parity in $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ we conclude that l and L are either both even or both odd. Charge-conjugation invariance then implies $s = S$. The conservation of total angular momentum leads to sets of selection rules from which states and transitions are deduced as classified in table 1 for $J \leq 3$.

We note that, for the case of $\bar{\Lambda}\Lambda$ spin-triplet production, the orbital angular momenta can be $L = l \pm 2$. Such “non-diagonal” transitions correspond to a spin-flip from $(s, s_3) = (1, \pm 1)$ to $(S, S_3) = (1, \mp 1)$. In the context of certain models describing the process $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$, the underlying “tensor” interaction with $L = l - 2$ appears to be an important and distinct feature.

The conservation of P and C in hadronic processes trivially implies that the combined symmetry CP is conserved as well. In that sense one may think of two spin-selection criteria apparent in table 1 as a consequence of CP invariance in strong interactions. Firstly, $\bar{p}p \rightarrow \bar{K}K$ can only proceed from the spin-triplet initial state, because CP conservation requires $(-1)^{s+1} = +1$. Secondly, in $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ the initial and final states are either both spin-singlet or spin-triplet, because CP conservation requires $(-1)^{s+1} = (-1)^{S+1}$. More generally, there are no singlet $\rightleftharpoons$ triplet spin transitions between the initial- and final-state fermion–antifermion systems. Contrasting this, singlet $\rightleftharpoons$ triplet spin transitions can occur in the $\bar{\Lambda}\Sigma^0$ or $\bar{\Sigma}^0\Lambda$ production, and they necessarily do occur when $\bar{p}p$ annihilates into two-boson states.

Table 1: States and transitions in $\bar{p}p$ annihilation for $J \leq 3$. The notation of the states listed is $^{2S+1}L_{JP}$. The allowed values of isospin (I, I_3) are: (0,0) for $\bar{\Lambda}\Lambda$; (1,0) for $\bar{\Lambda}\Sigma^0 + c.c.$; (0,0) or (1,0) for $\bar{K}K$; (0,0) for $\phi\phi$ or $\omega\phi$. The $K_S K_S$ component of $\bar{K}^0 K^0$ is restricted to $J^{PC} = (\text{even})^{++}$, and $\phi\phi$ as well as $\omega\phi$ are limited to $C = +1$.

$\bar{p}p$	$\bar{\Lambda}\Lambda$, or $\bar{\Lambda}\Sigma^0 + c.c.$	$\bar{K}K$	$\phi\phi$, or $\omega\phi$
$^1S_{0-}$	$^1S_{0-}$		$^3P_{0-}$
$^1P_{1+}$	$^1P_{1+}$		
$^1D_{2-}$	$^1D_{2-}$		$^3P_{2-}, ^3F_{2-}$
$^1F_{3+}$	$^1F_{3+}$		
$^3P_{0+}$	$^3P_{0+}$	$^1S_{0+}$	$^1S_{0+}, ^5D_{0+}$
$^3S_{1-}$	$^3S_{1-}, ^3D_{1-}$	$^1P_{1-}$	
$^3P_{1+}$	$^3P_{1+}$		$^5D_{1+}$
$^3D_{1-}$	$^3S_{1-}, ^3D_{1-}$	$^1P_{1-}$	
$^3P_{2+}$	$^3P_{2+}, ^3F_{2+}$	$^1D_{2+}$	$^5S_{2+}, ^1D_{2+}, ^5D_{2+}, ^5G_{2+}$
$^3D_{2-}$	$^3D_{2-}$		
$^3F_{2+}$	$^3P_{2+}, ^3F_{2+}$	$^1D_{2+}$	$^5S_{2+}, ^1D_{2+}, ^5D_{2+}, ^5G_{2+}$
$^3D_{3-}$	$^3D_{3-}, ^3G_{3-}$	$^1F_{3-}$	
$^3F_{3+}$	$^3F_{3+}$		$^5D_{3+}, ^5G_{3+}$
$^3G_{3-}$	$^3D_{3-}, ^3G_{3-}$	$^1F_{3-}$	

1.4 Duality of quark-gluon and meson-exchange mechanisms

The reaction mechanisms for $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ and $\bar{p}p \rightarrow \bar{\Lambda}\Sigma^0 + c.c.$ can be looked at in two different ways [1]. In this section these two approaches are discussed phenomenologically. Almost all detailed theoretical calculations of the reactions under study were performed after the precision experiments at LEAR had begun. Results from these calculations will therefore be presented further below in comparison with experimental data.

The quark-model pictures of particles participating in the reactions $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ and $\bar{p}p \rightarrow \bar{\Lambda}\Sigma^0 + c.c.$ suggest simple quark-line diagrams for these processes. The lowest-order diagram is shown in figure 1 (a). It is assumed that quark-antiquark pairs from the sea and virtual gluons in the confinement region do not contribute to the reaction.

As can be seen, the basic process underlying $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ and $\bar{p}p \rightarrow \bar{\Lambda}\Sigma^0 + c.c.$ at the quark level is $\bar{u}u \rightarrow \bar{s}s$. The light diquarks behave as “spectators”. Owing to their spin and isospin coupling, information on spin dynamics in $\bar{u}u \rightarrow \bar{s}s$ is entirely carried by the strange quarks. Therefore, in the limit of the static quark picture, the spin observables of the $\bar{\Lambda}\Lambda$ system, such as polarisation and spin correlation, should reflect those of the $\bar{s}s$ quark pair.

The central question is that of the mediator between the vertices of $\bar{u}u$ annihilation and $\bar{s}s$ creation. One may think of an “effective object” in terms of an exchange, an intermediate state, or another appropriate parameterization. This mediator would be electrically neutral and have isospin $I = 0$. For instance, it may be one or more massless gluons, or it may be a mesonic state with both non-strange and strange quark components. If a massive intermediate state with a finite decay width is formed, however, it may be likely to interact with the two light diquarks. Some possibilities can be envisaged and classified in terms of the quantum numbers J^P at the quark-antiquark vertex (see table 1).

Figure 1: Lowest-order quark-gluon (a) and meson-exchange (b) diagrams for the reaction $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$.

