Strangeness production in antiproton annihilation on nuclei

J. Cugnon, P. Deneye, and J. Vandermeulen
Université de Liège, Physique Nucléaire Théorique, Institut de Physique au Sart Tilman, Bâtiment B.5, B-4000 Liège 1, Belgium
(Received 19 June 1989)

The strangeness production in antiproton annihilation on nuclei is investigated by means of a cascade-type model, within the frame of the conventional picture of the annihilation on a single nucleon followed by subsequent rescattering proceeding in the hadronic phase. The following hadrons are introduced: N, Λ, Σ, $\bar{\Lambda}$, π, η, ω, K, and $\bar{K}$ and, as far as possible, the experimental reaction cross sections are used in our simulation. The numerical results are compared with experimental data up to 4 GeV/c. The $\bar{\Lambda}$ yield is correctly reproduced, while the Λ and K_s yields are overestimated in the $\bar{p}$Ta and $\bar{p}$Ne cases. On the other hand, the rapidity and perpendicular momentum distributions are well reproduced. It is shown that total strange yield is not very much affected by the associated production taking place during the rescattering process. It is also shown that the Λ/K_s ratio is largely due to the strangeness exchange reactions induced by antikaons. In particular, values of the order of 1 to 3 are expected in the energy range investigated here, independently of the detail of the hadronic phase dynamics. Finally, it is stressed that rapidity distributions are consistent with the rescattering process. Comparison with other works and implications of our results are examined.

I. INTRODUCTION

A considerable interest arose recently for the antiproton annihilation on nuclei and especially for the subsequent particle production. The reason is the appearance of new ideas[1-5] about the mechanism of the annihilation, which could be different from the conventional picture. In the latter, supported by the bulk of the experimental data (for a review, see Refs. 6 and 7), the antiproton is supposed to be annihilated on a single nucleon in the nuclear surface, generating a few pions which cascade through the nucleus. This process transfers, even for annihilation at rest, a few hundred MeV at least to the nucleus. This process is, however, not really explosive, but fragmentation of the nucleus can occur.

Recently, in a provocative article, Rafelski[2] claimed that some of the data concerning the annihilation of 4 GeV/c antiprotons by Ta nuclei give evidence for the formation of a cold quark-gluon plasma. According to this author, the antiquarks give rise to the merging of several nucleon bags (up to 13 in this particular example). The presence of a quark-gluon system would reflect on the multiplicity and the rapidity distributions of Λ and K_s particles.

The multiplicity of strange particles was also presented, for the time in Ref. 3, as a possible indicator for the presence of another special, although less spectacular phenomenon, namely the annihilation of an antiproton on two (or more) nucleons. According to Refs. 3 and 8, even if this phenomenon occurs in a pure hadronic phase, the strange particle yield should be enhanced, compared to the conventional picture. The possibility of this phenomenon is demonstrated by data on $\bar{p}d$ annihilation,[9,10] in particular by the very existence of the $\bar{p}d \rightarrow \pi^- p$ process.[10-12] In Ref. 13, convincing arguments are presented in favor of the occurrence of two-nucleon annihilation on nuclei. However, no detailed calculation, including properly the rescattering of produced particles and secondary production, exists up to now. Our purpose is to remedy to this situation and present the results of an intranuclear cascade type of calculation, still in the spirit of the conventional picture. We have been stimulated by the existing data on Λ and K_s production, as measured in Refs. 14 and 15. However, we are also interested in many other aspects, namely the spectra of these strange particles, the yield of other strange particles, and the yield and spectra for nonstrange particles (pions and η mesons). We concentrate also our attention on the various contributions to the total yields of the particles and we show that some of them have been poorly evaluated in the past.

Our paper is organized as follows. In Sec. II, we shortly describe our cascade model. In Sec. III, we discuss the basic ingredients of our calculation: model for Λ production and parametrization of the cross sections. In Sec. IV, we analyze the experimental results available up to now. In Sec. V, we concentrate on our results for strange particles and point out the various contributions. Section VI is devoted to the analysis of our results. In Sec. VII, we discuss the relationship of our work with previous calculations. Finally, Sec. VIII contains our conclusion.

II. NUMERICAL MODEL

Our model is a cascade model. Although our group has developed a complex intranuclear cascade code including nucleons, pions, and deltas, very successful at low energy,[7,13] we preferred to work with a simplified cascade picture. The reason is that at high energy a lot of different particles can be produced, which makes the code considerably slower. Also, some particles are produced with a low cross section, which would require very high statistics and therefore huge computation time.

We thus turn here to a simplified cascade model, still based on simulation, but taking the target nucleus as a continuous medium with a sharp boundary in which particles can travel on the basis of a mean free path picture. The first step is to determine the $\bar{p}$-annihilation site. The impact parameter is chosen at random, as well as the penetration depth in agreement with the experimental annihilation cross section.

The annihilation is supposed to occur as in free space. We use the experimental $\bar{p}N$ data which, at low energy, are quite complete. In particular the multiplicity of the various mesons π, K, ω, η are rather well known.

Antiproton annihilation frequently creates mesonic resonances, which eventually decay into π's and K's. Since we are interested in annihilations occurring in a nuclear medium, we have to distinguish between long-lived resonances (ω and η) and short-lived resonances, whose lifetime is so short that even in a nuclear medium, one can consider that they decay immediately. In $\bar{p}p$, the presence of long-lived resonances makes the multiplicity of "true" (direct) pions smaller than the "experimental" (asymptotic) ones.

At large momentum (4 GeV/c, e.g.,) the situation is more complex since, before it annihilates, the antiproton may have made, with an important probability (see Sec. III), an inelastic collision which can produce particles. To simplify the calculation, we stick with the annihilation site as determined by the annihilation cross section. But we then assume that either a single annihilation or an inelastic process followed by an annihilation occurs at the same place with the appropriate weights. In doing so, we introduce a slight error since, in reality, the inelastic process takes place ahead of the annihilation site. The corrections will be small anyway since the $\bar{p}$ mean free path is small and since the properties of the annihilation are weakly dependent upon energy. So, to summarize, the multiplicities of the various particles ($\pi, K, \bar{K}, \eta, \omega, \Lambda, \bar{\Lambda}$) are taken from experiment (Refs. 16–21 and Ref. 7 for a review).

The momentum of a produced particle is determined at random in accordance with the known particle spectra. They have a Boltzmann shape in the $\bar{p}N$ system, for most of them. We give more details in Sec. III.

The cascade of a produced particle is constructed on the basis of the mean free path picture. Let it be a pion, for instance. We choose at random the interaction point assuming the free path follows an exponential law. The type of interaction (absorption, elastic scattering, creation of particles), if many channels are possible, is chosen at random according to the respective cross sections. The interaction nucleon is supposed to have a momentum due to Fermi motion. The final state is then realized subject to energy-momentum conservation. The direction of propagation of the outgoing particles is chosen at random in relation with the known experimental angular distributions. The procedure is resumed for the outgoing particles, which then may interact, and so on.

The model used here differs from the standard intranuclear cascade (INC) model in two respects: (a) Only *one* particle issued from the annihilation is followed, but *all* the secondaries (except nucleons) are followed at the same time. Observables are calculated by summing events with appropriate weights. (b) The target is acting here as a continuous medium. By using procedure (a), we escape from the complications of enforcing energy-momentum conservation at the annihilation. Since we used experimental spectra for the produced particles, the latter is nevertheless recovered on the average. We checked on the final pion spectra that this procedure yields results close to those obtained by the full INC model. On the other hand, it allows a very flexible use and an accurate calculation of the observables even if it corresponds to a particle rarely produced in the annihilation. To illustrate this point, let a particle of species α be produced in the annihilation with a frequency $f(\alpha)$. Let also $N(\alpha)$ be the events that we generate with this particle initiating the cascade. Let finally $\mathcal{O}(\alpha,\zeta)$ be an observable calculated in the ζth event of these $N(\alpha)$ ones (it may be the multiplicity of another particle, for instance). The average value of $\mathcal{O}$ over all annihilations will be given by

$$\mathcal{O}=\frac{\sum_{\alpha} f(\alpha) N_{\alpha}^{-1} \sum_{\zeta \in N(\alpha)} \mathcal{O}(\alpha,\zeta)}{\sum_{\alpha} f(\alpha)} . \tag{2.1}$$

Even if $f(\alpha)$ is very small, we can generate a large number $N(\alpha)$ of events with particle α and then achieve an accurate calculation of $\mathcal{O}$. In other words, if one is interested in rare events, one can so disregard the noninteresting events.

Concerning point (b) above, it does not constitute a real limitation, since the nuclear density is never greatly perturbed[22] during the cascade process, at least at low energy. The mean free path picture in a continuous medium adopted here is the basic procedure commonly used in the cascade calculations of many groups.[6,23,24]

III. PHYSICAL INGREDIENTS

A. The annihilation

In the annihilation, the following particles may be created: π, ω, η, K, $\bar{K}$, Λ $\bar{\Lambda}$, Σ, and $\bar{\Sigma}$. Below the $\Lambda\bar{\Lambda}$ threshold, we use the existing data (that we average over $\bar{p}p$ and $\bar{n}p$ whenever possible). The most important ones can be found in the review.[7] They are also summarized in Table I. The spectrum of π, K, and $\bar{K}$ particles is taken as thermal with temperatures quoted in the same table. The spectrum of ω's and η's is described in Ref. 25: It contains a strong two-body ($\omega\rho$ and $\eta\rho$) component superimposed to a thermal component. These particles are supposed to be emitted isotropically in the annihilation frame. Above the meson production channel (see Fig. 1), the multiplicity of the various particles is corrected for a possible production prior to annihilation, as explained in Sec. II (here we include in the annihilation those process-

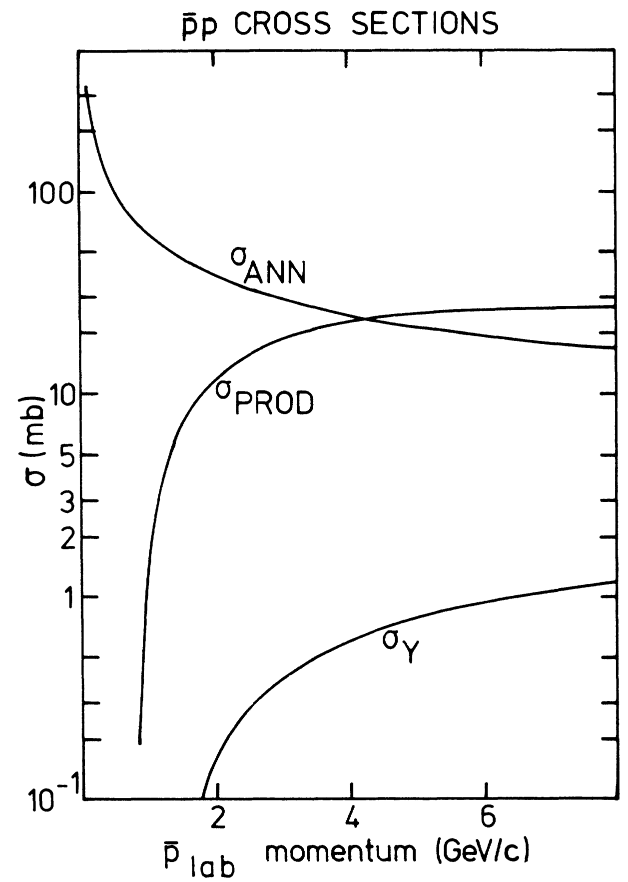

FIG. 1. Representation of the $\bar{p}p$ annihilation cross section (including all channels), of the production cross section (inelastic channels including a nucleon and an antinucleon), and of the strange production cross section, σ_Y (final channels containing a hyperon and/or an antihyperon), as a function of the antiproton incident momentum.

es by which a hyperon and/or an antihyperon appears, like $\bar{p}p \rightarrow \Lambda\bar{\Lambda}X, \Lambda\bar{p}KX, \ldots$). To be more precise, if, for a species α, the average multiplicity is $f_\alpha(p)$ in $\bar{p}N$ annihilation and $h_\alpha(p)$ in production at $\bar{p}$ lab momentum p, we simulate the annihilation and the production which may precede it at the same time by using an effective multiplicity

$$\overline{f_\alpha} = (1-P) f_\alpha(p) + P[h_\alpha(p) + f_\alpha(\overline{p_{\rm deg}})] , \tag{3.1}$$

where

$$P = \frac{\sigma_{\rm PROD}(p)}{\sigma_{\rm ANN}(p) + \sigma_{\rm PROD}(p)} . \tag{3.2}$$

In Eq. (3.1), $\overline{p_{\rm deg}}$ is the average degraded antiproton momentum after production. Note that at 4 GeV/c, $\overline{f_\alpha} > f_\alpha$ for pions, because about 1.8 pions are created in the production and the pion multiplicity in the annihilation is smoothly dependent upon p. For kaons, $\overline{f_\alpha} \approx f_\alpha$, since kaons do not appear significantly in the production and f_α is slowly varying with energy. Finally, for Λ particles, $\overline{f_\alpha} < f_\alpha$, since the $\bar{p}p \rightarrow \Lambda X$ yield is strongly increasing with energy. Actually, at 4 GeV/c, $f_\alpha = 5.65$, 0.178, 0.025, for π, K (or $\bar{K}$), and Λ, respectively.

