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Double strangeness production in low-energy antiproton–nucleus annihilation

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Abstract

Double strangeness production, i.e. the net production of two s quarks and two $\bar{s}$ quarks (carried inside hadrons) in antiproton–nucleus annihilations is investigated theoretically. The various mechanisms are identified, both for conventional $B = 0$ and for unusual $B = 1, 2$ annihilations. The double strangeness yield is estimated. The lack of precise input data for some reactions is underlined. The results are compared with the recent data of the DIANA collaboration. They seem to be consistent with the conventional processes.

1. Introduction

Strangeness production in annihilation of antiprotons on nuclei has attracted much attention in recent years. An important issue is the possible enhancement, compared to free-space nucleon–antinucleon annihilation. It was indeed suggested that an increase of strangeness production could provide a hint at the hypothetical formation of a cold quark–gluon plasma [1], or at the occurrence of a class of special annihilation events, namely the $B > 0$ annihilations [2]. The latter may be viewed as embodying the annihilation of the incident antinucleon on several nucleons at the same time, prior to any rescattering of the primary annihilation products. In addition, strangeness production needs the dominance of the so-called annihilation graphs and a possible enhancement of strangeness in antiproton–nucleus annihilation may shed some light on the annihilation mechanism.

Here, we concentrate on double strangeness production, consisting in the production of two strange quarks and two strange antiquarks, embedded, of course, inside produced strange hadrons. Recently, the identification of a few events of this kind has been

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Table 1
Secondary reactions, whose occurrence within a nucleus leads to double strangeness after $\overline{N}$ annihilation

Label	Secondary reaction
A	$M + N \to Y + K$
B	$\overline{K}$ (or $\overline{K}^\star$) $+ N \to Y + M$
C	$\overline{K}^\star + N \to \Xi + K$, $\Xi + N \to \Lambda + \Lambda$
D	$\phi + N \to Y + K$

reported [3], with a surprisingly high yield, of the order of 10^{-4}. Single strangeness production is of the order of $\simeq 5 \times 10^{-2}$. A naive estimate of double strangeness would consist of squaring the latter yield and multiplying by an extra factor, of the order of 10^{-2} at most, for taking account of the available phase space. This leads to an expected yield of the order of 10^{-6}. Recent estimates [3,4], based on calculations of a few channels gives a slightly higher yield. They may be questioned however, as four strange quarks may appear in various hadrons, through a wide variety of mechanisms, as we explain below. Our goal is to see whether this high yield might be explained by conventional processes or alternatively by a certain amount of $B > 0$ annihilations.

2. Various mechanisms leading to double strangeness in antinucleon–nucleus annihilation

In general, double strangeness production in conventional $B = 0$ annihilations at rest or at moderate momentum (i.e. below $\sim$ GeV/c) implies secondary reactions (rescattering) necessary to transform the primordial state into a final state with two $s - \bar{s}$ pairs. Indeed, the first direct double strangeness channel ($2K$ and $2\overline{K}$) has its threshold at 0.65 GeV/c. We list in Table 1 the secondary reactions apt to produce the required final states. The symbol M stands generically for a nonstrange meson (π, η, η' or ω). For simplicity, we do not generally distinguish between the $S = -1$ hyperons (denoted Y). The possible secondary reactions belong to three classes: (i) associated production induced by a nonstrange meson on a nucleon (A and D in Table 1); (ii) strangeness exchange between an antikaon and a nucleon leading to the formation of a hyperon (B in Table 1); (iii) formation of an $S = -2$ particle (Ξ), which may react with a nucleon to give two $S = -1$ hyperons.

In Table 2, we list the various mechanisms possibly leading to double strangeness production for annihilation at rest or at moderate antiproton momentum, i.e. below $\sim$ 1 GeV/c, disregarding the charge states, for simplicity. In the second column, we give the threshold energy (in GeV) and the corresponding $\bar{p}$ incident momentum (in GeV/c). The third column gives the primordial state, i.e. the state issued from the nucleon–antinucleon annihilation. The symbol m stands for one nonstrange meson (M) or a system of two or more such mesons. However, we single out some two-meson primordial states under case 6. We have not retained the $\Lambda\overline{\Lambda}$ channel which has its threshold at 1.44 GeV/c, nor the $KK\overline{K}\overline{K}^\star$ (and $KK^\star\overline{K}\overline{K}$) channel, whose threshold is at 1.85 GeV/c.