- $J^P = 1^-$ (“vector”). This case corresponds in lowest order to a one-gluon exchange or in general to an odd number of gluons, or it may be an effective ω - ϕ intermediate state. The simplest final state is $^3S_{1-}$, but with higher orbital angular momentum also $^3D_{1-}$ is possible.
- $J^P = 0^+$ (“scalar”). The vacuum quantum numbers can be due to exchange of an even number of at least two gluons, or it may be an intermediate state such as an effective f_0 . The final state is $^3P_{0+}$.
- $J^P = 0^-$ (“pseudoscalar”). An odd number of at least three gluons can be due to this case, or an effective η - η' intermediate state. The final state is $^1S_{0-}$.
- $J^P = 1^+$ (“pseudovector”). This corresponds to an even number of at least two gluons, or to an effective f_1 intermediate state. Final states $^1P_{1+}$ or $^3P_{1+}$ are possible.
- $J^P = 2^+$ (“tensor”). Again, this can be due to an even number of at least two gluons, or to an effective f_2 - f'_2 intermediate state. Final states $^3P_{2+}$ or $^3F_{2+}$ are possible.

We note in particular that some cases necessarily lead to spin-triplet production of $\bar{\Lambda}\Lambda$. One-gluon quantum numbers (“vector”) mean that the $\bar{\Lambda}\Lambda$ pair is produced with relative orbital angular momentum $L = 0$ (S-wave) or $L = 2$ (D-wave). In case of vacuum quantum numbers (“scalar”) it is produced with $L = 1$ (P-wave), whereas multiple-gluon quantum numbers (“tensor”) correspond to final-state production with $L = 1$ (P-wave) or $L = 3$ (F-wave). The final-state spin and orbital angular momenta are measurable quantities in $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$, and it is in fact due to experimental results that the “one-gluon exchange” or $^3S_{1-}$ model and the “vacuum pair-creation” or $^3P_{0+}$ model have received much attention in theoretical work.

Another, complementary way of describing the reactions $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ and $\bar{p}p \rightarrow \bar{\Lambda}\Sigma^0 + c.c.$ is that of a meson exchange between the $p - \Lambda$ (or $p - \Sigma^0$) and $\bar{p} - \bar{\Lambda}$ (or $\bar{p} - \bar{\Sigma}^0$) vertices. Refined $\bar{p}p$ optical potentials used in one-boson exchange calculations are of the general

complex form $U(\vec{r}) = V(\vec{r}) + iW(\vec{r})$. The real part $V(\vec{r})$ is usually taken as the G -parity transformed of the pp interaction. The imaginary part $iW(\vec{r})$ is empirical and accounts for annihilation processes. With improved knowledge about meson multiplets having $J^P = 0^-, 1^-, 0^+, 2^+$, the non-strange mesons included as possible exchange particles are: the isoscalars $\eta, \eta', \omega, \phi, f_0, f_2, f'_2$; and the isovectors π, ρ, a_0, a_2 .

The schematic representation of a one-meson exchange in $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ is shown in figure 1 (b). Clearly, in this case the exchanged particle must carry electric charge and, most importantly, strangeness. The strangeness exchange can thus be mediated by charged kaonic mesons:

- K, with a mass of 494 MeV and $J^P = 0^-$;
- $K^*(892)$, with a mass of 892 MeV and $J^P = 1^-$;
- $K_0^*(1430)$, with a mass of 1429 MeV and $J^P = 0^+$;
- $K_2^*(1430)$, with a mass of 1425 MeV and $J^P = 2^+$.

Theoretical investigations of $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ and $\bar{p}p \rightarrow \bar{\Lambda}\Sigma^0 + c.c.$ have focused on exchanges of K and $K^*(892)$, and to some extent also of $K_2^*(1430)$. As a general rule, heavier exchanged particles probe shorter-ranged interactions. These may be considered more important in processes, where the final-state particles are sufficiently different in mass from the initial-state particles and where therefore large momentum transfers are involved. It should be noted that one-meson exchanges can lead to spin-triplet as well as to spin-singlet in the final states, in contrast to the above-mentioned 3S_1 - and 3P_0 - models inspired from QCD and underlying quark-gluon interactions. Recent calculations suggest, however, that $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ is dominated by “tensor”-force transitions with spin-triplet initial and final states. Prominent examples for such spin-flips to final-state orbital angular momenta $L = 0, 1, 2$ are (see table 1): $^3D_1 \rightarrow ^3S_1$; $^3F_2 \rightarrow ^3P_2$; and $^3G_3 \rightarrow ^3D_3$. But considerable uncertainties still exist about the detailed form of the strangeness-exchange interaction, in particular the relative importance of K and $K^*(892)$ exchanges, and about the role of distortions due to initial- and final-state interactions.

The two frameworks for theoretical descriptions, one of them being inspired from quark-gluon interactions and the other one using one-boson exchanges, are clearly different in detail and in spirit. The first one is believed to be fundamental at the level of QCD and the Standard Model, but it is very difficult to perform calculations in this non-perturbative regime. The second one is less difficult to treat in calculations, but it is not fundamental in the sense of QCD as the theory underlying strong interactions. Both pictures, quark-gluon as well as one-boson exchange, apparently can connect the same initial- and final-state particles with each other. The first model is related to the so-called “direct” or s -channel resonance (s being the total invariant mass squared), in the sense that one can speak of an intermediate state being formed, be it one or more gluons or a mesonic state. In the second model, the t -channel exchange (t being the four-momentum transfer squared), it is the transferred momentum that plays the role of the energy available for the transition from an initial to a final state.

The two complementary s -channel and t -channel pictures are connected by the concept of “duality”. The theorem is that, after having summed up over all possible contributions separately for s -channel resonance and t -channel exchange mechanisms, the two approaches yield the same results. When applying this to the reactions $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ or

$\bar{p}p \rightarrow \bar{\Lambda}\Sigma^0 + c.c.$, it may in fact be ultimately impossible to distinguish between the two underlying mechanisms, quark–gluon interaction and strange-meson exchange. Nonetheless, present and future experiments on selective processes should give answers as to which of the possible contributions are the most important ones in either of the models, thereby providing very detailed information about the underlying interactions. Also, in both approaches initial- and final-state interactions as well as spin-dependent effects have been found vital for the adequate description of experimental observations such as significant polarisations.

2 SELECTED EXPERIMENTAL RESULTS

2.1 Experiment and data analysis

The detector system constructed by the PS185 Collaboration for measurements of $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ and $\bar{p}p \rightarrow \bar{\Lambda}\Sigma^0 + c.c.$ at LEAR is a forward spectrometer recording the delayed charged decays of hyperons. Important features are the small size of the interaction volume (a few mm³), the low mass in the way of particles, and the complete solid-angle coverage in the centre-of-mass system. The experimental set-up includes [3]:

- a target system and a scintillator hodoscope, which together form the on-line trigger for the signature $\bar{p}p \rightarrow$ “neutral” $\rightarrow$ “charged” of the events sought;
- stacks of MWPC and drift-chamber planes placed in between the target and the hodoscope, which constitute the decay volume for the particles and the tracking volume for their charged decay products;
- a weak-field (0.1 T) solenoidal magnet with drift chambers, which allows hyperons and antihyperons to be distinguished in the off-line analysis.