Above the $\Lambda\bar{\Lambda}$ threshold, we have to account for hyperon production. The Λ momentum is chosen at random according to the law described in Fig. 2. The first two peaks correspond to the two-body $\Lambda\bar{\Lambda}$ and $\Lambda\bar{\Sigma}$ channels, respectively. The continuum is due to many-body channels, like $\Lambda\bar{\Lambda}n\pi$ or $\Lambda\bar{N}Kl\pi$. According to Ref. 19, the Λ's are produced preferentially in the backward direction. We tentatively described the angular distribution by

$$\frac{d\sigma}{dt} \propto e^{B(\sqrt{s})t} , \tag{3.3}$$

where s and t are the usual Mandelstam variables. We

TABLE I. Characteristics of the data used in our calculation for the particles produced in the annihilation. The multiplicity refers to the quantity $\overline{f_\alpha}$, defined in Eq. (3.1).

	608 MeV/c			4 GeV/c		
Particle	Multiplicity	Spectrum	Temperature (MeV)	Multiplicity [$\overline{f_\alpha}$, Eq. (3.1)]	Spectrum	Temperature (MeV)
π	4.05	thermal	110	6.50	thermal	110
η	0.07	nonthermal		0.07	nonthermal	
ω	0.28	nonthermal		0.28	nonthermal	
K or $\bar{K}$	0.05	thermal	90	0.178 (Ref. 20) 0.12 (Ref. 7)	thermal	90
Λ or $\bar{\Lambda}$				0.013	nonthermal (see Fig. 2)	

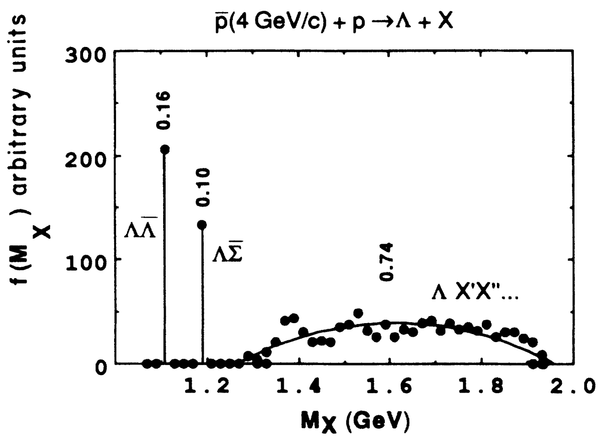

FIG. 2. Missing mass spectrum in inclusive Λ production by interaction of 4 GeV/c antiprotons with protons. The dots are the experimental points of Ref. 19 and the curve is our parametrization for the three- or more body final state contribution. The numbers give the relative contributions of the indicated channel to the cross section.

first used $B(\sqrt{s}\,)$ the same as the one which describes the NN elastic cross section. This, however, gives a too narrow and too skew rapidity distribution for the Λ's produced in $\bar{p}p$ (see Fig. 3). A reasonable description of this distribution is achieved with half this value, i.e., $B=3.34$ (GeV/c)^2.

B. Subsequent reactions

The following reactions are introduced:

$$\pi+N\rightarrow\pi+N,\ \eta+N,\ \omega+N,\ \Lambda+K,\ \Sigma+K\ , \quad (3.4a)$$

$$\pi+NN\rightarrow NN\ , \quad (3.4b)$$

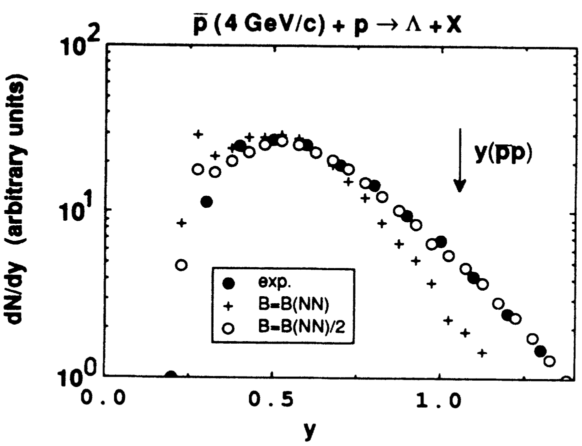

FIG. 3. Rapidity (y) distribution of Λ particles produced in $\bar{p}p$ collisions at 4 GeV/c. Full dots: data of Ref. 19, crosses and open dots: our model with two values of the parameter B [Eq. (3.3)]. See text for details.

$$K+N\rightarrow K+N\ , \quad (3.5)$$

$$\bar{K}+N\rightarrow\bar{K}+N,\ \pi+\Lambda,\ \pi+\Sigma\ , \quad (3.6)$$

$$\eta+N\rightarrow\eta+N,\ \pi+N,\ \Lambda+K,\ \Sigma+K\ , \quad (3.7)$$

$$\omega+N\rightarrow\omega+N,\ \pi+N,\ \Lambda+K,\ \Sigma+K\ , \quad (3.8)$$

$$\Lambda+N\rightarrow\Lambda+N,\ \Sigma+N\ , \quad (3.9)$$

$$\Sigma+N\rightarrow\Sigma+N,\ \Lambda+N\ , \quad (3.10)$$

$$\bar{\Lambda}+N\rightarrow K+n\pi\ , \quad (3.11)$$

as well as the ω decay:

$$\omega\rightarrow 3\pi\ . \quad (3.12)$$

All the cross sections corresponding to processes (3.4)–(3.10), except for (3.4b) and $\pi N\rightarrow\pi N$, are taken from current data tables[21,26–28] and are parametrized simply. The most important parametrizations are given in the Appendix. For these reactions, we use free space cross sections. Pauli blocking is nevertheless taken into account for all reactions with a nucleon in the final state (except for not very important reactions induced by ω and η mesons). This is realized by multiplying free cross section by an average Pauli blocking factor, similar to corrections introduced by Kikuchi and Kawai[29] and Brenig[30] for NN collisions. On the contrary, the pion-nucleon elastic scattering and the pion absorption (3.4b) cross sections are taken from Refs. 24 and 34, where the effect of the Δ resonance, the correction due to medium on the Δ propagator, and possible absorption on three nucleons are taken into account.

IV. EXPERIMENTAL RESULTS

Concerning strange particle production on targets heavier than deuteron, there have been essentially five measurements: the KEK measurement of Miyano *et al.*[14,32] [$\bar{p}$ (4 GeV/c)+^{181}Ta, bubble chamber], the streamer chamber measurement[15] of the PS179 experiment at LEAR [$\bar{p}$ (0.6 GeV/c)+Ne], the measurement by Condo *et al.*[33] [$\bar{p}$ (0–0.45 GeV/c)+C,Ti,Ta,Pb], the electronic counter measurement of Smith *et al.*[11] ($\bar{p}$ at rest+C,U), and the recent ASTERIX measurement for $\bar{p}$ at rest on ^{14}N target.[12] Not all experiments measure all the strange species. The data are summarized in Table II. Most of the measurements are devoted to inclusive cross sections. The most prominent features are the relative independence of the Λ/K_s ratio with energy (≈ 2.3) (this refers in fact only to data of Refs. 14 and 15), the large independence of the Λ multiplicity (≈ 0.02) with respect to the target mass (Ref. 33). Special emphasis was put on the strong enhancement (a factor ~ 6) of the Λ/K_s ratio in $\bar{p}$Ta (≈ 2.3) with respect to the value of $\bar{p}p$ (≈ 0.4). These data are, however, subject to large experimental error bars. Besides the usually quoted statistical error bars, there are also disturbing aspects in the analysis. In Ref. 15, there are very few (much less than expected) K_s tracks with short length. The total K_s yield is nevertheless obtained from the extrapolation of long tracks. Also the early results of Ref. 33 are with standard deviation of

TABLE II. Summary of the existing measurements concerning strange particle production in $\bar{p}$ annihilation on nucleus. See text for details.

Exp	$\bar{p}$ (4 GeV/c) +Ta	$\bar{p}$ (0–450 MeV/c) +C,Ti,Ta,Pb	$\bar{p}$ (608 MeV/c) +Ne	$\bar{p}$ (at rest) +C,U
Multiplicities	$\Lambda, K_s, \bar{\Lambda}$	Λ	Λ, K_s	$K^{\pm}/\pi^-$
Rapidity spectrum	Λ, K_s		Λ, K_s	
$p_\perp$ spectrum				$K^{\pm}, \pi^-, p$
Exclusive measurement	yes	no	no	yes

about 30%. Finally, the bubble chamber measurements of Ref. 32, which give information on semiexclusive measurements (like $\bar{p}\Lambda \rightarrow \Lambda\Lambda X$), reveal intriguing data. Indeed, the following cross sections are quoted: σ $(\bar{p}\text{Ta} \rightarrow \Lambda X) = 193 \pm 12$ mb, σ $(\bar{p}\text{Ta} \rightarrow \Lambda K_s^0 X) = 24.8 \pm 2.8$ mb, σ $(\bar{p}\text{Ta} \rightarrow \Lambda\bar{\Lambda} X) = 1.9 \pm 0.8$ mb. Disregarding double associated production, which should be rather rare, one has

$$\sigma(\bar{p}\text{Ta} \rightarrow \Lambda X) = \sigma(\bar{p}\text{Ta} \rightarrow \Lambda K X) + \sigma(\bar{p}\text{Ta} \rightarrow \Lambda \bar{Y} X) , \tag{4.1}$$

where Y designates a hyperon (either Λ or Σ). This can be written in first approximation as

$$\sigma(\bar{p}\text{Ta} \rightarrow \Lambda X) \approx 4\sigma(\bar{p}\text{Ta} \rightarrow \Lambda K_s X) + \sigma(\bar{p}\text{Ta} \rightarrow \Lambda \bar{Y} X) . \tag{4.2}$$

We neglect here the charge asymmetry which would slightly increase the factor 4. Taking the values quoted in Ref. 32 (see above), the right-hand side amounts to ~ 102 mb, which is substantially smaller than the inclusive Λ-production cross section. So, one has to be careful in analyzing the data and in drawing conclusions from comparison with theory.

Here, we will mainly be concerned with inclusive measurements. However, semi-inclusive data we well as s-quark production cross section should retain our attention.