Table 2
Possible double strangeness production processes in $B = 0$ ($\overline{N}N$) annihilations on a nucleus

Channel	Threshold E_{cm}, p_{lab}	Primordial state	Secondary reaction	Strange content of the final state
1	1.975, 0.646	$KK\overline{K}\overline{K}$	-	$KK\overline{K}\overline{K}$
			B	$KK\overline{K}Y$
			B+B	$KKYY$
2		$K\overline{K}m$	A	$KK\overline{K}Y$
			A+B	$KKYY$
3		m	A+A	$KKYY$
4		$\overline{K}^{\star}Km$	A	$KK\overline{K}Y$
		$K^{\star}\overline{K}m$	A+B	$KKYY$
		$\overline{K}^{\star}K^{\star}m$	C	$KKYY$
5	2.039, 0.866	$\phi\phi$	-	$KK\overline{K}\overline{K}$
			D	$KK\overline{K}Y$
			D+D	$KKYY$
6		$\omega\omega$		
		$\omega\eta$	A+A	$KKYY$
		$\omega\eta'$		

Column 4 lists the secondary reactions necessary to transform the primordial state into a final state with two $s\bar{s}$ pairs. For simplicity, the $K^{\star} \to K\pi$ decays are not indicated. Finally, the last column gives the double strangeness content of the final state. Here too, for simplicity, we did not distinguish the $S = -1$ hyperons, denoted generically by Y.

A conclusion can be drawn directly from Table 2: except if two $\overline{K}$'s are formed in association with two K's from the very beginning, it is rather uncommon to have two kaons in the final state without having at least one hyperon at the same time. This remark will take its importance when we discuss the experimental data.

3. Calculation of the double strangeness yields

3.1. Branching ratios of the primordial states

We successively discuss the possible channels as they appear in Table 2. The yield of channel 1 is not known in the energy region discussed here. Estimates based on a statistical model embodying hindrance for strangeness production, adjusted on existing inclusive data at higher energies, predict a cumulated yield of $K\overline{K}\phi$ and $2K2\overline{K}$, that can be grouped together as channel 1 for simplicity, amounting to 2.5×10^{-5} at 0.9 GeV/c and more than one order of magnitude less at p_{lab} = 0.8 GeV/c [5]. Therefore, one may consider this contribution as negligible below this incident momentum (see however Section 5).

Channel 2 may be discussed in association with channel 4. Together, they correspond to the observed inclusive $K\overline{K}$ production. The most accurate experimental value for the frequency of the latter is $(5.75 \pm 0.02) \times 10^{-2}$ [6]. The fraction of primordial states with direct K and $\overline{K}$ production (i.e. containing no $K^\star$ or $\overline{K}^\star$) is not well known. From compilation of existing data [7], it seems reasonable to consider that this fraction lies around $\frac{3}{4}$. Also, the number of π, η or ω mesons accompanying the $K\overline{K}$ pair is not really known, even on the average. We decided to scale the known average π, η and ω multiplicities [6,8,9] in nonstrange annihilations proportionally to the energy available to the nonstrange mesons in reaction $p\overline{p} \rightarrow K\overline{K}M$. At rest, this yields $\langle\pi\rangle \approx 1.8$, $\langle\eta\rangle \approx 0.03$, $\langle\omega\rangle \approx 0.12$. It is remarkable that this simple estimate for the ω gives a value of the average branching ratio for $\langle K\overline{K}\omega\rangle$ of $\sim \frac{3}{4} \times 5.75 \times 10^{-2} \times 0.12 \approx 0.52 \times 10^{-2}$, very close to the measured value of the yield for the three-body channel $K\overline{K}\omega$, namely $(4.81 \pm 0.51) \times 10^{-3}$ [10], $(3.5 \pm 0.5) \times 10^{-3}$ [11]. For channel 3, the mean multiplicities are given in Refs. [6,8,9] and the total branching ratio for these nonstrange channels is 0.94. The branching ratio for channel 5 is known at higher energy only [12], where it lies around 0.3×10^{-4}, but a strong threshold effect is expected in the energy range under consideration (see Section 5). This contribution is probably negligible as well as the direct $2K2\overline{K}$ channel. The yields of the two-body primordial state in channel 6 have been (re)measured recently [13]. They are equal to $(3.32 \pm 0.34) \times 10^{-2}$, $(1.51 \pm 0.12) \times 10^{-2}$ and $(0.78 \pm 0.08) \times 10^{-2}$ for $\omega\omega$, $\omega\eta$ and $\omega\eta'$, respectively. The other two-body channels of that kind are at least an order of magnitude smaller [13] and are therefore not considered here.