During a number of data-taking periods performed from 1984 to 1991, more than 10^{12} antiprotons from LEAR were received on the PS185 target. Data were obtained at beam momenta ranging from the $\bar{\Lambda}\Lambda$ threshold at 1.435 GeV/*c* up to 1.92 GeV/*c*. In most of the runs emphasis was put on the $\bar{\Lambda}\Lambda$ channel, and in some cases also $\bar{\Lambda}\Sigma^0 + c.c.$ data were collected. The last run focused on the charged channels $\bar{\Sigma}^\pm \Sigma^\pm$.

The reconstruction of events $\bar{p}p \rightarrow \bar{\Lambda}\Lambda \rightarrow \bar{p}\pi^+p\pi^-$ is based on the charged-particle track information provided by the MWPC and the drift-chamber planes. Full advantage is taken of kinematical constraints and of distinctive signatures of the $2V^0$ -type events sought. The analysis procedure includes the following logical steps [3]:

- search for 2D-tracks in the MWPC and the drift chambers;
- combination of two different 2D-tracks in the chambers to a 3D-track;
- search for pairs of 3D-tracks featuring a small distance of closest approach;
- combination of two vertices to a $2V^0$ event candidate;
- checks for coplanarity involving the production target, the found vertex candidates, and the beam axis;

- distinction of pion and proton from their track angles with respect to the hyperon direction;
- kinematical fit of the remaining event candidates under the hypothesis of $\bar{p}p \rightarrow \Lambda_1 \Lambda_2 \rightarrow (p_1 \pi_1)(p_2 \pi_2)$;
- distinction of Λ and $\bar{\Lambda}$ vertices using the information provided by drift chambers positioned in the magnet.

In the case of $\bar{p}p \rightarrow \bar{\Lambda}\Sigma^0 + c.c.$ one deals effectively with a three-particle final state because of the decay $\Sigma^0 \rightarrow \gamma\Lambda$ ($\bar{\Sigma}^0 \rightarrow \gamma\bar{\Lambda}$). Due to the recoil momentum carried away by the γ , the direction of the decay Λ differs somewhat from the direction of the initial Σ^0 . In general this “kink” is small. Therefore, if the decay γ is not measured [4], it is not easy to distinguish Λ from Σ^0 ($\bar{\Lambda}$ from $\bar{\Sigma}^0$) or, likewise, the state $\bar{\Lambda}\Sigma^0$ from its charge-conjugate case $\bar{\Sigma}^0\Lambda$. When analysing the charged-hyperon channel $\bar{p}p \rightarrow \bar{\Sigma}^+\Sigma^+$, a major complication lies in the fact that from either one of the two main decay modes, $\Sigma^+ \rightarrow p\pi^0$ or $\Sigma^+ \rightarrow n\pi^+$, only the charged half of all particles are recorded in the detector. In this case the kinematical reconstruction must make use of the beam-momentum vector as well as the Σ^+ track stub [5].

2.2 Differential and integrated cross-sections

For hyperon–antihyperon production at a given incident antiproton momentum, the differential cross-section $d\sigma/d\Omega$ in the centre-of-mass system is evaluated from the number of analysed events, the experimental acceptance function, and the total luminosity obtained. Figure 2 (top) compares the differential cross-sections for $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ at 1.477 GeV/c and for $\bar{p}p \rightarrow \bar{\Lambda}\Sigma^0 + c.c.$ at 1.695 GeV/c incident momentum [4]. In both cases the excess energy is nearly the same, $\epsilon \approx 14.7$ MeV. The shapes of these distributions are strikingly similar. They are strongly anisotropic, which reveals large contributions from orbital angular momenta $L > 0$ even at these small excess energies. The ratio of integrated cross-sections was determined to be $r_{exp}^0 = \sigma(\bar{\Lambda}\Sigma^0 + c.c.)/\sigma(\bar{\Lambda}\Lambda) = 0.29 \pm 0.02$ for the data shown in figure 2 (top). High-precision data on $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ were obtained at 1.642 GeV/c beam momentum, the number of reconstructed events exceeding 40000 here [6]. The corresponding differential cross-section is displayed in figure 2 (bottom). A preliminary analysis of charged-hyperon production at 1.918 GeV/c beam momentum [5] revealed the ratio of cross-sections $r_{exp}^+ = \sigma(\bar{\Sigma}^+\Sigma^+)/\sigma(\bar{\Lambda}\Lambda) = 0.15 \pm 0.06$ at excess energies $\epsilon \approx 24$ MeV.

It is also instructive to consider the differential cross-sections in terms of Lorentz-invariant variables, the squared total invariant mass s and the squared four-momentum transfer t . The latter has the form

$$t = m_p^2 + m_\Lambda^2 - 0.5s + 0.5\sqrt{(s - 4m_p^2)(s - 4m_\Lambda^2)} \cos\theta. \quad (4)$$

We note that t is always negative, the numerically smallest value t_0 (largest value t_{180}) corresponding to the case where the antihyperon is produced along (opposite to) the direction of the incoming beam. Since the physical range of t strongly varies with the energy, it is convenient to take the reduced four-momentum transfer squared,

$$t' = t - t_0 = -0.5\sqrt{(s - 4m_p^2)(s - 4m_\Lambda^2)}(1 - \cos\theta). \quad (5)$$

Figure 2: Differential cross-sections for hyperon-antihyperon production. Shown are: (top) data on $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ at 1.477 GeV/c and $\bar{p}p \rightarrow \bar{\Lambda}\Sigma^0 + c.c.$ at 1.695 GeV/c, both corresponding to excess energies $\epsilon \approx 14.7$ MeV; (bottom) high-statistics data on $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ taken at 1.642 GeV/c or $\epsilon = 72.9$ MeV. The errors are statistical only.

The differential cross-sections $d\sigma/dt$ as a function of t' indicate a very similar qualitative behaviour. For small momentum transfers, say $t' > -0.2 \text{ (GeV/c)}^2$, it approaches an exponential form,

$$\frac{d\sigma}{dt} = \frac{d\sigma}{dt}\bigg|_{t'=0} \cdot e^{bt'}, \quad (6)$$

the slope parameter $b \approx 8.6 \text{ (GeV/c)}^{-2}$ being only weakly dependent on the energy. In analogy to absorptive hadronic scattering off a disk, an “interaction radius” $R = 2\sqrt{b} \approx 1.16 \text{ fm}$ can be deduced from this.