V. RESULTS

A. The $\bar{p}$ (4 GeV/c)+Ta data

1. Multiplicities

Our prediction of the production cross sections for several particles are contained in Table III, as well as the so-called primordial cross sections, i.e., those which are obtained from the production cross sections in $\bar{p}p$ by scaling with the ratio between $\bar{p}$Ta (1628±30 mb, Ref. 32) and $\bar{p}p$ (24.2 mb, Refs. 7 and 21). One can see immediately that the rescatterings of the particles are very important. Actually the detail is presented in Table IV, where we split the predicted multiplicities into their different contributions.

The Λ particles produced in the annihilation (see Sec. II) account for 21.2 mb. Some of them disappear, by strangeness exchange on nucleons $\Lambda N \rightarrow \Sigma N$. However, the most important contributions come from the subse-

TABLE III. Predicted cross sections (in mb) for several kinds of particles in the $\bar{p}$ annihilation on ^{181}Ta nucleus at 4 GeV/c, compared to experiment (last line). See text for details.

	Λ	K_s	$\bar{\Lambda}$	π	s squark
Primordial	21.2	145	21.2	10 582	311
Final (no Σ)	207	134	2.5	6102	377
Final (12% $K\bar{K}$)	200 "Λ":228	109	2.5	5965	358
Final (with Σ)	244 "Λ":275	142	2.5	5985	454
Exp (Ref. 32)	193±13	82±6	3.8±2.0		277±21

quent production by pions (~ 49 mb) and strangeness exchange induced by antikaons ($\bar{K}N \to Y\pi$) whose contribution amounts to ~ 90 mb. Note that the most important (positive) contribution pertains to the $\Sigma N \to \Lambda N$ process. The Σ's are mainly produced by $\pi N \to \Sigma K$ and $\bar{K}N \to \Sigma\pi$ reactions (see Table IV and below). Let us also notice that the (negative) contribution of the $\Lambda N \to \Sigma N$ process is larger than the primordial cross section. This is of course due to the fact that the Λ-destruction cross section deals with primordial as well as secondary Λ's. Actually, about 20% of the primordial Λ's survive. Since the Σ^0 particles decay in $\Lambda + \gamma$, and since therefore Σ^0 and Λ are hardly distinguishable in bubble chambers, we sum up the Λ yield and one third of Σ yield (assuming charge symmetry) before comparing with experiment. We denote by "Λ" the resulting yield.

The case of the $\bar{\Lambda}$'s is very simple. They are produced in the annihilation which gives primordial contribution of 21.2 mb and can be annihilated afterwards on a nucleon $\bar{\Lambda}N \to K + n\pi$. In the absence of precise knowledge of this cross section, we took $\sigma_{\rm ann} = 48/\sqrt{p}$ (in mb, if the $\bar{\Lambda}$ momentum p is expressed in GeV/c), following the indications of Ref. 34. This gives a final value of $\sigma(\bar{\Lambda}) = 2.5$ mb, which agrees with the experimental value (3.8 ± 2) mb. Note that if the $\bar{\Lambda}$ annihilation cross section is changed by $\sim 10\%$, the final value will be $\sigma(\bar{\Lambda}) = 3.0$ mb, which gives an idea of the sensitivity of the calculation.

The K_s production is much more complicated. If the cumulated number of primordial kaons and antikaons is very much the same as for the final ones, there is nevertheless an important transformation of $\bar{K}$'s into strange baryons and a roughly equal amount of K's created through annihilation of $\bar{\Lambda}$'s and more importantly through associated production induced by π, η, and ω mesons. We predict a larger K_s cross section (~ 140 mb) than the experimental one (82 mb). Note, however, that this results from the large primordial yield. The latter is taken from the measurements of Ref. 20, but if we took

TABLE IV. Multiplicity (last column) for several particles, with the contributions of the primordial annihilation and of various reactions, in the $\bar{p}$ annihilation on ^{181}Ta nucleus at 4 GeV/c. For the pions, only the most important contributions are indicated. See text for details.

	Primordial	Reactions						Final
		$\Lambda N \to \Sigma N$	$\Sigma N \to \Lambda N$	$\pi N \to \Lambda K$	$\bar{K}N \to \Lambda\pi$	$\eta N \to \Lambda K$	$\omega N \to \Lambda K$	
Λ	0.013	-0.026	0.076	0.030	0.046	0.007	0.004	0.150
		$\bar{\Lambda}N \to Kn\pi$						
$\bar{\Lambda}$	0.013	-0.011						0.0015
		$\bar{K}N \to \Lambda\pi$	$\bar{K}N \to \Sigma\pi$					
$\bar{K}$	0.178	-0.046	-0.060					0.072
		$\pi N \to \Lambda K$	$\pi N \to \Sigma K$	$\bar{\Lambda}N \to KX$	$\eta N \to YK$	$\omega N \to YK$		
K	0.178	0.030	0.036	0.011	0.011	0.011		0.277
		$\pi NN \to NN$	$\pi N \to YK$	$\bar{K}N \to Y\pi$	$\eta N \to \pi N$	$\omega N \to \pi N$	$\omega \to 3\pi$	
π	6.50	-2.94	-0.066	0.106	0.072	0.062	0.168	3.676
		$\eta N \to \pi N$	$\eta N \to \Lambda K$	$\eta N \to \Sigma K$	$\pi N \to \eta N$			
η	0.070	-0.072	-0.007	-0.004	0.123			0.109
		$\omega N \to \pi N$	$\omega N \to \Lambda K$	$\omega N \to \Sigma K$	$\omega \to 3\pi$	$\pi N \to \omega N$		
ω	0.280	-0.062	-0.004	-0.008	-0.056	0.083		0.232
		$\Sigma N \to \Lambda N$	$\Lambda N \to \Sigma N$	$\pi N \to \Sigma K$	$\bar{K}N \to \Sigma\pi$	$\eta N \to \Sigma K$	$\omega N \to \Sigma K$	
Σ	0	-0.076	0.026	0.036	0.060	0.004	0.008	0.057
		$\pi N \to YK$	$\eta N \to YK$	$\omega N \to YK$				
$s(\bar{s})$	0.191	0.066	0.011	0.011				0.279

the systematic of Ref. 7, the primordial multiplicity would be of the order of ~ 0.12, which would result in a much better agreement. Note also that neglecting the Σ prediction (see Table V) reduces also the k_s yield by $\sim 16\%$.

It is interesting to analyze the sensitivity of the calculation upon the physical ingredients. We illustrate this point in Fig. 4(a), which shows that the $\pi N \rightarrow YK$ rate results from a delicate balance of increasing cross sections and of an exponentially decreasing spectrum. The situation is less critical for strangeness exchange reactions $\bar{K}N \rightarrow Y\pi$, as shown in Fig. 4(b).

2. *Spectra*

As emphasized in Ref. 2, a credible model should not only predict multiplicities, but must also describe particle spectra with reasonable accuracy. We present our results below. The rapidity distribution for Λ particles is displayed in Fig. 5. The agreement is satisfactory, although the predicted spectrum favors too much the negative rapidities. In Fig. 5, the total spectrum is split into the contributions pertaining to cascade induced by primordial Λ's, π's, and $\bar{K}$'s, respectively. They have roughly the same shape, although the $\bar{K}$ contribution is the most peaked around $y \approx 0$. In Fig. 6, we give arguments showing that the $y<0$ part is largely due to rescattering of Λ's and (especially) $\bar{K}$'s. A perfect agreement is obtained when the rescattering of these particles is suppressed.

Our results for the K_s, as well as the various contributions, are shown in Fig. 7. We obtain a rapidity distribution of roughly the same shape as in the experiment, with still a slightly too large intensity for $y \approx 0$. Our predictions for pions, η's, ω's, and $\bar{\Lambda}$'s are given in Figs. 8 and 9, respectively. The absorption of the $\bar{\Lambda}$'s does not seem to change significantly the y distribution. The large average rapidity of the $\bar{\Lambda}$'s is due to the forward $\bar{\Lambda}$ production in the elementary process. It is of course the symmetrical counterpart of the Λ spectrum (Fig. 3) with respect to the

TABLE V. Same as Table IV for $\bar{p}$ annihilation on Ne at 608 MeV/c.

	Primordial	Reactions						Final
Λ	0	$\Lambda N \rightarrow \Sigma N$	$\Sigma N \rightarrow \Lambda N$	$\pi N \rightarrow \Lambda K$	$\bar{K}N \rightarrow \Lambda\pi$	$\eta N \rightarrow \Lambda K$	$\omega N \rightarrow \Lambda K$	0.027
		−0.0009	0.010	0.0014	0.010	0.0015	0.005	
$\bar{\Lambda}$	0	$\bar{\Lambda}N \rightarrow Kn\pi$						0
		0						
$\bar{K}$	0.050	$\bar{K}N \rightarrow \Lambda\pi$	$\bar{K}N \rightarrow \Sigma\pi$					0.024
		−0.010	−0.016					
K	0.050	$\pi N \rightarrow \Lambda K$	$\pi N \rightarrow \Sigma K$	$\bar{\Lambda}N \rightarrow KX$	$\eta N \rightarrow YK$	$\omega N \rightarrow YK$		0.063
		0.0014	0.001	0	0.002	0.009		
π	4.05	$\pi NN \rightarrow NN$	$\pi N \rightarrow YK$	$\bar{K}N \rightarrow Y\pi$	$\eta N \rightarrow \pi N$	$\omega N \rightarrow \pi N$	$\omega \rightarrow 3\pi$	2.681
		−1.561	−0.0024	0.026	0.0025	0.060	0.115	
η	0.070	$\eta N \rightarrow \pi N$	$\eta N \rightarrow \Lambda K$	$\eta N \rightarrow \Sigma K$	$\pi N \rightarrow \eta N$			0.055
		−0.0025	−0.0015	−0.0004	0.012			
ω	0.280	$\omega N \rightarrow \pi N$	$\omega N \rightarrow \Lambda K$	$\omega N \rightarrow \Sigma K$	$\omega \rightarrow 3\pi$	$\pi N \rightarrow \omega N$		0.174
		−0.060	−0.005	−0.004	−0.038	0.0014		
Σ	0	$\Sigma N \rightarrow \Lambda N$	$\Lambda N \rightarrow \Sigma N$	$\pi N \rightarrow \Sigma K$	$\bar{K}N \rightarrow \Sigma\pi$	$\eta N \rightarrow \Sigma K$	$\omega N \rightarrow \Sigma K$	0.012
		−0.010	−0.0009	0.001	0.016	0.0004	0.004	
$s(\bar{s})$	0.050	$\pi N \rightarrow YK$	$\eta N \rightarrow YK$	$\omega N \rightarrow YK$				0.063
		0.0025	0.0019	0.009				

rapidity of the $\bar{p}p$ rest frame, $y_{\bar{p}p} \approx 1.1$, for 4 GeV/c $\bar{p}$'s in the laboratory system.

The p_T^2 spectra, for Λ, K_s, and $\bar{\Lambda}$ particles, are given in Fig. 10 and compared with experiment. The general agreement is rather good. A slight discrepancy seems to appear for large p_T Λ particles. The $\bar{\Lambda}$ spectrum is less steep than the experimental one, although the experimental errors do not allow one to draw definite conclusions.