3.2. Calculations

As we are looking for estimates based on sometimes uncertain input data and since the double strangeness data of Ref. [3] are based on very few events, we are using simplifying assumptions when the process under consideration is of secondary importance.

Let us start with channel 3 which is the simplest case. We use the detailed intranuclear cascade calculations of Refs. [14,15], where the single associated production has been calculated with the full momentum spectrum of the primary mesons (and the full complexity of the rescattering process) in order to determine the average associated production yield per meson $M(=\pi,\eta,\omega)$. We use these numbers to evaluate double associated production, considering only (ω,π), (η,π) and (π,π) as the only pairs of mesons initiating double associated production. The double associated production yield is assumed to be the product of the strangeness production yield for each type of particle and the corresponding pair multiplicity in this class of events. The case of (ω,ω) and (ω,η) are treated separately (see channel 7).

For channels containing a $\overline{K}$, we also use the calculations of Refs. [14,15] giving the probability of having strangeness exchange ($\overline{K}N \rightarrow Y\pi$). Since this cross section is not very much energy dependent in most of the relevant part of the $\overline{K}$ spectrum [15] and since the $\overline{K}$ spectrum is not expected to change too much from one channel to the other, we will take this probability as channel independent. For simplicity and because of a lack of experimental data, we also consider the strangeness exchange cross section induced by $\overline{K}^\star$ as equal to the $\overline{K}$ one at the same c.m. energy.

The calculation of the Ξ production and subsequent double Λ production (channel 4) requires some explanation. We assume the $\overline{K}^{\star}N \to \Xi X$ reaction cross section to be equal to the measured $\overline{K}N \to \Xi X$ reaction cross section [16]. We also take the same value for the probability of producing a Ξ among the reaction channels both by $\overline{K}$ or $\overline{K}^{\star}$ particles. For the $\Xi N \to \Lambda\Lambda$ reaction, we use the value obtained by multiplying the $\Sigma N \to \Lambda N$ cross section by a strangeness suppression factor γ_s ($\sim 3.5 \times 10^{-2}$), which accounts for the occurrence of another strange particle in the final state. This factor is tentatively determined by looking at the production of a Λ particle from πN and NN initial states, and reflects the overall hindrance of the production of strange hadrons in low-energy hadronic processes [16-18].

If we denote by x the range travelled by the particles (assuming straight-line motion) in a uniform matter and if λ_{d} is the decay length of a $\overline{K}^{\star}$ (into $\overline{K}\pi$), λ_{a} the absorption length of a $\overline{K}^{\star}$, where $\lambda_{\mathrm{a}}^{-1} = \rho\sigma_{\mathrm{inel}}(\overline{K}^{\star}N)$, λ_{p} the production length ($\lambda_{\mathrm{p}}^{-1} = \rho\sigma(\overline{K}^{\star}N \to \Xi K)$) and λ_s is the double Λ production length

$$\lambda_s^{-1} = \rho\sigma(\Xi N \to \Lambda\Lambda),$$

it is easy to show that the average number of Ξ and $\Lambda\Lambda$, as functions of x are given by

$$N_{\Xi}(x) = \frac{\lambda_s \Lambda}{\lambda_{\mathrm{p}}(\lambda_s - \Lambda)} \left[\exp\left(-\frac{x}{\lambda_s}\right) - \exp\left(-\frac{x}{\Lambda}\right)\right], \tag{1}$$

$$N_{\Lambda\Lambda}(x) = \frac{\Lambda}{\lambda_{\mathrm{p}}(\lambda_s - \Lambda)} \left(\lambda_s \left[1 - \exp\left(-\frac{x}{\lambda_s}\right)\right] - \Lambda\left[1 - \exp\left(-\frac{x}{\Lambda}\right)\right]\right), \tag{2}$$

where

$$\Lambda^{-1} = \lambda_{\mathrm{d}}^{-1} + \lambda_{\mathrm{a}}^{-1}. \tag{3}$$

Taking an average momentum of $\overline{K}^{\star} \approx 0.3$ GeV/c, which might be optimistic, since it corresponds to $\overline{K}^{\star}K^{\star}$ channel, one finds, for the average range travelled inside a ^{131}Xe nucleus, the following results:

$$N_{\Xi} \approx 14 \times 10^{-3} \quad \text{per } \overline{K}^{\star} \tag{4}$$

and

$$N_{\Lambda\Lambda} \approx 3.2 \times 10^{-3} \quad \text{per } \overline{K}^{\star}. \tag{5}$$