A compilation of integrated cross-sections for exclusive hyperon–antihyperon production in $\bar{p}p$ annihilations as measured with the PS185 experiment [3, 4, 5, 6, 7], [8, 9, 10, 11] is displayed in figure 3. Previous data are included as well [12]. No significant structure can be seen in the $\bar{\Lambda}\Lambda$ excitation function. However, we can look at the vicinity of the threshold in a magnified view, because the modular structure of the target system allows the $\bar{\Lambda}\Lambda$ production cross-section to be evaluated for many different excess energies ranging from 1 MeV below the threshold to 6 MeV above it. This is displayed in figure 4, which reveals a small irregularity just above threshold [7, 13]. Also shown is a fit to the data, its functional form representing the superposition of phase space for $L \leq 1$ and a Breit–Wigner curve. A remarkably strong $L > 0$ contribution of nearly 20 % is seen even at these very small energies. The resonance parameters extracted from the fit are $E_{res} = \epsilon \approx 1 \text{ MeV}$ and $\Gamma \approx 0.6 \text{ MeV}$. Resonant and non-resonant cross-sections appear to be of similar strengths here, each contributing with about $1 \mu\text{b}$. However, the statistical significance of the structure is not quite three standard deviations, which calls for a more accurate investigation of this most interesting effect. To this end, a good-precision scan of the $\bar{\Lambda}\Lambda$ near-threshold excitation function and angular distributions will be performed [13] in early 1994.

We can summarise the main characteristics of the cross-section data as follows.

- The differential cross-sections $d\sigma/d\Omega$ measured for $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ and $\bar{p}p \rightarrow \bar{\Lambda}\Sigma^0 + \text{c.c.}$ exhibit a pronounced forward peak characteristic for peripheral processes, a relatively flat shape elsewhere, and the data show no enhanced backward production.
- The differential and integrated cross-sections of $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ measured down to $\epsilon \approx 0$, give evidence for strong $L \geq 1$ production. At somewhat higher energies, measured up to $\epsilon \approx 170 \text{ MeV}$, contributions with $L \geq 2$ are of rapidly increasing importance.
- The differential cross-sections $d\sigma/dt$ show a typical and consistent dependence on the reduced four-momentum transfer squared, t' . The forward part approaches an exponential form, the slope parameter $b \approx 8.6 \text{ (GeV/c)}^{-2}$ being approximately independent of the total invariant mass squared, s .
- The differential cross-sections for $\bar{\Lambda}\Lambda$ and $\bar{\Lambda}\Sigma^0 + \text{c.c.}$ production measured at nearly the same excess energies $\epsilon \approx 14.7 \text{ MeV}$ are very similar. The ratio of integrated cross-sections is measured to be $r_{exp}^0 = \sigma(\bar{\Lambda}\Sigma^0 + \text{c.c.})/\sigma(\bar{\Lambda}\Lambda) = 0.29 \pm 0.02$ here. At excess energies $\epsilon \approx 24 \text{ MeV}$, the ratio $r_{exp}^+ = \sigma(\bar{\Sigma}^+\Sigma^+)/\sigma(\bar{\Lambda}\Lambda) = 0.15 \pm 0.06$ is determined.
- The $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ near-threshold excitation function indicates the possible presence of a resonant structure near $\epsilon \approx 1 \text{ MeV}$, which will be further investigated by means of a forthcoming experiment at LEAR.

Figure 3: Compilation of exclusive hyperon-antihyperon production cross-sections measured in $\bar{p}p$ annihilations with PS185 (full symbols) and earlier experiments (open symbols).

2.3 Spin observables

The decay $\Lambda \rightarrow p\pi^-$ proceeds by parity-violating weak interactions [1]. Conservation of total angular momentum allows the orbital angular momenta to be $l = 0$ or 1 in the final state. The S-wave case corresponds to the spin vectors of Λ and p being equal. Since the final-state parity is $(-1)^{l+1}$, the S-wave decay changes parity from the value $+1$ of Λ to -1 in the $p\pi^-$ system whereas the P-wave decay conserves parity. This parity-violating mixture of S- and P-wave decay amplitudes manifests itself in a spatial asymmetry of the decay angular distribution. In the Λ ($\bar{\Lambda}$) rest frame the outgoing nucleon is emitted preferentially along (opposite to) the parent-hyperon spin direction. Parity conservation in the hadronic production process restricts non-zero components of hyperon polarisations to be those transverse to the production plane. The latter is defined, for instance, by the directions of the incoming $\bar{p}$ the outgoing $\bar{\Lambda}$. However, if these are collinear, there is no such plane to be assigned, hence the polarisation vanishes at extreme forward or backward centre-of-mass production angles. For a hyperon sample with given production angle and polarisation P , the normalised angular distribution of the decay nucleons from $\Lambda \rightarrow p\pi^-$ known to be of the form

$$I(\theta_p) = \frac{1}{4\pi} (1 + \alpha P \cos \theta_p), \quad (7)$$

where the angle θ_p is measured between the normal to the production plane and the nucleon direction in the hyperon rest frame. The value of the decay-asymmetry parameter $\alpha = 0.642 \pm 0.013$ for $\Lambda \rightarrow p\pi^-$ is known from other experiments [14]. It characterises the degree of mixing of parities in the decay. In the limit of CP conservation in hyperon

Figure 4: Excitation function of $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ near threshold. The solid line shows a fit to the data with a superposition of undisturbed waves $L \leq 1$ and a Breit–Wigner resonance.

Figure 5: Polarisations of Λ (open) and $\bar{\Lambda}$ (full) measured at 1.642 GeV/c beam momentum. The errors shown are statistical only.

non-leptonic decays [15], the corresponding decay-asymmetry parameter for $\bar{\Lambda} \rightarrow \bar{p}\pi^+$ is expected to be $\bar{\alpha} = -\alpha$. From eqn. 7 we obtain the expression

$$P = \frac{3}{\alpha} \langle \cos \theta_p \rangle, \quad (8)$$

which gives the hyperon polarisation in terms of the expectation value of the nucleon decay angle.