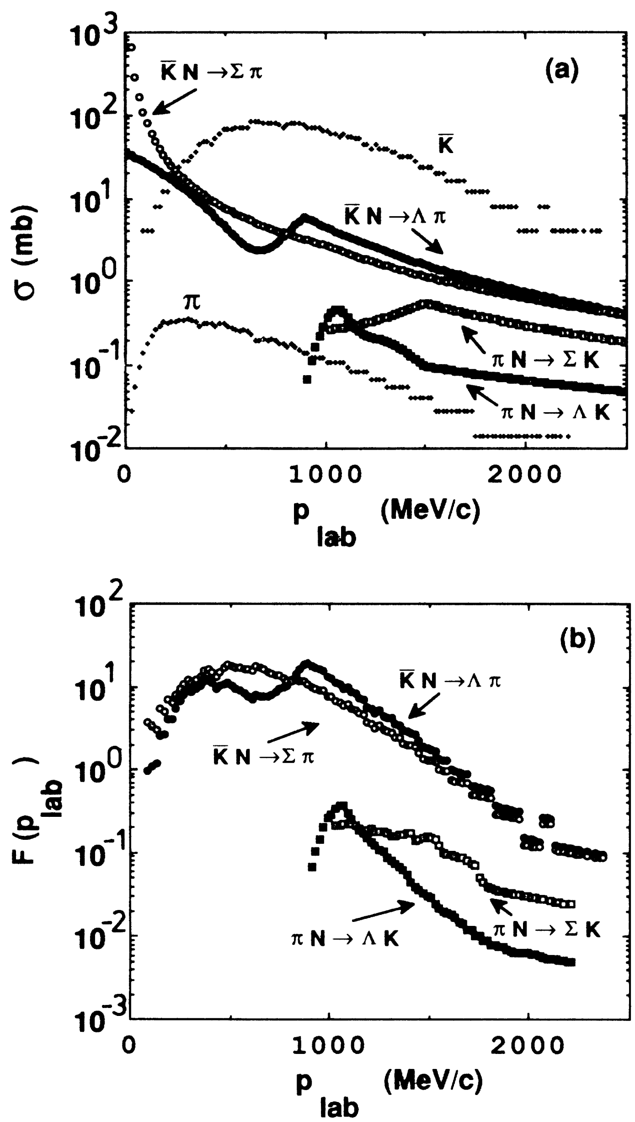

FIG. 4. (a) Cross sections for some $\bar{K}$-induced and π-induced reactions, as functions of the laboratory momentum. The curves made of crosses give (in arbitrary units) the lab momentum distribution of the pions and of the antikaons, issued from the annihilation of 4 GeV/c antiprotons. (b) The curves give the product of the (pion or antikaon) momentum distribution depicted in (a) with σv, where σ is the respective reaction cross section and v is the relative velocity of the reacting particles. The integral of the function $F(p_{\rm lab})$ gives, up to a constant, the reaction rate.

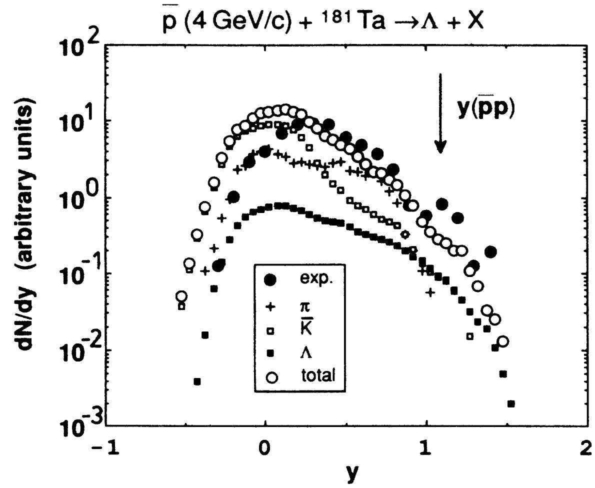

FIG. 5. Rapidity (y) distribution of Λ particles produced after $\bar{p}$ annihilation on Ta nuclei at 4 GeV/c. Full dots: data of Ref. 32, open dots: our calculation. The other symbols give the contribution to the Λ distribution due to the cascade initiated by the pions, the antikaons, and the lambdas, issued from the annihilation. All the curves are normalized on the corresponding multiplicities. See text for details.

The correct shape of the Λ and K_s spectra at low p_T indicate that the rescattering process is generally well described in our approach.

B. The $\bar{p}$ (608 MeV/c)+Ne data

In Table V, we present the calculated multiplicities and the contribution of the various reactions. It is interesting to see that Λ's are produced by many processes, the most important of which is the associated production induced

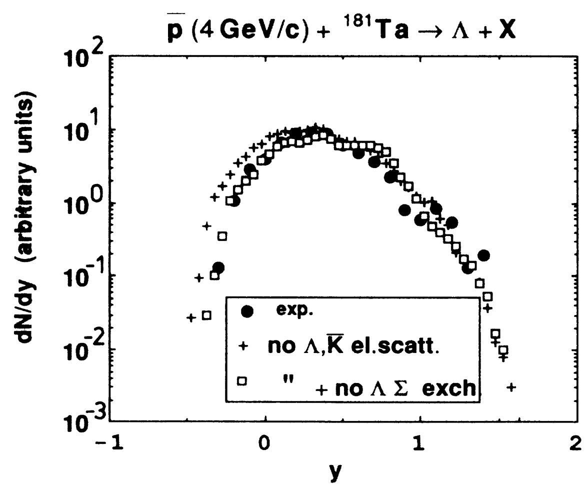

FIG. 6. Rapidity (y) distributions of the Λ particles produced after $\bar{p}$ annihilation on Ta nuclei at 4 GeV/c. Full dots: data of Ref. 32. Crosses: our calculation when Λ and $\bar{K}$ elastic scatterings are neglected. Open squares: our calculation when, in addition, $\Sigma N \leftrightarrow \Lambda N$ processes are neglected.

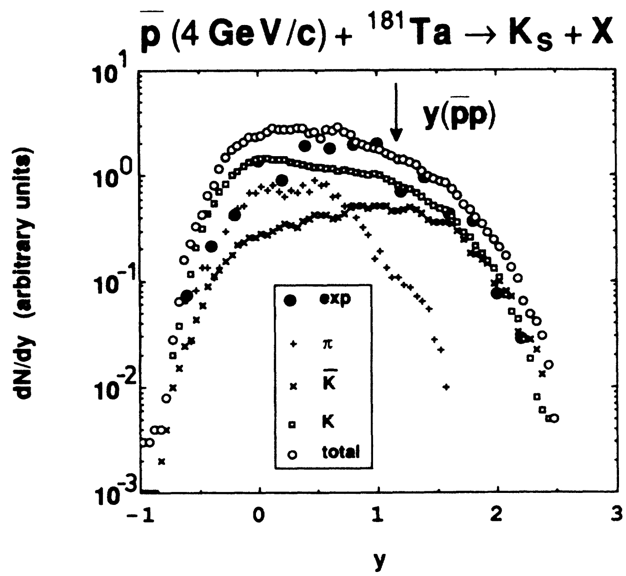

FIG. 7. Same as Fig. 5 for the K_s production.

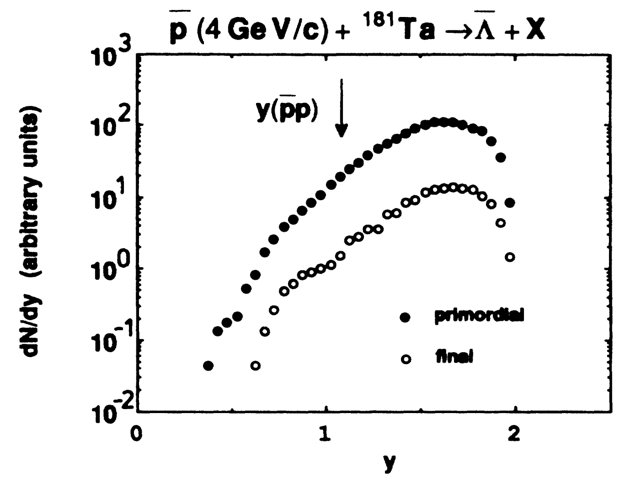

FIG. 9. Rapidity (y) distribution of primordial and final $\bar{\Lambda}$ particles after $\bar{p}$ annihilation on ^{181}Ta nuclei at 4 GeV/c, as calculated by our model.

by pions. At so low an energy, the cumulated number of kaons and antikaons is decreased by the cascade process. However, our calculation does not indicate so strong a reduction as the experimental data. The K_s yield is largely overestimated (see Table VI).

The Λ and K_s rapidity distributions are displayed in Fig. 11. They are rather well reproduced. The experimental K_s spectrum is, however, somewhat flatter.

C. The 0–450 MeV/c data

In Table VII, we compare our results for the Λ multiplicity on various targets with the experimental data of Condo *et al.*[31] Except for Ta, for which the experimental yield is surprisingly smaller than for the other targets, the agreement is rather good. In this energy range the Λ yield comes for almost equal amounts from π-induced associated production, strangeness exchange, and η, ω-induced associated production.

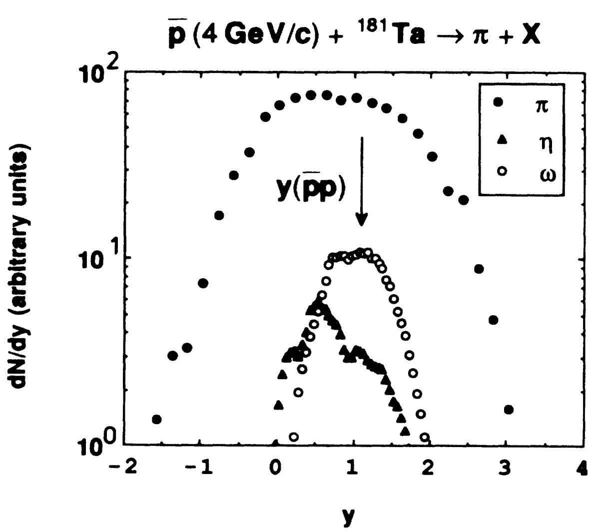

FIG. 8. Rapidity (y) distributions of pions, η particles, and ω particles, produced after $\bar{p}$ annihilation on ^{181}Ta nuclei at 4 GeV/c, as calculated by our model. All curves are normalized on the respective multiplicities.

D. Annihilation at rest

We have made an exploratory calculation in this case, assuming a very slow antiproton. This brings uncertainty on the annihilation site. However, as we concentrate on produced fast particles, this does not matter so much. In Fig. 12, we show the calculated π^+, K^+, and K^- spectra (above 500 MeV/c) for the case of a U target. All spectra have the same slope, consistent with the measurements of Ref. 11. The relative yields above 500 MeV/c are $K^+/\pi^- = 1.2\%$ and $K^-/\pi^- = 1.0\%$, which are substan-

TABLE VI. Same as Table III for $\bar{p}$ annihilation on Ne at 608 MeV/c. See text for details.

	Λ	K_s	π	s
Primordial	0	15.8	2556	31.5
Final (no Σ)	14.8	14.5	1692	36.4
Final (no res)	11.9 "Λ":13.8	12.2	2005	33.4
Final	17.0 "Λ":19.6	13.7	1692	39.7
Exp (Ref. 15)	12.3±2.8	5.4±1.1		16.9

tially smaller than the experimental values,[11] respectively 3.0 and 3.2%. We have no explanation for this discrepancy.