Let us finally consider the two-body channels 6. At rest, they cannot contribute to double strangeness, since, if one of the mesons enters the nucleus, the other goes in the opposite direction. For annihilation in flight, the situation is a little bit more favourable, since both particles can go inside the nucleus. By looking at the paths travelled into a sphere, one may easily establish a formula giving the ratio $\mathcal{R}$ of the probability for double production (in the limit of small cross sections) to the product of average single production probabilities. One finds

$$\mathcal{R} = \frac{(2R - d)d}{R^2}, \tag{6}$$

Table 3
Estimate of the various double strangeness yields in $\bar{p}$Xe annihilations at antiproton momenta 0–0.4 GeV/c. The channel numbers in first row correspond to the mechanism indicated in Table 2

Channel	$KK\overline{KK}$	$KK\overline{K}\Lambda$	$KK\Lambda\Lambda$	ΞKK
1	–	–	–	
2		1.6×10^{-4}	3.18×10^{-5}	
3	–	–	1.29×10^{-7}	
4	–	–	4.4×10^{-5}	1.9×10^{-4}
5	–	–	–	
6	–	–	3.1×10^{-6}	
total		1.6×10^{-4}	7.9×10^{-5}	1.9×10^{-4}

where d is the mean annihilation depth ($= 1/\sigma_{\text{ann}}\rho$) and R is the nuclear radius.

3.3. Results

The calculated results are summarized in Tables 3–5. The empty boxes correspond to forbidden processes or insignificant contributions. The asterisks indicate the contributions from the Ξ production channel (secondary reactions of type C).

Before comparing to experiment, we can make a few remarks. There are two main contributions to the double strangeness yield. The first one is coming from the primordial $K\overline{K}\omega$ production followed by the $\omega N \rightarrow KY$ reaction. For instance, in the highest momentum range (Table 5), this contribution amounts to $\simeq 2.1 \times 10^{-4}$. The second one is the Ξ formation process, which leads to a substantial yield for the ΞKK final state.

The predominant contribution of the $K\overline{K}\omega$ among the various $K\overline{K}m$ channels (channel 2 in Table 2) proceeds from more favourable kinematic conditions, as illustrated in Fig. 1. In the latter, the distribution of the invariant mass of the system composed of a meson $M(= \pi, \eta, \omega)$ produced in the reaction $\bar{p}p \rightarrow K\overline{K}M$ at rest and of a target nucleon (neglecting the Fermi motion) is displayed. Only in the case of the ω meson the invariant mass can be larger than the ΛK threshold with a substantial probability. Of course, Fermi motion and increasing $\bar{p}$ momentum smear out the invariant mass spectra

Table 4
Estimate of the various double strangeness yields in $\bar{p}$Xe annihilations at antiproton momenta 0.4–0.65 GeV/c. The channel numbers in first row correspond to the mechanism indicated in Table 2

Channel	$KK\overline{KK}$	$KK\overline{K}\Lambda$	$KK\Lambda\Lambda$	ΞKK
1	–	–	–	
2		1.9×10^{-4}	3.7×10^{-5}	
3	–	–	3.6×10^{-6}	
4	–	–	2.5×10^{-7}	2.0×10^{-4}
			4.6×10^{-5} *	
5	–	–	–	
6	–	–	4.0×10^{-6}	
total		1.9×10^{-4}	8.8×10^{-5}	2.0×10^{-4}

Table 5
Estimate of the various double strangeness yields in $\bar{p}$Xe annihilations at antiproton momenta 0.65-0.9 GeV/c. The channel numbers in first row correspond to the mechanism indicated in Table 2

Channel	$KK\overline{KK}$	$KK\overline{K}\Lambda$	$KK\Lambda\Lambda$	ΞKK
1	1.3×10^{-6}	-	-	
2		2.1×10^{-4}	4.0×10^{-5}	
3	-	-	4.4×10^{-6}	
4	-	5.8×10^{-6}	2.3×10^{-7} 4.7×10^{-5} *	2.0×10^{-4}
5	-	-	-	
6	-	-	6.5×10^{-6}	
total	1.3×10^{-6}	2.2×10^{-4}	9.8×10^{-5}	2.0×10^{-4}

of Fig. 1 a little bit.