The product αP and its error can be readily obtained from the data by applying to eqn. 7 a “straight-line method” or a “weighted-sums method” in terms of $\cos \theta_p$. Such a procedure is performed separately for Λ and $\bar{\Lambda}$ decays. The resulting polarisations as a function of the $\bar{\Lambda}$ centre-of-mass production angle are displayed in figure 5 for 1.642 GeV/c beam momentum [6]. At given angular bins, the Λ and $\bar{\Lambda}$ polarisations agree within statistical errors. This is in fact required from the conservation of charge-conjugation invariance in the hadronic interaction $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$. The polarisations exhibit a prominent pattern: they are positive at forward centre-of-mass angles and strongly negative elsewhere. Polarisation have also been obtained for data measured more close to the $\bar{\Lambda}\Lambda$ threshold. Values ranging up to $|P| \approx 0.5$ are in fact observed at excess energies down to a few MeV. A general and characteristic feature of the final-state polarisation is the change of sign at sizeable four-momentum transfers. This occurs at t' values that are apparently determined by the superposition of various partial waves with distinctly different behaviour.

In case of $\bar{p}p \rightarrow \bar{\Lambda}\Sigma^0 + c.c.$, the polarisation analysis is not quite as easy. For a sample of polarised Σ^0 , seen in their rest frame, the electromagnetic decay $\Sigma^0 \rightarrow \gamma\Lambda$ produces

longitudinally polarised Λ hyperons. When averaging over photon polarisations and Λ directions, one obtains for the transverse polarisations

$$P_{\Sigma^0} = -3 P_{\Lambda} . \quad (9)$$

As a net result, the Σ^0 polarisation is diluted to some extent in its decay, which has been seen to manifest itself in larger errors of the experimental data [4].

Having seen that $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ produces strong final-state polarisations, a logical question is that of a possible correlation between Λ and $\bar{\Lambda}$ spins. When considering the double decay $\bar{\Lambda}\Lambda \rightarrow \bar{p}\pi^+p\pi^-$, the combined angular distribution of decay nucleons in the respective hyperon rest frames is given by

$$I(\theta_p, \theta_{\bar{p}}) = \frac{1}{16\pi^2} [1 + \alpha P \cos \theta_p + \bar{\alpha} P \cos \theta_{\bar{p}} + \alpha \bar{\alpha} \sum_{i,j=x,y,z} C_{ij} \cos \theta_{p_i} \cos \theta_{\bar{p}_j}] . \quad (10)$$

The $\Lambda - \bar{\Lambda}$ spin-correlation coefficients C_{ij} are defined as expectation values of products of the three Λ and three $\bar{\Lambda}$ spin-vector components,

$$C_{ij} = \frac{9}{\alpha \bar{\alpha}} \langle \cos \theta_{p_i} \cos \theta_{\bar{p}_j} \rangle . \quad (11)$$

The nine coefficients are not all independent. Parity conservation in $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ provides the restriction $C_{xy} = C_{yx} = C_{yz} = C_{zy} = 0$, and charge-conjugation invariance imposes the symmetry $C_{ij} = C_{ji}$. The only possible non-zero elements are thus C_{xx} , C_{yy} , C_{zz} , and $C_{xx} = C_{zz}$, which are, however, dependent on the hyperon production angles. All spin-correlation coefficients vanish near extreme forward or backward production angles, owing to the same argument of lack of orientation in space as in the polarisation case.

The coefficients C_{ij} and their errors can be evaluated adapting a “method of moments”. We note that, for any number N of analysed events, the statistical error on C_{ij} is about a factor $\sqrt{3}|\alpha|^{-1} = 2.7$ larger than that of P . For instance, an accuracy on C_{ij} of 0.1 requires that there be more than 5000 analysed events in each angular bin.

Good-statistics data measured with PS185 over a wide range of excess energies have revealed that the final-state spins in exclusive $\bar{\Lambda}\Lambda$ production are in fact strongly correlated [1]. The diagonal elements of the spin-correlation matrix provide a means for determining the relative weights of spin-0 and spin-1 states. The so-called “singlet fraction” is defined as the expectation value of the spin-0 projection operator,

$$F_0 = \frac{1}{4} (1 - \langle \vec{\sigma}_{\Lambda} \vec{\sigma}_{\bar{\Lambda}} \rangle) = \frac{1}{4} (1 + C_{xx} - C_{yy} + C_{zz}) , \quad (12)$$

where $\vec{\sigma}$ denote Pauli spin matrices. We should expect to find $F_0 = 0$ if the $\bar{\Lambda}\Lambda$ pair is in a pure spin-triplet ($\uparrow\uparrow$) state or $F_0 = 1$ in case of a pure spin-singlet ($\uparrow\downarrow$) state. Uncorrelated spins would be represented by the statistical weight $F_0 = 1/4$. We note that Monte Carlo events, generated without polarisations and without spin correlations, yielded F_0 values compatible with that of a statistical mixture.

Figure 6 shows a compilation of singlet-fraction data obtained with PS185 for exclusive $\bar{\Lambda}\Lambda$ production [3, 6, 10, 11]. For a given beam momentum, the value shown is the average over all $\bar{\Lambda}$ centre-of-mass production angles. The result is most striking, as it constitutes clear evidence that $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ produces the final-state particles in an essentially pure spin-triplet state ($\uparrow\uparrow$), hence with their spins being directed parallel. The small non-zero

Figure 6: Compilation of singlet-fraction data from $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ measurements. Shown are probabilities for spin-0 production, at given beam momentum averaged over the whole $\bar{\Lambda}$ centre-of-mass angular range.

value measured at the highest beam momentum [11] may be an indication that the spin-0 production probability is not exactly zero.

The results on final-state polarisations and spin correlations can be summarised as follows.

- Large final-state transverse polarisations of the order of $|P| \approx 0.5$ or more are observed in $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ at all excess energies measured, ranging from 170 MeV down to 1 MeV. Non-zero polarisations are also observed for $\bar{\Lambda}\Sigma^0 + c.c.$ final states.
- The measured Λ and $\bar{\Lambda}$ polarisations agree within experimental errors, as required from C -invariance in the hadronic production process.
- The $\Lambda - \bar{\Lambda}$ averaged polarisations are positive at very forward centre-of-mass production angles. They switch to large negative values for sizeable four-momentum transfers of the order of $t' \approx -0.2 \text{ (GeV/c)}^2$. Owing to specific partial-wave behaviour, another sign change may occur for even larger t' values.
- The final-state particle spins in $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ are measured to be strongly correlated. The t' -dependence of the spin-correlation coefficients appears to be approximately energy-independent.
- Over a wide range of excess energies, the diagonal elements of the spin-correlation matrix reveal that the $\bar{\Lambda}\Lambda$ pairs are produced in an essentially pure spin-triplet state.