VI. ANALYSIS OF THE RESULTS

A. The s cross section

Our calculation allows us to study the s-quark production cross section, equal, of course, to the $\bar{s}$-quark cross section. Theoretically, this quantity is simpler to analyze, since strange quarks can be created either in the an-

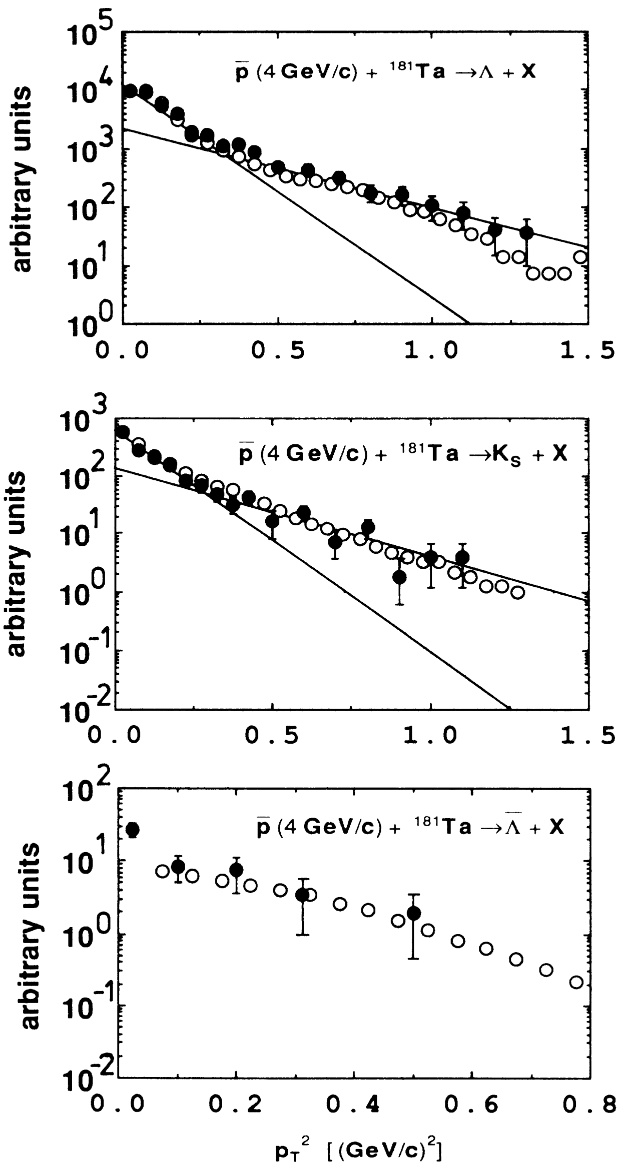

FIG. 10. Perpendicular momentum p_T distribution of Λ, K_s, and $\bar{\Lambda}$ particles produced after $\bar{p}$ annihilation on ^{181}Ta nuclei at 4 GeV/c. The full dots are the data of Ref. 32. The open dots give our results. The two curves are normalized on the same value for $p_T^2 \approx 0.2$ (GeV/c)^2. The straight lines are fit of the experimental data, provided by the authors of Ref. 32.

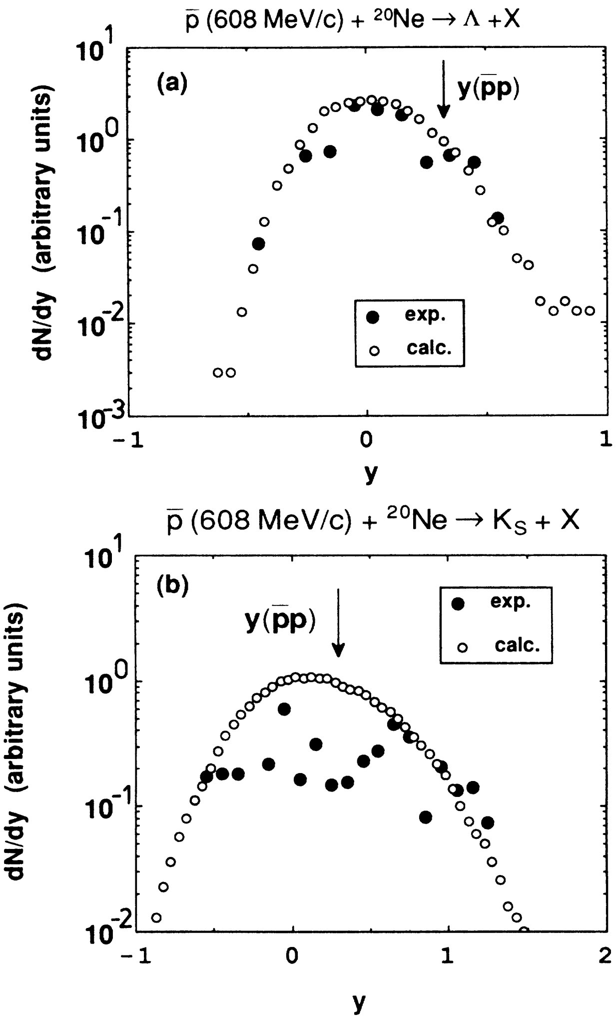

FIG. 11. Rapidity (y) distributions of Λ (a) and K_s (b) particles following $\bar{p}$ annihilations on Ne nuclei at 608 MeV/c. The full dots represent the experimental data of Ref. 15, and open dots give our results. The curves are normalized on the respective multiplicities.

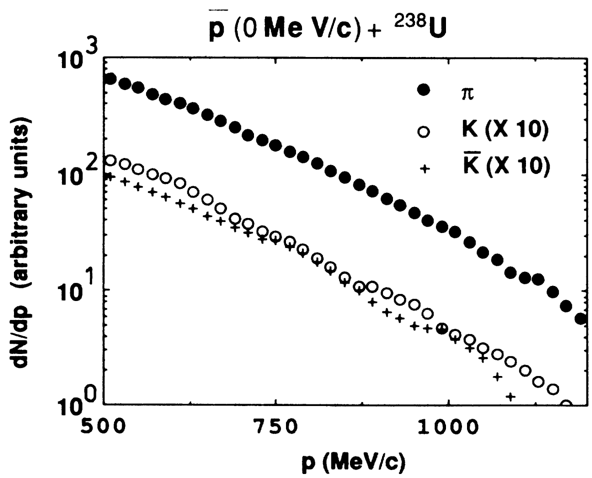

FIG. 12. Calculated pion, kaon, and antikaon momentum distribution above 500 MeV/c, for particles produced after $\bar{p}$ annihilation at rest on ^{238}U nuclei. The curves are normalized on the respective multiplicities.

TABLE VII. Multiplicity of Λ particles produced in $\bar{p}$ annihilation on several nuclei at low energy. We have also indicated the most important partial contributions.

Target	Exp. (Ref. 33)	$\bar{p}$ (0–450 MeV/c)+ $A \rightarrow \Lambda X$ Our calculation	$\pi N \rightarrow \Lambda X$	$\bar{K}N \rightarrow \Lambda X$	$\Sigma N \rightarrow \Lambda N$
C	0.023±0.006	0.021 "Λ":0.024	0.005	0.008	0.007
Ti	0.021±0.007	0.027 "Λ":0.030	0.0006	0.009	0.011
Ta	0.013±0.004	0.034 "Λ":0.037	0.007	0.010	0.016
Pb	0.027±0.011	0.035 "Λ":0.038	0.008	0.011	0.016

nihilation itself or via associated production, but the strangeness exchange reactions do not modify their yield. This point was already pointed out by Gibbs in Ref. 35. Furthermore, in such systems as those we study here, the destruction of strange quarks is negligible because this requires close encounters of s and $\bar{s}$ quarks. Experimentally, the s-quark cross section cannot be reached directly. If one restricts oneself to the particles listed in the first row of Tables IV and V, one can write

$$\sigma(s)=\sigma(``\Lambda")+\sigma(\bar{K})+\sigma(``\Sigma") \tag{6.1}$$

and

$$\sigma(\bar{s})=\sigma(\bar{\Lambda})+\sigma(K) , \tag{6.2}$$

where $\sigma(``\Sigma")=\frac{2}{3}\sigma(\Sigma)$ (see Sec. V A 1). These relations are rather useless, for one cannot extract for instance $\sigma(\bar{K})$ from $\sigma(K^-)$ and $\sigma(K_s)$. However, if we sum Eqs. (6.1) and (6.2), we get, using $\sigma(s)=\sigma(\bar{s})$,

$$\sigma(\bar{s})=\tfrac{1}{2}[\sigma(``\Lambda")+\sigma(\bar{\Lambda})+\sigma(\bar{K})+\sigma(K)+\sigma(``\Sigma")] . \tag{6.3}$$

We then use relation $\sigma(\bar{K})+\sigma(K)=4K_s$, which is correct in the limit of isospin symmetric systems. (Note that the correction will be only in second order in isospin asymmetry. This also applies to Λ and Σ^0 particles). We thus write

$$\sigma(s)=\tfrac{1}{2}[\sigma(``\Lambda")+\sigma(``\Sigma")+\sigma(\bar{\Lambda})]+2\sigma(K_s) . \tag{6.4}$$

The experimentally determined cross sections [in the case of $\bar{p}$Ta, we have to make an assumption about the "Σ" cross section: We took the same "Σ"/"Λ" ratio experimentally as theoretically, which corresponds to σ("Σ") ($\approx$29 mb)] as well as the calculated ones are given in Tables III and VI. We see that the quark cross sections are largely overestimated, especially for the Ne case. Tables IV and V also show that in our calculation strange quarks are mainly created in the annihilation (we recall that in this context, this label covers the $\bar{p}p \rightarrow \Lambda\bar{\Lambda}X, \ldots$ processes). Only 20% for $\bar{p}$Ne and 30% for the $\bar{p}$Ta are created by the subsequent cascade. It is hardly conceivable that medium effects on the rescattering can change this contribution by a factor 2 or so (see, however, Sec. VI F for a discussion of possible uncertainties). Even if the strange quark production is suppressed in the rescattering, the overall yield is too large. We thus arrive at the surprising conclusion that, as far as strangeness production is concerned, the $\bar{p}$ annihilation might not follow the free-space regime. Indeed, we just assumed that the primordial yield is kept the same as in $\bar{p}p$ and the cross section is just scaled by $\sigma_{pA}^{\rm ann}/\sigma_{\bar{p}p}^{\rm ann}$. If one attributes this disagreement to medium effect on the annihilation solely, one can account for this effect by writing the primordial multiplicity for a strange species ζ in $\bar{p}A$:

$$\langle \zeta \rangle_{\rm prim}=\gamma\langle \zeta \rangle_{\bar{p}p} , \tag{6.5}$$

where $0<\gamma<1$. We checked that an average value of $\gamma\sim0.7$ for Λ's and $\gamma\sim0.5$ for $K\bar{K}$'s is necessary to reach agreement with experiment both for $\bar{p}$Ta and for $\bar{p}$Ne. This medium effect is quite surprising in view of the rather small density expected at the annihilation site.

B. The Λ/K_s ratio

As explained in the Introduction, this ratio has attracted very much attention. However, as we showed in Sec. V, this ratio is not so much related to strangeness yield itself, but mainly to the reshuffling of the strange s quarks from one species to the other by strangeness exchange. As a matter of fact, if we neglect $\bar{\Lambda}$ and "Σ" production (which in our case is not so important), we can approximately rewrite Eqs. (6.1) and (6.2) as

$$\begin{aligned} &\sigma(``\Lambda")\approx x\sigma(s) , \\ &\sigma(\bar{K})\approx(1-x)\sigma(s) , \\ &\sigma(K)\approx\sigma(\bar{s}) . \end{aligned} \tag{6.6}$$

Using $\sigma(K_s)=\frac{1}{4}[\sigma(K)+\sigma(\bar{K})]$ and $\sigma(s)=\sigma(\bar{s})$, one readily obtains

$$\frac{\text{“}\Lambda\text{”}}{K_s}\approx\frac{2x}{1-\frac{x}{2}}\ , \tag{6.7}$$

i.e., a function of the parameter x governing the repartition of the strange quarks into baryons and antikaons. If one analyzes Tables IV and V carefully, one observes that x results from the transformation of the $\bar{K}$'s into baryons and to a lesser extent, from the subsequent associated production. Roughly speaking, for small contribution of associated production x represents also the percentage of primordial $\bar{K}$'s transformed into hyperons. It turns out that about one-half of the primordial $\bar{K}$'s are transformed, both for $\bar{p}$Ne and $\bar{p}$Ta. To our opinion this (quasi) equal value for both cases results from a compensation between the size of the target, which favors a larger transformation in heavy targets and an average cross section which increases with decreasing energy (see Fig. 4). Indeed, the $\bar{K}N\to Y\pi$ cross section decreases with energy, but the $\bar{K}$ spectrum in the laboratory system is softer in the Ne case: In the annihilation system, the $\bar{K}$ spectrum looks like a thermal spectrum with a roughly constant temperature ≈ 80 MeV, but the Lorentz boost makes it softer for 608 MeV/c $\bar{p}$'s compared to the 4 GeV/c ones. The subsequent associated production, creating additional hyperons, shifts the value of x from $x\approx 0.5$ towards $x\approx 0.7-0.8$, which through formula (6.7), yields a Λ/K_s ratio of the order of 2–2.5. We do not believe that this ratio can be considered as a universal value valid for any target in a large domain of energy. However, Eq. (6.7) shows that, provided a few rescattering occur, it will always lie between ~ 1 and its maximum value 4.