We want to emphasize that we did not incorporate the Σ hyperons in our calculations, for simplicity. If the final channels indicated in Table 3 that are to be compared to the experiment, one should include the Σ^0 hyperon which often indistinguishable from Λ particles. This should be compensated by the fact that some of the Λ particles can be attached to the target nucleus and therefore may so escape from direct measurement. In this energy range, these two effects are of the order of 10-20 % and compensate each other more or less [14,15,19]. It is beyond the scope of this paper and not really appropriate, in view of the existing data, to produce a detailed calculation of these effects.

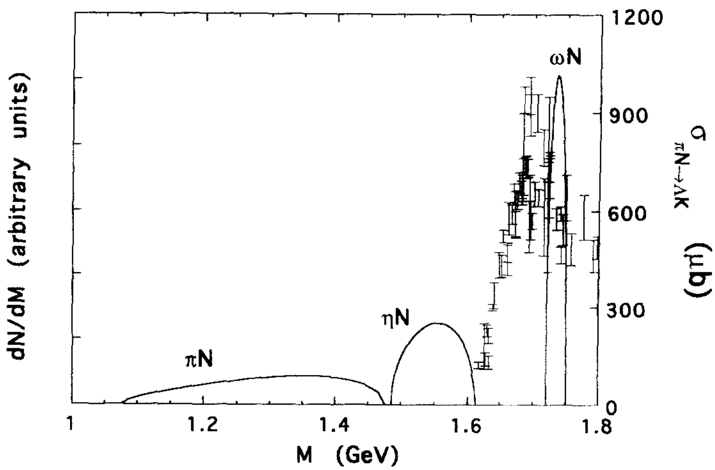

Fig. 1. Distribution of the invariant mass of πN, ηN and ωN pairs (full curves, see text for detail). The points show the $\pi N \to K\Lambda$ yield cross section, with the scale on the right.

Table 6
Comparison of the data from Ref. [20] with our predictions. All numbers are multiplied by 10^4

Momentum	K^+K^+X		$K^+K^0\Lambda X$		Total DS
(GeV/c)	exp.	calc.	exp.	calc.	calc.
0–0.4	0.25 ± 0.14	0.16	1.2 ± 0.8	1.59	4.3
0.4–0.65	0.32 ± 0.16	0.19	2.5 ± 1.4	1.76	4.7
0.65–0.9	0.5 ± 0.4	0.22	2.5 ± 1.4	1.9	5.2

4. Comparison with experimental data

The data being rather scarce [20,21] (only 32 events), comparison of our results with the data is not obvious. First of all, not all strange particles are identified. Some events contain $2K^+$ but the accompanying antikaons (or hyperons) are not detected. Furthermore, not all charge states were detected. For instance, no K^0K^0 or K^-K^- pairs have been detected.

It is therefore difficult to compare with data for specific channels without resorting to some assumptions. To tentatively perform a comparison, we consider the most important channels, namely the $KK\omega$ and ΞKK channels. We assume that the charge states of the KK pair is given by the annihilation itself and the first ω or Ξ rescattering. Counting the possibility of having annihilation and rescattering on a proton or a neutron, one can easily calculate the probability of a given KK charge state and obtain the weight for the specific final states. Of course, this neglects the possible charge exchange between the KK pair and the rest of the system. The results are given in Table 6 for the K^+K^+X and the $K^+K^0\Lambda X$ channels, where X does or does not contain a Λ particle.

We also give in Table 6 the calculated total double strangeness yield (last column). It is difficult to assess the uncertainty of the calculations. The latter arises from the simplifications used in the calculations and, more importantly, from uncertainty due to the poor knowledge of some cross sections. An uncertainty of 30 % seems a reasonable estimate. We want to stress that the uncertainty in the result for a specific channel may be much higher, since further assumptions are needed in this case. On the other hand, because all charge states and all strange particles are not detected in the experiment, the evaluation of the experimental double strangeness yield is not straightforward. Assuming perfect charge symmetry for the two kaon system, an estimate can be done from the preliminary results of Ref. [21], resting on the analysis of a larger set of events: one finds $(2.7 \pm 1.6) \times 10^{-4}$ for $p_{\rm lab} < 0.4$ GeV/c, $(8.0 \pm 3.6) \times 10^{-4}$ for 0.4 GeV/$c < p_{\rm lab} < 0.9$ GeV/c.