3 THEORETICAL UPDATE

3.1 Kaon-exchange models

The detailed results on cross-sections and spin observables, as it has been forthcoming from the PS185 experiment at LEAR, have triggered a large amount of theoretical activity. Both one-boson exchange and quark-gluon inspired approaches have been used. However, in either case “correct” results can be assumed to require as input a “realistic” treatment of strangeness production with longer- and shorter-ranged components as well as of distortions and spin-dependent effects.

The more conventional way of describing the reaction $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ is in the form of one-kaon exchanges in the t -channel. Pioneering work of this kind was performed by Tabakin and Eisenstein [16] using a density-matrix approach and K, K^*, K_2^* as exchanged particles, by Niskanen et al. [17] employing a coupled-channels formalism with K - or K^* -exchanges, and by Kohno and Weise [18] in a DWBA framework with only ground-state kaon-exchange. Whereas $\bar{p}p$ initial-state interactions can be deduced from a large amount of experimental data, the $\bar{\Lambda}\Lambda$ final-state interactions as implemented in the calculations rely on model assumptions. Strong annihilation effects, proceeding dominantly from S -wave, led to a relatively strong P -wave appearance even close to the $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ threshold, quite in agreement with experimental observations. An approach based on DWBA with K -exchange only was also applied by LaFrance and Loiseau [19].

Timmermans, Rijken and de Swart [20] recently developed a P -matrix model for $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ using the so-called “Nijmegen potential”. The applied coupled-channels formalism takes into account that there are various competing baryon-antibaryon channels in

the relevant energy region, and in addition to these also important initial- and final-state interactions. Strange mesons included in the calculations are K , K^* , K_0^* , K_2^* . The complex P -matrix defines the interaction range, and some of its elements are chosen so as to reproduce elastic and charge-exchange cross-section data. Resulting from these calculations, K - and K^* -exchanges, and in particular their constructively coherent contributions to the “tensor” part of the interaction, appeared to be a prominent feature for the model description of $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$. As a consequence, more than 50 % of the reaction cross-section was accounted for by “tensor”-force transitions with $L(\bar{\Lambda}\Lambda) = l(\bar{p}p) - 2$, such as (see table 1): ${}^3D_{1-} \rightarrow {}^3S_{1-}$; ${}^3F_{2+} \rightarrow {}^3P_{2+}$; and ${}^3G_{3-} \rightarrow {}^3D_{3-}$. Transitions to 3P final states were seen to be the cause for non-zero polarisation near threshold, and their interference with “tensor”-force contributions generated a change of sign of the polarisation. Dominant “tensor” transitions gave the correct shape of spin-correlations coefficients, and the overall strength of spin-singlet partial waves was found to be negligibly small when compared with that of the spin-triplet parts, which again is in agreement with the experimental observations.

While the results obtained by Timmermans, Rijken and de Swart [20] are in part based on parameters adjusted so as to reproduce $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ data measured at various energies, we note that such a procedure apparently helps to identify the most significant partial waves, hence those that are likely to be responsible for the behaviour of cross-sections and spin variables observed in the experiments. A large number of data points on cross-sections and polarisations measured with experiment PS185 for $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ at beam momenta below 1.55 GeV/c was recently used by the same group [21] to extract the $\Lambda p K$ coupling constant. The fitted value is $g_{\Lambda p K}^2/4\pi = 15.4 \pm 1.5$. As a consistency check, the mass of the exchanged particle was determined to be $m = (480 \pm 60)$ MeV, which indicates that one is indeed looking at a kaon-exchange mechanism here.

Extensive work on $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ in a coupled-channels framework including K and K^* exchanges has been performed recently by Haidenbauer et al. [22] using the so-called “Bonn potential”. Again, these calculations reveal the strong P-wave components near threshold and also the clear dominance of spin-triplet transitions with $L(\bar{\Lambda}\Lambda) = l(\bar{p}p) - 2$, hence spin-flip of the type $(\uparrow\uparrow) \rightarrow (\downarrow\downarrow)$. The latter account for about 50 % of the production cross-section. The Nijmegen and Bonn-Jülich calculations appear to be very similar in spirit and in the overall consistency of their results, the main differences being detailed partial-wave cross-sections.

Haidenbauer, Holinde and Speth [23] extended their model to the reactions $\bar{p}p \rightarrow \bar{\Lambda}\Sigma^0 + c.c.$ and $\bar{p}p \rightarrow \bar{\Sigma}^+\Sigma^+$. In the first case, K - and K^* -exchange contribute with opposite signs, the consequence being a reduced “tensor” force and, likewise, a somewhat reduced spin-triplet production. Another type of transition, the case ${}^3P_{1+} \rightleftharpoons {}^1P_{1+}$ which is forbidden for $\bar{\Lambda}\Lambda$, accounts for about 10 % of the $\bar{\Lambda}\Sigma^0$ or $\bar{\Sigma}^0\Lambda$ production cross-section. The basic features of $\bar{\Sigma}^+\Sigma^+$ production appear to be quite similar to those of $\bar{\Lambda}\Lambda$, albeit with a reduced “tensor” force due to a smaller coupling constant. The cross-sections calculated for $\bar{\Lambda}\Sigma^0 + c.c.$ or $\bar{\Sigma}^+\Sigma^+$ production relative to that of $\bar{\Lambda}\Lambda$ at comparable excess energy show a good agreement with measurements.

According to Dalkarov, Protasov and Shapiro [24], the strongly attractive ω exchange in baryon-antibaryon systems like $\bar{p}p$ should lead to a number of P-wave states in particular near threshold. Consequently, the occurrence of such quasi-nuclear bound states was offered as an explanation for the relatively strong $L > 0$ contributions experimentally observed in the $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ cross-sections. The calculations were performed in a

coupled-channels approach employing effective optical potentials. Among others, a ${}^3\text{P}_{1+}$ quasi-bound $\bar{\Lambda}\Lambda$ state emerged from this, with a mass of 2237 MeV corresponding to $\epsilon \approx 6$ MeV, a total width of 8 MeV, and a $\bar{p}p \rightarrow X_{1+} \rightarrow \bar{\Lambda}\Lambda$ cross-section calculated as $10 \mu\text{b}$.