C. Scatter plot in moving frames

The authors of Ref. 32 insist very much on the distribution of the strange particles in some moving frame. In particular, they produce a scatter plot of the observed Λ's in a plane whose coordinates are y_{13} and p_{13}, respectively the rapidity and the total momentum in a frame having the velocity of the c.m. of the system composed of the incoming antiproton and of 13 target nucleons. In such a system the experimental rapidity distribution peaks around $y_{13}\approx 0$. Note that the number of target nucleons (13) is not sharply defined. Our calculated distribution in such a frame is displayed in Fig. 13. The calculated average rapidity is somewhat smaller than the experimental one, a result which is already visible in Fig. 5 (see also Fig. 6). Our scatter plot shows accumulation for $y_{13}<0$ and $p_{13}<700$ MeV/c and, as experimentally, a tail extending to large y_{13} and p_{13}. In our picture, this simply

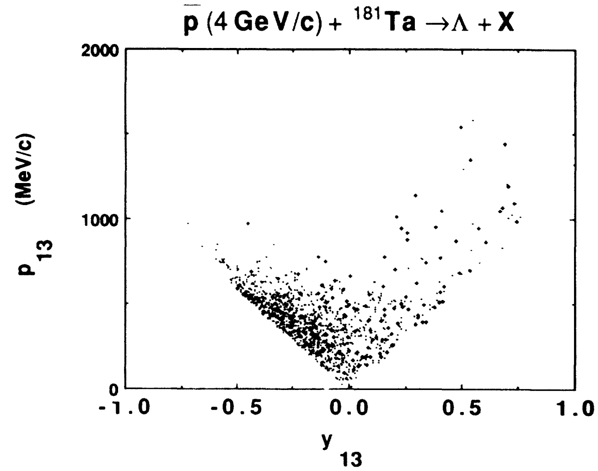

FIG. 13. Scatter plot of Λ particles produced after $\bar{p}$ annihilation on ^{181}Ta nuclei at 4 GeV/c in the (y_{13},p_{13}) plane. The meanings of these kinematical variables are given in the text. The small dots represent the Λ particles produced in cascades induced by antikaons issued from the annihilation, whereas the large dots refer to cascades induced by pions. The large dots are given with a weight five times larger than the small dots. See text for details.

TABLE VIII. Calculated multiplicities for several particles for different targets at 4 GeV/c (^{48}Ti, ^{101}Ru, ^{181}Ta) and at low momentum (^{12}C,^{48}Ti,^{181}Ta,^{208}Pb).

	4 GeV/c			0–400 MeV/c			
	^{48}Ti	^{101}Ru	^{181}Ta	^{12}C	^{48}Ti	^{181}Ta	^{208}Pb
Λ	0.095	0.124	0.150	0	0	0	0
“Λ”	0.113	0.144	0.169	0.024	0.030	0.037	0.038
K_s	0.086	0.086	0.087	0.022	0.021	0.022	0.022
$\bar{\Lambda}$	0.003 0	0.002 14	0.001 5	0	0	0	0
η	0.107	0.107	0.109	0.056	0.051	0.046	0.046
ω	0.256	0.245	0.232	0.189	0.165	0.143	0.142
“Λ”/K_s	1.31	1.67	1.94	1.10	1.43	1.68	1.73

reflects the possible rescattering of the Λ particles and does not need a stopping of the antiproton by a bunch of nucleons.

D. Mass dependence

We studied this aspect in relation with the Condo data and for 4 GeV/c antiprotons (see Table VIII). At low energy, strange particle multiplicities are fairly independent of the target size (at least for targets heavier than C), especially the K_s's. Therefore all cross sections scale as $A^{2/3}$ as a direct consequence of the strong $\bar{p}$ absorption cross section.

At high energy, the K_s multiplicity is remarkably independent of the target mass, whereas the Λ multiplicity increases with the mass, a consequence of the Λ generation by strangeness exchange reactions.

E. Energy dependence

The energy dependence is hard to assess as there are only two or three experimental points. We make a theoretical study of the energy dependence for the case of ^{181}Ta. The results are given in Fig. 14. The K_s yield roughly follows the trend of the strange yield in $\bar{p}p$, with a steeper slope, however (for this calculation we used a $K\bar{K}$ primordial frequency varying linearly from 5% at rest to 17.8% at 4 GeV/c). The Λ yield increases linearly, but is quite different from the Λ primordial yield, which roughly follows the ratio $\sigma_Y/\sigma_{\rm ANN}$ (see Fig. 1). As a result, the "Λ"/K_s ratio is fairly independent of $\bar{p}$ momentum, once again an illustration of the discussion of point (B) above.

F. Sensitivity to input data

Although our work constitutes a much detailed calculation, in the frame of multiple scattering within hadronic phase, it cannot be considered as free of uncertainty. The simplified cascade model is not really a limitation compared to full many-particle cascade codes. On the other hand, the multiplicities in the annihilation itself are not known with great accuracy at large $\bar{p}$ energy. We think particularly at the K and $\bar{K}$ multiplicity. The measurements of Ref. 20 do not seem to follow the systematics of Ref. 7, based on previous measurements at several momenta extending from rest to 7 GeV/c, which are, however, admittedly scattered. The effect of a modification of the $K\bar{K}$ multiplicity on our results is indicated in Table III. The various cross sections entering the calculation of the rescattering process following the annihilation are rather well known. The most important ones, because they give the largest contributions, i.e., the $\Lambda N \rightleftarrows \Sigma N$ and $\bar{K}N \to Y\pi$ reactions, are known with accuracy of the order of ~30% and ~10%, respectively. Some of the reaction cross sections are badly known, like for instance $\eta N \to YK$ and $\omega N \to YK$. They have not even been measured. Estimates[25,36] may differ by a factor 2 to 3. Fortunately, they give small contributions (a few percent) to Λ and K_s yield. So, altogether, we may quantify the uncertainty of this calculation due to limited knowledge of used cross sections as ~10%.

We analyze also the possible errors coming from the reactions which are neglected in our calculation. Most of them are unimportant. Others have been neglected because of the lack of detailed information (if not on the cross section, at least on angular distributions, spectra, etc.). One of these may have non-negligible effects, however. It is the inelastic πN scattering, basically $\pi N \to 2\pi N$. The main effect of this process (only effective in the $\bar{p}$-Ta case) is the softening of the tail of the pion spectrum, reducing so the number of pions contributing to associated production, and therefore the s-quark yield coming from this process. The other main pion energy degrader process (included in our calculation) is the elastic πN scattering. Both processes have comparable (isospin averaged) cross sections, 15–20 mb. So at first sight, we might have overestimated the s-quark yield in associated production induced by pions $[s]_{\pi N}$ (0.066 per annihilation; see bottom of Table IV) by a factor 2. However, this may be partially compensated by other features. For instance, we used an isotropic pion emission pattern in the annihilation frame. If this is certainly correct at low energy, the forward and backward directions are favored at 4 GeV/c annihilations (see Fig. 6 of Ref. 37), giving more energetic pions in the forward direction. Second, we used a roughly isotropic πN elastic scattering in the c.m. frame which certainly overestimates the momentum degradation in the 1–1.5 GeV/c range. From indications on the actual distribution, we expect a pion with momentum ≈1.5 GeV/c to lose 100–150 MeV/c per scattering, while our assumption yields a value close to ~500 MeV/c. Furthermore, in the $\pi N \to 2\pi N$ reaction (modeled as $\pi N \to \pi\Delta$ with roughly the same angular dependence as the elastic scattering), we expect a momentum loss of ~400 MeV/c for the fastest pion. So we overestimated the pion momentum degradation in the elastic πN process while we underestimated it by neglecting the inelastic process. So we think that the quantity

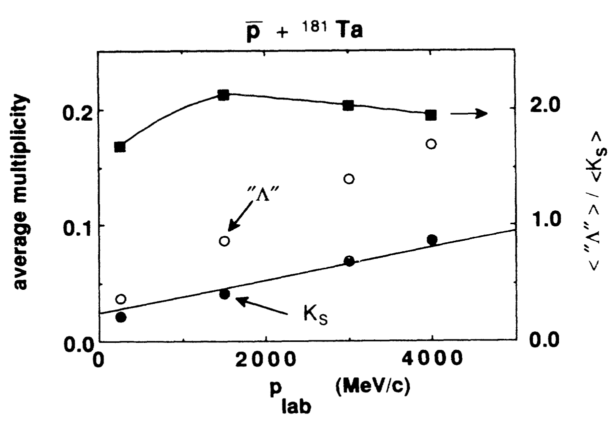

FIG. 14. Antiproton momentum dependence of some strange particle production yields, as predicted by our model for the case of ^{181}Ta target. Full dots: multiplicity of K_s particles. Open dots: multiplicity of Λ-like particles. Square: ratio of the multiplicities, scale on the right side. The straight line gives the general trend of the K_s multiplicity in $\bar{p}p$ annihilation.

$[s]_{\pi N}$ might be overestimated by 30% at the most, possibly bringing $[s]_{\pi N}$ down to ~ 0.045. However, we have to mention that other uncertainties may still affect this number. For instance, the true pion absorption is very badly known in this momentum range. In our opinion, all these uncertainties cannot be removed before the pion input data are tuned on the pion observables (yield, spectrum, etc.), which are unfortunately lacking for the $\bar{p}$-Ta case. Note also that associated production induced by η's and ω's is less subject to similar effects since the $\eta N \rightarrow \Lambda K$ threshold is rather low and $\omega N \rightarrow YK$ has no threshold.

In conclusion, the predicted cross section for s-quark production in rescattering should thus perhaps be ≈ 100 mb rather than 143 mb in the $\bar{p}$-Ta case (see Table III). There remains a large excess in the final yield (~ 410 mb) compared to experiment, coming in part from the annihilation itself, as underlined in Sec. VI A. If we admit a possible reduction of the associated production as just discussed above, the parameters γ introduced at the end of Sec. VI A would then be of the order of ~ 0.8 and ~ 0.7, respectively.