It is also to be noted that the experiment of Ref. [3] is able to identify Ξ particles. According to the analysis of Ref. [21], the ΞKK yield is $(1.2 \pm 0.6) \times 10^{-4}$ for 0.4 GeV/$c < p_{\rm lab} < 0.9$ GeV/c.

It is satisfying to notice that the average double strangeness yield may be more or less accounted for by the theory. This is also true for the specific semi-inclusive channels indicated in Table 6. In view of the complexity of the problem and the uncertainty of some input data (see discussion below), this is a remarkable achievement.

Taking the (average) experimental values for granted, disturbing aspects are however emerging. The data indicate a rather strong dependence on the antiproton momentum, which is not reproduced by calculations. This is really puzzling, since the few processes which show a strong momentum dependence, like the $\pi N \to \Lambda K$ process [14] have a very small contribution (see also Section 5). One has to underline that associated production, induced by η and ω as well as the strangeness exchange, induced by $\overline{K}$ and $\overline{K}^{*}$, are all exothermic processes and thus do not benefit much from an increase of the momentum of the annihilating system. Finally, it should be noticed that the ΞKK channel yield comes a factor ~ 2 too large in our calculation.

5. Threshold effects on direct channels

As we already mentioned in the previous section, some processes may experience threshold effects in the momentum range under investigation. They may thus be sensitive to Fermi motion, especially to the tail of the Fermi distribution. An example, encountered in Section 3, is provided by the rescattering $\pi N \to \Lambda K$ and $\eta N \to \Lambda K$ processes. For evaluating the importance of these processes, we have used the calculations of Ref. [15], where the Fermi motion with a sharp boundary at $p_{\mathrm{F}} = 270$ MeV/c is accounted for. The contributions of these processes are however rather small. For instance in the entries for channel 2 in Table 5, the $\pi N \to \Lambda K$ contributes 6 % and the $\eta N \to \Lambda K$ 15 %, the rest coming from the $\omega N \to \Lambda K$ process. Therefore, the total yield for channel 2 is not likely to be sensitive to a further refinement of the description of the rescattering process.

We want to pay more attention here to the $p\overline{p} \to \phi\phi \to 2K2\overline{K}$ process (channel 5), which also experiences threshold effects in the momentum range under consideration. The cross section of the $p\overline{p} \to \phi\phi$ reaction is given in Ref. [12] for the invariant collision energy $\sqrt{s} > 2.22$ GeV. We parametrize it following the usual dependence on the available phase space for two-body channels, as

$$\sigma(\overline{p}p \to \phi\phi, \sqrt{s}) = \beta(\sqrt{s} - \sqrt{s_0})^{1/2}, \tag{7}$$

where $\sqrt{s_0}$ is the threshold c.m. energy. The parameter β turns out to be equal to $\beta = 2.64\ \mu\mathrm{b/GeV}^{1/2}$. The $KK\overline{KK}$ (through $\phi\phi$) production cross section in $\overline{p}$ annihilation on a nucleus A is given by

$$\sigma(\overline{p}A \to \phi\phi \to 2K2\overline{K}) = N_A \int \Phi(\boldsymbol{q})\sigma(\overline{p}N \to \phi\phi, \sqrt{s})\,\mathrm{d}\boldsymbol{q}, \tag{8}$$

where N_A stands for the effective nucleon number and where $\Phi(\boldsymbol{q})$ is the nucleon momentum distribution. We take the following form:

$$\Phi(\boldsymbol{q}) = \left(\frac{b}{\pi}\right)^{3/2} \exp(-bq^2), \tag{9}$$

where a slope parameter $b = 38$ (GeV/c)$^{-2}$. This is consistent with the experimental data of Frullani and Mougey [22]. The number N_A can be obtained by assuming that

Table 7
Possible double strangeness production processes in $B = 1$ $(\overline{N}NN)$ annihilations on a nucleus