The question as to whether pronounced $L > 0$ contributions, experimentally observed in $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ all the way down to threshold, are conceived in terms of S-wave suppression or in terms of P-wave enhancement is more than an academic one. Different physical origins stand behind these pictures: annihilation effects proceeding most strongly from S-waves on the one side, or resonant baryon-antibaryon states in P-waves on the other one. Very recently, the near-threshold structure observed in the PS185 data (see figure 4) was investigated theoretically by Carbonell, Protasov and Dalkarov [25]. The resonance centroid was calculated to be below the $\bar{\Lambda}\Lambda$ threshold, at $\epsilon = -2$ MeV. Due to its narrow width $\Gamma = 1.8$ MeV, only the resonance tail shows up in the actual $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ production cross-section, whereas it appears fully in the related channel $\bar{p}p \rightarrow \bar{K}^* K^*$. The ${}^3\text{SD}_1$ partial wave held responsible for the resonance implies $J^{PC} = 1^{--}$. In view of all this, and its possible connection with the $\xi/f_4(2220)$ or the long-standing question of “baryonium”, the new high-statistics measurement [13] to be performed at LEAR deserves special attention.

Double-strangeness reactions such as $\bar{p}p \rightarrow \Xi^- \Xi^-$ can be reached only by two-boson exchange, which may cause the initial state to have a somewhat reduced influence on the final-state properties when compared to the one-boson exchange case $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$. The $\Xi^- \Xi^-$ channel suffers from an almost complete lack of experimental data [12]. However, recent predictions made by Haidenbauer et al. [26] for 3.0 GeV/c antiproton momentum attribute to it an integrated production cross-section of $0.34 \mu\text{b}$, an almost flat angular distribution of the Ξ^- , and a polarisation that is on average smaller than that of Λ .

3.2 Quark–gluon approaches

In terms of genuine QCD, the reaction $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ is based on $\bar{u}u \rightarrow \bar{s}s$ and thus mediated by gluon- or meson-exchanges in the s -channel. For the computation of absolute cross-sections one would need to know the strong coupling constant α_s at the strange-quark mass. Therefore, one considers only cross-section ratios in most cases. Genz et al. [27] developed a model based on the “internal fusion” of a quark-antiquark pair into an object with “vector” or “pseudoscalar” quantum numbers at the vertex, ${}^3\text{S}_1$ - or ${}^1\text{S}_0$ -, respectively. We note that no final-state polarisation can be generated in this way. However, the comparison between theoretical and experimental cross-section ratios showed a clear preference for the “vector” case, hence “one-gluon fusion”, which has built into it that the final state is in a spin-triplet state. The same concept has also been used to include double-annihilation processes such as $\bar{p}p \rightarrow \Xi^- \Xi^-$ or excited hyperon-antihyperon production which require beam momenta above those at LEAR. From their calculations, Genz et al. [27], Rubinstein and Snellman [28], and Furui and Faessler [29] obtained cross-section ratios $r_{th}^0 = \sigma(\bar{\Lambda}\Sigma^0 + c.c.)/\sigma(\bar{\Lambda}\Lambda) = 0.259, 0.235, \text{ and } 0.247$, respectively, which in spite of different approaches are all in good agreement with the experimental value $r_{exp}^0 = \sigma(\bar{\Lambda}\Sigma^0 + c.c.)/\sigma(\bar{\Lambda}\Lambda) = 0.29 \pm 0.02$.

It has been argued by Alberg, Henley and Wilets [30] that either one of the prominent ${}^3\text{S}_1$ - and ${}^3\text{P}_{0+}$ models should not be used alone, but rather simultaneously as two components of an overall scheme. In a superposition of “vector” and “scalar” interactions, the former would represent a short-range exchange of a gluon or a “vector” particle,

and the latter would represent a long-range confining “scalar” exchange. It was indeed found [30] that the combined model fits experimental data better than either one of its two components alone. Alberg et al. [31] subsequently extended their model in order to account for distortions and spin-dependent effects. Both the differential cross-sections and polarisations measured at various beam momenta for $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ and $\bar{p}p \rightarrow \bar{\Lambda}\Sigma^0 + c.c.$ were fitted best with “scalar” and “vector” strengths of the same order of magnitude. It was also found that high-quality data on $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ might be used in the future for extracting valuable information about various components of the yet largely unknown $\bar{\Lambda}\Lambda$ interaction.

While “scalar” or “vector” exchanges between the quark–antiquark vertices necessarily lead to spin-triplet production, it is of general interest to evaluate the strength of “pseudoscalar” s -channel exchange giving rise to a 1S_0 - state, hence spin-singlet. This was in fact done [27, 32], the result being that s -channel exchange with $J^P = 0^-$ is suppressed by up to two orders of magnitude. When one interprets the “pseudoscalar” exchange in terms of an $\eta - \eta'$ intermediate state, a further reduction of its size occurs due to the fact that these lightest “pseudoscalar” mesons are mixed and their contributions tend to cancel each other [32].

3.3 Model-independent partial-wave analyses

It is conceivable that the behaviour of cross-sections, polarisations, and spin correlations experimentally observed in $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ at low energies may result from a small number of significant amplitudes. The “universal” t' -dependence of some observables may be due to the fact that the relevant amplitudes do not change very much over the energy range considered. Therefore it is both interesting and instructive to study systematics of the data by means of a model-independent phenomenological analysis. This was done by Kudryavtsev and Samoilov [33] for the energy region near threshold, and also by Timmermans, Rijken and de Swart [20]. Schneider-Neureither et al. [34] applied a scattering-length expansion of S-, P- and D-waves to study the relevant amplitudes.

In a recent and elaborate work performed by Tabakin, Eisenstein and Lu [35] the results from an amplitude analysis for $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ are compared with all presently available PS185 data on cross-sections and spin observables. In an LS basis, the reaction $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ is expressed in terms of six amplitudes, which represent the cases of spin-singlet with $^1L_{J=L}$, uncoupled spin-triplet with $^3L_{J=L}$, and coupled spin-triplet with $^3L_{J=L\pm 1}$. Near threshold the $\bar{\Lambda}\Lambda$ final state contains a few partial waves with low orbital angular momenta only. Therefore, a restricted set of seven states is considered relevant, which includes all possible LS states with $J \leq 1$ or $L = 1$. Very good fits to differential cross-sections were obtained up to about 1.6 GeV/c incident momentum, whereas at somewhat higher momenta the need for including waves with $L \geq 2$ becomes apparent. Fits to the polarisation data revealed that neither 3S_1 - nor 3P_0 can account for the observed node at intermediate values of t' . The exact position of that node is determined by the specific t' -dependences of contributing partial waves and the interplay between them. Applying the scattering-length limit, one obtains eqn. 3 for the production cross-section, and the polarisation takes on the form $P \propto p_\Lambda \sin \theta \cdot F(p_\Lambda, \cos \theta)$. This work shows [35] that many characteristic features, such as the onset of an intermediate node in the polarisation data at a “critical” Λ momentum is a normal behaviour of a reaction near its threshold, hence without need for invoking “exotic” explanations.