We also neglected the $\bar{p}p \rightarrow \Sigma X$ process, because of lacking information. At 608 MeV/c, this process is not possible. At 4 GeV/c, it is allowed, and if the hyperon production is roughly independent of the kind of hyperon (except for trivial mass effect), this would bring a sizable enhancement of the Λ production. However, an important Σ production seems to be ruled out by the existing data.[21]

VII. COMPARISON WITH OTHER CALCULATIONS

We want here to compare with calculations in the same spirit as ours. However, before we would like to comment on some aspects of the work by Rafelski,[2] advocating the formation of quark-gluon plasma in $\bar{p}$ annihilation on nuclei (other works[38,39] also exploit this idea). The most important argument in favor of this picture is based on the y distribution of strange particles. The maximum occurs at $y \approx 0.1$, which is interpreted as indicating a Λ "evaporation" process of a plasma formed by the coalescence of the incoming antiproton with 13 target nucleons. A somewhat disturbing aspect is that a similar interpretation tells us that K_s particles are produced by a plasma formed with three target nucleons only, and thus traveling faster. The Λ and K_s would thus be emitted by different sources, an idea which is difficult to reconcile with the fact that strange particle production necessarily proceeds by $s\bar{s}$ pair creation. In our calculation the low rapidity of the Λ particles appears naturally from the slowing down due to collisions inside matter. In $\bar{p}p \rightarrow \Lambda \bar{Y} n\pi$, the Λ's are already produced in the backward direction. For $\bar{p}$ at 4 GeV/c, this would correspond to $y \approx 0.4$ only ($y_{\rm inc} = 1.1$). As a matter of fact, if the Λ's interact as in free space, they may even be too strongly decelerated as compared to experiment (see Sec. V A). Kaons are produced isotropically in $\bar{p}p$ system, i.e., with an average rapidity ~ 0.55 with a broad distribution. They are slowed down quite efficiently, which broadens their y distribution appreciably. In summary, without criticizing the possibility of plasma formation (after all, baryon-antibaryon annihilation is presumably the most appropriate process favoring partial deconfinement of quarks[2,8,40]), we claim that y distributions are consistent with multiple scattering and do not demand formation of a slowly moving hot zone.

Let us come to comparison with works realized in the same spirit as ours, i.e., with the works by Ko and Yuan[41] and by Dover and Koch.[42] The comparison with the first work is rather easy since the authors considered about the same contributions as we do for Λ production in $\bar{p}$ (4 GeV/c)+Ta, although they make a real calculation for the $\pi N \rightarrow \Lambda K$ contribution only (they did not consider K_s production). We obtain a somewhat smaller contribution of the primordial Λ's, because we allow for a slowing down of the antiproton prior to annihilation, due to the production of pions. The contribution coming from $\pi N \rightarrow \Lambda K$ comes larger in our work (see Table IX), presumably because we account for pion production prior to annihilation, for multiple interactions of the pions, for the pions coming from mesonic resonances, and for a complete three-dimensional (3D) propagation of the pions. A larger discrepancy between the two works arises for the strangeness exchange, from kaons to hyperons $\bar{K}N \rightarrow \Lambda\pi$ and between hyperons $\Lambda N \leftrightarrow \Sigma N$. The difference for the first process is easy to trace back. The estimate of Ref. 39 is based on a cross section of 7 mb. A look at Fig. 4(a) immediately shows that the effective cross section is rather $\sim 20-30$ mb. It is so because the $\bar{K}$ spectrum is very broad (and not at all concentrated around the $\bar{p}p$ c.m. rapidity, as assumed in Ref. 41, and because the cross section is strongly increasing when the $\bar{K}$ momentum is decreasing. The comparison is a little bit more complicated for the $\Lambda N \leftrightarrow \Sigma N$ process. Looking at Fig. 4 and Table IV, we see that an important number of Σ's are produced by the $\bar{K}N \rightarrow \Sigma\pi$ process and transformed back into Λ's. This contribution is indeed neglected by Ko and Yuan. Again, Fig. 4 tells us that this is not reasonable since, due to the broad $\bar{K}$ spectrum, the effective $\bar{K}N \rightarrow \Sigma\pi$ cross section is ~ 10 mb, which is quite important.

Let us come to the work by Dover and Koch. First of all, they assume that observed Λ's correspond to all hy-

TABLE IX. Tentative comparison between the works of Refs. 39 and 40 and ours concerning calculated contributions to Λ-production cross sections (in mb) in the $\bar{p}$ (4 GeV/c)+^{181}Ta system.

	Ko and Yuan (Ref. 41)	Dover and Koch (Ref. 42)	Our work
Λ prim	33	32	21
$\pi N \rightarrow \Lambda K$	29	32	49
$\omega N \rightarrow \Lambda K$	12		6.5
$\eta N \rightarrow \Lambda K$		1.5	11
$\bar{K}N \rightarrow \Lambda\pi$	27	65	75
$\Lambda N \leftrightarrow \Sigma N$	33	32	81
$\rho N \rightarrow \Lambda K$		40	
Total	123	215	244

perons. Therefore, they consider $\Lambda+\Sigma$ at the same time and do not split into the respective contributions. However, the main difference between this work and ours (and also the work by Ko and Yuan) is the scaling law applied to calculate primordial multiplicities. In Ref. 41 and in this work, the primordial cross section for the species ζ is taken as

$$\sigma_{\rm prim}(\bar{p}A\to\zeta x)=\sigma(\bar{p}p\to\zeta x)\frac{\sigma_{\rm ann}(\bar{p}A)}{\sigma_{\rm ann}(\bar{p}p)} . \quad (7.1)$$

This ensures that summing over all final states, one recovers the total $\bar{p}A$ annihilation cross section. Instead, the authors of Ref. 42 use

$$\sigma_{\rm prim}(\bar{p}A\to\zeta x)=A_{\rm eff}\sigma(\bar{p}p\to\zeta x) , \quad (7.2)$$

where $A_{\rm eff}$ is the effective number of target nucleons participating in the annihilation. This effective number is taken from $(\bar{p},\bar{n})$ measurements.[43] It is not clear what is the true physical meaning of $A_{\rm eff}$ but, if used for annihilation channels, it does not at all ensure the summation of all channels to be equal to the total annihilation cross section. Furthermore, it is not certain that one can borrow concepts that are relevant for more or less coherent processes, like $(\bar{p},\bar{n})$, and use them for incoherent annihilation processes. In any case, this makes an important numerical difference since a value of $A_{\rm eff}\approx 18$ is quoted in Ref. 42 for the $\bar{p}$Ta system, whereas the ratio appearing in Eq. (7.1) ≈ 1628 mb/24 mb≈ 68, so the comparison is rather difficult. The primordial Λ contribution comes about the same, because in Ref. 42, there is a compensation between the small value of $A_{\rm eff}$ and the inclusion of all hyperons (see above). The pion-induced associated production is about the same (in all works). The $\bar{K}$-induced strangeness exchange is about of the same order in Ref. 41 as in our work. Here again, there is a compensation between the small $A_{\rm eff}$ value and the large $\bar{K}N\to YK$ cross section (40 mb) used, still supposed to include all hyperons with the same weight (see Fig. 4 for comparison). The associated production induced by heavy mesons is treated quite differently in both works. The $\eta N\to\Lambda K$ contribution is not calculated in Ref. 42, whereas the authors obtain a large $\pi N\to YK$ contribution. In our work, we neglect short-lived mesons, because they have a good chance to decay before colliding with another nucleon.

We want to close this section by saying a few words about Ref. 13. Therein, it was argued that strange particle yield in $\bar{p}A$ could not be accounted for by the conventional ($\bar{p}N$+rescattering) picture and thus the author pointed out the necessity of having $\bar{p}NN$ annihilation. The results presented here are at variance with the discussion in Ref. 13. The explanation is that therein, the associated production (and also the strangeness exchange) is largely underestimated. As Fig. 4 reveals, using an average momentum to estimate reaction yield (neglecting details of the momentum distributions) is sometimes unsafe.

VIII. DISCUSSION AND CONCLUSION

We recall here the main physical aspects of our approach. The antiproton is supposed to annihilate on a single nucleon, possibly after making an inelastic scattering. The particles (baryons, antibaryons, and mesons) issued from these interactions can cascade through the nucleus, making various reactions. In short, our model embodies multiple scattering and reactions proceeding in a hadronic phase. The motion is treated semiclassically, but as carefully as possible (no restriction to Glauber forward approximation, Pauli blocking, etc.). Furthermore, except for pions, no medium correction is applied. As we explained in the preceding sections, within this frame, the calculation is not free from uncertainty, due to limited or incomplete knowledge of some elementary processes: $K(\bar{K})$ multiplicity, Σ production in the primordial annihilation, η and ω-induced reaction cross sections, etc. We can estimate that this uncertainty may be of the order of 10–15 %. Furthermore, we did not include all possible reactions. For instance, we did not include short-lived mesons, like the $\rho, f_2, \ldots$ mesons and the K^* mesons. Their effect is negligible at low energy, but may be appreciable at high energy, because of Lorentz time dilatation. We recall, however, that the introduction of a heavy meson in the annihilation, even if it has a large multiplicity, does not automatically lead to a large effect. What matters indeed is the difference between production yield induced by these heavy mesons and the one induced by the pions it can produce asymptotically in free space. After comparison of the respective cross sections (not very well known) and the respective multiplicities and taking account of the possible decays, one can estimate that the ρ contribution would be less than or equal to ~ 1.5 times the ω contribution. This would not alter our conclusion (see Tables III and IV). Furthermore, it one considers that some hadronization time is needed before a hadron becomes real or effective, i.e., possesses its known interaction properties, so short-lived an object as the ρ would hardly interact in the processes considered here.

In spite of these uncertainties, our work handles all the complexities of the multiple scattering, and, at least from this point of view, is probably a very elaborate description of the collision process in hadronic phase. We calculate the particle yields but also their spectrum. Furthermore, we showed that in several cases at least (e.g., $\bar{K}N\to Y\pi$), it is crucial to treat all the 3D-momentum distributions of the colliding particles in order to have a correct reaction yield.

Even though we have realized the most satisfactory (and still tractable) approach in the hadronic phase, assuming elementary interactions, it neglects some part of physics. This does not only refer to the transition to a quark-gluon plasma. It was our initial purpose to contrast the two hypotheses. But, our approach neglects, for instance, medium effects, both on the annihilation process and in the rescattering (see below). Another important aspect is the hadronization time, which has not been studied very much.

Our results compare relatively well with experiment. The rapidity distributions, the mass dependence, and the energy dependence relative to strangeness production are relatively well reproduced. The Λ yield is fairly well reproduced for the Condo data, and for the 4 GeV/c data. If the mesons resonances and/or the Σ's are neglected, we achieve a very good agreement. The $\bar{\Lambda}$ yield is well described but the latter is determined by simple aspects of the dynamics. We overestimate strongly the K_s yield (we want to stress that our calculation is the only one available for this yield). One of our important results is the demonstration that a Λ/K_s ratio of the order of 2.5 is easily achieved by the rescattering process. We also showed that this ratio mainly comes from the transfer of the s quarks from the original $\bar{K}$ mesons to the hyperons and to a lesser extent from associated strangeness production which brings a rather small additional contribution compared to the primordial production (occurring in the annihilation). The observed strange yield by no means requires exotic processes. This conclusion is very much akin to the one obtained in Ref. 42, although there are sensitive differences between the two works. Similarly, the results of this work suggest that there is no need for annihilation on several nucleons. This should be contrasted with the discussion of Ref. 13. But, as we already explained, this latter underestimates the contribution to Λ yield of the strangeness exchange processes. Therefore, the only available measurements in favor of two-nucleon annihilation are those of $\bar{p}d$, where the signal is clear, and the hypernucleus formation,[44] which still have to be analyzed carefully.

To make a last comment on the K_s yield, comparison with experiment seems to indicate that either the $K(\bar{K})$ multiplicity in the annihilation is changed when the latter occurs inside nuclei, or that the strangeness exchange is inhibited inside matter. Both possibilities are interesting and we believe that calculation (and measurements) of more exclusive cross sections will shed light on the strangeness production and propagation mechanisms inside matter.

We thank Dr. K. Miyano and Dr. Y. Yoshimura for an interesting correspondence.