Channel	Threshold E_{cm}, p_{lab}	Primordial state	Secondary reaction	Strange content of the final state
1	2.913, 0.55	$NKK\overline{K}\overline{K}$	–	$KK\overline{K}\overline{K}$
			B	$KK\overline{K}Y$
			B+B	$KKYY$
		$\Lambda KK\overline{K}m$	–	$KK\overline{K}Y$
			B	$KKYY$
2		$NK\overline{K}m$	A	$KK\overline{K}Y$
			A+B	$KKYY$
		ΛKm	A	$KKYY$
3		Nm	A+A	$KKYY$
4		$\overline{K}^{*}Km$	A	$KK\overline{K}Y$
		$K^{*}\overline{K}m$	A+B	$KKYY$
		$\overline{K}^{*}K^{*}m$	C	$KKYY$
5	2.039, 0.866	$\phi\phi$	–	$KK\overline{K}\overline{K}$
			D	$KK\overline{K}Y$
			D+D	$KKYY$
6		$\omega\omega$		
		$\omega\eta$	A+A	$KKYY$
		$\omega\eta'$		

the annihilation cross section is given by a relation similar to (8) and adjusting for the observed annihilation on ^{131}Xe nuclei, i.e. 1290 mb. This gives $N_A \approx 13$. This calculation gives a $2K2\overline{K}$ yield of 0.04×10^{-5}, 1.2×10^{-5} and 1.8×10^{-5} for the three momentum ranges, respectively. It should be understood however that the presence of a long tail in $\Phi(q)$ would favour subthreshold production.

Let us also comment on the $\overline{K}N \rightarrow \Xi K$ reaction whose threshold is at a $\overline{K}$ momentum of ~ 1.1 GeV/c. The momentum spectrum of the $\overline{K}$'s issued from $\overline{p}p$ annihilation is not soft enough for allowing a sizeable subthreshold production in the momentum range under consideration.

6. $B > 0$ annihilations

It is tantalizing to look for a possible contribution of $B > 0$ annihilations to double strangeness production, as it has been predicted [23] that $B > 0$ annihilations may enhance the (single) strangeness yield. One has to admit that the available data at low energy are somewhat contradictory concerning the existence of this enhancement [24]. Nevertheless, for the sake of completeness, we investigated the double strangeness production mechanisms that are made possible by the occurrence of $B = 1$ and 2 annihilations. In Tables 7 and 8, we list the possible reactions leading to double strangeness final states (including K, $\overline{K}$, Λ and Ξ only). The same conventions as in Table 2 are adopted.

The striking difference with $B = 0$ annihilations (Table 2) is the appearance of Λ

Table 8
Possible double strangeness production processes in $B = 2$ ($\overline{N}NNN$) annihilations on a nucleus

Channel	Threshold E_{cm}, p_{lab}	Primordial state	Secondary reaction	Strange content of the final state
1	3.851, 0.516	$NNKK\overline{K}\overline{K}$	-	$KK\overline{K}\overline{K}$
			B	$KK\overline{K}Y$
			B+B	$KKYY$
		$N\Lambda KK\overline{K}m$	-	$KK\overline{K}Y$
			B	$KKYY$
		$\Lambda\Lambda KK$	-	$KKYY$
		$N\Xi KK$	-	ΞKK
2		$NNK\overline{K}m$	A	$KK\overline{K}Y$
			A+B	$KKYY$
		$N\Lambda Km$	A	$KKYY$
3		NNm	A+A	$KKYY$
4		$NN\overline{K}^{*}Km$	A	$KK\overline{K}Y$
		$NNK^{*}\overline{K}m$	A+B	$KKYY$
		$NN\overline{K}^{*}K^{*}m$	C	$KKYY$
5	3.915, 0.681	$NN\phi\phi$	-	$KK\overline{K}\overline{K}$
			D	$KK\overline{K}Y$
			D+D	$KKYY$
6		$NN\omega\omega$		
		$NN\omega\eta$	A+A	$KKYY$
		$NN\omega\eta'$		