Given the large variety of theoretical models that can more or less correctly describe the main features of $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$, it seems difficult to distinguish meson-exchange and quark-gluon approaches on the basis of cross-sections or polarisations. As has been pointed out, the $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ reaction occurs dominantly in spin-triplet. In terms of coherent K- and K*-exchange, this is due to non-diagonal “tensor”-force transitions with $L(\bar{\Lambda}\Lambda) = l(\bar{p}p) - 2$, hence by flipping the spin like $(\uparrow\uparrow) \rightarrow (\downarrow\downarrow)$. In terms of $^3P_{0+}$ or $^3S_{1-}$ quantum numbers at the quark-antiquark vertices, such transitions are suppressed or forbidden, respectively, so that spin-triplet production is dominated by diagonal non-flip transitions like $(\uparrow\uparrow) \rightarrow (\uparrow\uparrow)$ without change of orbital angular momentum. However, new experimental information can be provided by using a polarised beam or target in $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ measurements. A strong dependence of the spin transfer on the underlying mechanism has been predicted [36] as a decisive signature. To this end, it has been suggested [36, 37] to perform a measurement of the spin-transfer or depolarisation parameter $D_{nn} = [\sigma(i = f) - \sigma(i \neq f)]/[2\sigma_0]$ using a “frozen-spin” polarised target in a PS185-type experiment at LEAR. We note that such a measurement, or that of another strangeness-producing reaction, could also unravel the question of the strange-quark content in the nucleon [38].

4 SUMMARY AND OUTLOOK

The measurements of cross-sections and spin observables for the reaction $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ near threshold have revealed a number of interesting features. In the differential and the integrated cross-sections strong contributions from partial waves with non-zero orbital angular momenta are observed even very close to threshold. At all energies the hyperons are seen to emerge with large polarisations. Both the differential cross-sections and the polarisations exhibit characteristic dependences on the four-momentum transfer, which are the same for all values of the total invariant mass. From the measured spin correlations it is deduced that the $\bar{\Lambda}\Lambda$ pairs are always produced with their spins aligned. In view of the spin-isospin couplings of quarks in hyperons it can be concluded that this essentially pure spin-triplet production is a feature of the constituent $\bar{3}s$ quark pair as well. Production cross-sections have also been measured for $\bar{p}p \rightarrow \bar{\Lambda}\Sigma^0 + c.c.$ and $\bar{p}p \rightarrow \bar{\Sigma}^+\Sigma^+$, and their sizes relative to that of $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ at similar excess energies compare remarkably well with model calculations.

The strong dynamical selectivity of the reaction $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ is based on strangeness production in the underlying process $\bar{u}u \rightarrow \bar{3}s$ as well as on the small set of isospin-0 transitions and final states available in terms of angular momenta and parity. Various theoretical models have been applied for describing the observed features. They range from calculations based on one-kaon exchanges in the t -channel to approaches based on effective quark-gluon interactions and s -channel exchanges inspired by QCD. These theoretical descriptions have reached a good level of understanding of the interplay between longer- and shorter-ranged aspects of the interaction, and consequently they aim at combining both of them in appropriate ways. Many of the models can reproduce experimental observations on cross-sections and even spin observables rather well. Based on theory-experiment comparisons, the detailed understanding of the most relevant aspects of some models begins to emerge, yet a clear distinction of the different underlying reaction mechanisms is difficult.

The experimental data available for the reaction $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ have reached a high and unprecedented precision, and there are more results to come. Together with high-statistics data on the isospin-1 channel $\bar{p}p \rightarrow \bar{\Lambda}\Sigma^0 + c.c.$ and on charged-hyperon channels $\bar{p}p \rightarrow \bar{\Sigma}^\pm \Sigma^\pm$, which are being analysed, differences between the descriptions based on kaon exchange and quark-gluon interactions may become more apparent. Also of interest in this context is the reaction $\bar{p}p \rightarrow \pi^0 \bar{\Lambda}\Lambda$.

A number of issues are to be addressed in future measurements at LEAR. The very accurate investigation of $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$, $\bar{p}p \rightarrow \bar{K}^0 K^0$ and $\bar{p}p \rightarrow \bar{K}^* K^*$ in the vicinity of the $\bar{\Lambda}\Lambda$ threshold may answer the long-standing question of resonant behaviour in this region. Spin-correlation data with very good statistics give a precise and quantitative measure of the spin-0 and spin-1 production probabilities, which can be used to deduce stringent limits on the relative strengths of “pseudoscalar” versus “scalar” or “vector” exchanges in the s -channel. Spin-transfer measurements in $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ using a polarised target and/or beam can help answer fundamental questions on the physical origin of polarisation phenomena in strangeness production and on the possible strange-quark content in the nucleon. Charged-hyperon production $\bar{p}p \rightarrow \bar{\Sigma}^\pm \Sigma^\pm$ at very small final-state energies may reveal interesting atomic effects.

In view of the energy limit at LEAR, the $\bar{\Sigma}^+ \Sigma^+$ and $\bar{\Sigma}^- \Sigma^-$ channels are also prime physics objectives for SuperLEAR. Should such a machine become available it would open the interesting field of multiple strangeness production in reactions like $\bar{p}p \rightarrow \bar{\Xi}^- \Xi^-$ or $\bar{p}p \rightarrow \bar{\Omega}^- \Omega^-$. In addition, many excited hyperon-antihyperon channels can be investigated, thereby extending the physics possibilities into poorly explored areas of baryon spectroscopy. The strange-quark physics in $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ can be naturally complemented at SuperLEAR by studying its counterpart in the charm-quark sector with the reaction $\bar{p}p \rightarrow \bar{\Lambda}_c^+ \Lambda_c^+$. This is based on the quark process $\bar{u}u \rightarrow \bar{c}c$ and requires beam momenta above 10 GeV/c. A ratio of production cross-sections as large as $R_{c,s} = \sigma(\bar{\Lambda}_c^+ \Lambda_c^+)/\sigma(\bar{\Lambda}\Lambda) \approx 10^{-2}$ may be expected for energies not too close to threshold.

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