particles in the primordial state. Due to the complexity of the numerous possible mechanisms, it is out of scope to make a detailed calculation of all contributions. As a matter of fact, due to the exploratory character of our investigation, a close inspection of Tables 7 and 8 allows drastic simplifications. Indeed, there is a clear correspondence between the channels that do not contain Λ particles in the primordial state of $B > 0$ annihilations and the $B = 0$ channels (that is why we kept the same numeration). It is expected that the meson multiplicity and momentum spectra are not significantly different (see indications in Ref. [23]). Therefore, these channels in the $B \neq 0$ annihilations are essentially contributing like in the $B = 0$ case. Taking account of the primordial state with a Λ particle in $B = 1$ annihilations does increase the yield by about 20 % on the average. The most important fact allowed by $B > 0$ annihilations is the appearance of two Λ particles in $B = 2$ annihilations (channel 1 in Table 8). This is in fact the most economical way, from the energetic point of view, of creating double strangeness. Using the same statistical model as in Ref. [23], we found that the branching ratio of the $\Lambda\Lambda KK$ state in $\overline{p} - NNN$ annihilation is equal to $\sim 10^{-4}$ at rest, $\sim 2 \times 10^{-4}$ in the 0.6–0.9 GeV/c range. If one adds the Σ^0's coming from the $\Lambda\Sigma\overline{K}K$ and $\Sigma\Sigma KK$ channels, evaluated in the same model, the total contribution of primordial $\Sigma\Sigma KK$ raises to $\sim 5\times 10^{-4}$ at 0.9 GeV/c. The sum of the other contributions amounts to about 7×10^{-4}. The conclusion is that the $B = 2$ annihilations, described with the help of the statistical model of Ref. [23], are largely able to account for the observed double strangeness yield. It would be however doubtful to attempt a fit of the data with a mixture of $B = 0$ and 2 annihilations because of the crude nature of the calculations. Taking the figures in Table 6 seriously, the $B = 2$ frequency necessary to reproduce the observed yield would lie between 0.2 and 0.4, which look rather large.

It is also interesting to notice that $B = 2$ annihilations allow a $N\Xi KK$ primordial state, which, in the same statistical model, has a branching ratio of $\sim 3 \times 10^{-4}$ at rest and up to $\sim 8 \times 10^{-4}$ at 0.9 GeV/c.

7. Discussion and conclusion

We have investigated the mechanisms leading to double strangeness production in antiproton annihilation on nuclei. The number of possible mechanisms is strikingly large, especially for $B > 0$ annihilations. Even keeping with the conventional $B = 0$ annihilations, there are at least a dozen of ways of producing double strangeness with final states containing only $K, \overline{K}$ and Λ. Yet, we have seen that the most important mechanisms are

$$\overline{N}N \to K\overline{K}\omega, \qquad \omega N \to \Lambda K \text{ with or without } \overline{K}N \to \Lambda\pi \tag{10}$$

and

$$\overline{N}N \to K\overline{K}^\star, \qquad \overline{K}^\star N \to \Xi K, \qquad \Xi N \to \Lambda\Lambda. \tag{11}$$

These channels are the most efficient ones, because the available energy in the annihilation is stored first in heavy hadrons, which can lead to double strangeness by *exothermic* reactions. This is nicely illustrated by Fig. 1. Our analysis raises a theoretical problem however. The $\omega N \to \Lambda K$, $\overline{K}^\star N \to \Xi K$ and $\Xi N \to \Lambda\Lambda$ cross sections are not known. Here we used reasonable assumptions. Let us recall them:

$$\sigma(\omega N \to \Lambda K, \sqrt{s}) = \sigma(\pi N \to \Lambda K, \sqrt{s}), \tag{12}$$

$$\frac{\sigma(\overline{K}^\star N \to \Xi K, \sqrt{s})}{\sigma_{\text{inel}}(\overline{K}^\star N, \sqrt{s})} = \frac{\sigma(\overline{K}N \to \Xi K, \sqrt{s})}{\sigma_{\text{inel}}(\overline{K}N, \sqrt{s})} \tag{13}$$

and

$$\sigma(\Xi N \to \Lambda\Lambda, \sqrt{s}) = \sigma(\Sigma N \to \Lambda N, \sqrt{s}) \times \gamma_s, \tag{14}$$

where γ_s is the reduction factor for strangeness production, based on low-energy hadronic phenomenology [16,17].

There is however no real indication that these assumptions provide upper or lower bounds. Therefore, our results appear as reasonable, but should be taken with some caution.

We have also shown that $B > 0$ annihilations may increase, as expected, the estimated yield, based on conventional processes and the above assumptions, which is already in satisfactory agreement with the data. If, however, the average values of the data had to be taken seriously, a substantial amount of $B = 2$ annihilations ($B = 1$ annihilations are not so helpful) would be needed. The basic effect of these annihilations is the possible production of two Λ's in the primordial state. It would be however inappropriate in the present status of the experimental information to attach too much meaning to the cited $B = 2$ annihilation yield.

In conclusion, the observed double strangeness yield seems to be explained by conventional processes, the most important of which are characterized by the transformation of most of the annihilation energy into strange particles by a chain of exothermic reactions. However, an improvement of the experimental situation is needed. A more elaborate theoretical calculation would then be justified and allow for more precise conclusions, especially for the yield of specific channels.

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