APPENDIX: CROSS SECTIONS

A. Simple parametrizations of experimental cross sections

We first list simple but reasonably accurate parametrizations of experimental cross sections. Below, all cross sections are given in mb and p denotes the incident momentum in GeV/c:

(a) Pion-induced reactions

$$\sigma(\pi^- p \to \Lambda K^0) = 0, \quad p < 0.9,$$
$$= 0.65 p^{42}, \quad 0.9 < p < 1,$$
$$= 0.65 p^{-1.67}, \quad 1 < p < 10, \tag{A1}$$

$$\sigma(\pi^+ p \to \Sigma^+ K^+) = 0, \quad p < 0.9,$$
$$= 0.1 p^{4.8}, \quad 1.05 < p < 1.5,$$
$$= 1.48 p^{-1.85}, \quad 1.5 < p < 10, \tag{A2}$$

$$\sigma(\pi^- p \to \Sigma^- K^+) = 0, \quad p < 1.03,$$
$$= 0.12 p^{1.6}, \quad 1.03 < p < 1.5,$$
$$= 1.12 p^{-3.9}, \quad 1.5 < p < 5, \tag{A3}$$

$$\sigma(\pi^- p \to \Sigma^0 K^0) = 0, \quad p < 1.03,$$
$$= 0.31 p^{-1.53}, \quad 1.03 < p < 15, \tag{A4}$$

$$\sigma(\pi^- p \to \eta n) = 0, \quad p < 0.69,$$
$$= 1.47 p^{-1.68}, \quad 0.69 < p < 100, \tag{A5}$$

$$\sigma(\pi^- p \to \omega n) = 0, \quad p < 1.095,$$
$$= 13.76 \frac{p - 1.095}{p^{3.33} - 1.07}, \quad 1.095 < p < 10, \tag{A6}$$

(b) Kaon-induced reactions

$$\sigma(K^+ p \to K^+ p) = 3 + 11.5 \left[1 + \exp\left[\frac{p - 1.06}{0.8} \right] \right]^{-1}, \tag{A7}$$

$$\sigma_{\text{tot}}(K^+ n) = 18.6 p^{0.86}, \quad p < 1.150,$$
$$= 0.6 p^2 - 4.4 p + 25, \quad 1.150 < p < 10, \tag{A8}$$

$$\sigma_{\text{inel}}(K^+ n) = 0, \quad p < 0.8,$$
$$= \frac{100 p - 80}{7}, \quad 0.8 < p < 1.5,$$
$$= 10, \quad 1.5 < p, \tag{A9}$$

$$\sigma(K^- n \to K^- n) = 20 p^{2.74}, \quad 0.5 < p < 1,$$
$$= 20 p^{-1.8}, \quad 1 < p < 4, \tag{A10}$$

$$\sigma(K^- p \to K^- p) = 13 p^{-0.9}, \quad 0.25 < p < 4, \tag{A11}$$

$$\sigma(K^- p \to \bar{K}^0 n) = 3.5 p^{-0.93}, \quad 0.1 < p < 1,$$
$$= 3.5 p^{-1.78}, \quad 1 < p < 40, \tag{A12}$$

$$\sigma(K^- p \to \Sigma^0 \pi^0) = 0.6 p^{-1.8}, \quad 0.2 < p < 1.5, \tag{A13}$$

$$\sigma(K^- n \to \Sigma^0 \pi^-) = 1.2 p^{-1.3}, \quad 0.5 < p < 1,$$
$$= 1.2 p^{-2.3}, \quad 1 < p < 6, \tag{A14}$$

$$\sigma(K^- p \to \Lambda \pi^0) = 50 p^2 - 67 p + 24, \quad 0.2 < p < 0.9,$$
$$= 3 p^{-2.6}, \quad 0.9 < p < 10, \tag{A15}$$

(c) Hyperon-induced reactions

$$\sigma(\Lambda p \to \Lambda p) = 12.2 p^{-1.42}, \quad 0.1 < p < 0.9,$$
$$= 14.4 p^{-0.38}, \quad 0.9 < p < 2.0, \tag{A16}$$

$$\sigma(\Lambda p \to \Sigma^0 p) = 0, \quad p < 0.636,$$
$$= 30 p^{4.9}, \quad 0.636 < p < 0.8,$$
$$= 5.7 p^{-2.5}, \quad 0.8 < p < 1.7, \tag{A17}$$

$$\sigma(\Sigma^+ p \to \Sigma^+ p) = 38 p^{-0.62}, \quad 0.15 < p < 1.0, \tag{A18}$$

$$\sigma(\Sigma^- p \to \Sigma^- p) = 13.5 p^{-1.25}, \tag{A19}$$

$$\sigma(\Sigma^- p \to \Sigma^0 n) = 13.5 p^{-1.25}, \quad 0.1 < p < 0.7 , \tag{A20}$$

$$\sigma(\Sigma^- p \to \Lambda n) = 13.2 p^{-1.18}, \quad 0.1 < p < 0.7 . \tag{A21}$$

Some remarks are in order. Expression (A9) is an estimate of the inelastic $K^+ n$ cross section based on the various final channels containing a pion which are given in the literature. The parametrization of the exothermic reactions (A12)–(A16) and (A21) do not respect the expected $1/v$ law. We nevertheless used them down to $p=0$. But, in our case, the possible error at very low momentum is not serious because, in general, very few slow particles contribute to the reactions rates (as exemplified by Fig. 4). The same remark applies to the elastic K^--p and hyperon-proton cross sections.

B. Isospin averaged cross sections

For a reaction $A+B \to C+D$, the isospin averaged cross section is defined by

$$\bar{\sigma}(A+B \to C+D) = \frac{1}{2T_A+1}\frac{1}{2T_B+1}\sum_{m_A}\sum_{m_B}\sum_{m_C}\sum_{m_D}\sigma(m_A m_B \to m_C m_D) , \tag{A22}$$

where the cross sections appearing to the sum applies to definite members of the isospin multiplets. If the reaction proceeds through a single value of the total isospin T, it is sufficient to know the value of only one of the $\sigma(m_A m_B \to m_C m_D)$ quantities (provided it does not vanish) to evaluate $\bar{\sigma}$. If the reaction proceeds through several values of T (two in the examples below), it is then necessary to make assumptions about the interference between the different amplitudes. Below we neglect these interferences (or which gives equivalent results, we assume no phase between the various amplitudes). We then arrive at the following expressions:

$$\bar{\sigma}(\pi N \to \Lambda K) = \tfrac{1}{2}\sigma(\pi^- p \to \Lambda K^0) , \tag{A23}$$

$$\bar{\sigma}(\pi N \to \Sigma K) = \tfrac{1}{2}[\sigma(\pi^+ p \to \Sigma^+ K^+) + \sigma(\pi^- p \to \Sigma^- K^+) + \sigma(\pi^- p \to \Sigma^0 K^0)] , \tag{A24}$$

$$\bar{\sigma}(\pi N \to \eta N) = \tfrac{1}{2}\sigma(\pi^- p \to \eta n) , \tag{A25}$$

$$\bar{\sigma}(\pi N \to \omega N) = \tfrac{1}{2}\sigma(\pi^- p \to \omega n) , \tag{A26}$$

$$\bar{\sigma}(KN \to KN) = \tfrac{1}{2}[\sigma(K^+ p \to K^+ p) + \sigma_{\text{tot}}(K^+ n) - \sigma_{\text{inel}}(K^+ n)] , \tag{A27}$$

$$\bar{\sigma}(\bar{K}N \to \bar{K}N) = \tfrac{1}{2}[\sigma(K^- n \to K^- n) + \sigma(K^- p \to K^- p) + \sigma(K^- p \to \bar{K}^0 n)] , \tag{A28}$$

$$\bar{\sigma}(KN \to \Sigma N) = \tfrac{3}{2}[\sigma(K^- p \to \Sigma^0 \pi^0) + \sigma(K^- n \to \Sigma^0 \pi^-)] , \tag{A29}$$

$$\bar{\sigma}(\bar{K}N \to \Lambda \pi) = \tfrac{3}{2}\sigma(K^- p \to \Lambda \pi^0) , \tag{A30}$$

$$\bar{\sigma}(\Lambda N \to \Lambda N) = \sigma(\Lambda p \to \Lambda p) , \tag{A31}$$

$$\bar{\sigma}(\Lambda N \to \Sigma N) = 3\sigma(\Lambda p \to \Sigma^0 p) , \tag{A32}$$

$$\bar{\sigma}(\Sigma N \to \Sigma N) = \tfrac{1}{2}[\sigma(\Sigma^+ p \to \Sigma^+ p) + \sigma(\Sigma^- p \to \Sigma^- p) + \sigma(\Sigma^- p \to \Sigma^0 n)] . \tag{A33}$$

All the cross sections are expressed in terms of the experimentally known cross sections listed above.

[1]J. Rafelski, Phys. Lett. **91B**, 281 (1980).

[2]J. Rafelski, Phys. Lett. B **207**, 371 (1988).

[3]J. Cugnon and J. Vandermeulen, Phys. Lett. **146B**, 16 (1984).

[4]E. Hernandez and E. Oset, Phys. Lett. B **184**, 1 (1987).

[5]L. A. Kondratyuk and M. G. Sapozhnikov, in *Physics at LEAR with Low Energy Antiprotons*, edited by C. Amsler, G. Backenstoss, R. Klapisch, C. Leluc, D. Simon, and L. Tauscher (Harwood, Academic, Chur, Siwtzerland, 1988), p. 771.

[6]Ye. S. Golubeva, A. J. Iljinov, A. S. Botvina, and N. M. Sobolevsky, Nucl. Phys. **A483**, 539 (1988).

[7]J. Cugnon and J. Vandermeulen, Ann. Phys. (Paris) **14**, 49 (1989).

[8]J. Cugnon and J. Vandermeulen, Phys. Rev. C **39**, 39 (1989).

[9]R. Bizzarri *et al.*, Lett. Nuovo Cimento **2**, 431 (1969).

[10]B. Y. Oh, P. S. Eastman, Z. Ming Ma, D. L. Parker, G. A. Smith, and R. J. Sprafka, Nucl. Phys. **B51**, 57 (1973).

[11]G. A. Smith, in *The Elementary Structure of Matter*, edited by J.-M. Richard, E. Aslanides, and N. Boccara (Springer-Verlag, Berlin), 1988, p. 219.

[12]J. Riedlberger *et al.*, Phys. Rev. C **40**, 2717 (1989).

[13]J. Cugnon, in *The Elementary Structure of Matter*, edited by J.-M. Richard, E. Aslanides, and N. Boccara (Springer-Verlag, Berlin, 1988), p. 211.

[14]K. Miyano *et al.*, Phys. Rev. Lett. **53**, 1725 (1984).

[15]F. Balestra *et al.*, Phys. Lett. B **194**, 192 (1987).

[16]G. Levman, R. Singer, and T. Fields, Phys. Rev. D **21**, 1 (1980).

[17]L. Tauscher, in *Physics at LEAR with Low Energy Antiprotons*, edited by C. Amsler, G. Backenstoss, R. Klapisch, C. Leluc, D. Simon, and L. Tauscher (Harwood, Academic, Chur, Switzerland, 1988), p. 397.

[18]M. Chiba *et al.*, in *Physics at LEAR with Low Energy Antiprotons*, edited by C. Amsler, G. Backenstoss, R. Klapisch, C. Leluc, D. Simon, and L. Tauscher (Harwood, Academic,

Chur, Switzerland, 1988), p. 401.
[19]S. Noguchi *et al.*, Z. Phys. C **24**, 297 (1984).
[20]F. Ochiai *et al.*, Z. Phys. C **23**, 369 (1984).
[21]A. Baldini, V. Flaminio, W. G. Moorhead, and D. R. O. Morrison, in *Total Cross Sections for Reaction of High Energy Particles,* Vol. 12 of Landolt-Börnstein New Series, edited by H. Schopper (Springer-Verlag, Berlin, 1988).
[22]J. Cugnon, P. Jasselette, and J. Vandermeulen, Nucl. Phys. **A470**, 558 (1987).
[23]M. R. Clover, R. M. De Vries, N. J. Di Giacomo, and Y. Yariv, Phys. Rev. C **26**, 2138 (1982).
[24]E. Hernandez and E. Oset, Nucl. Phys. **A455**, 584 (1986).
[25]J. Cugnon, P. Deneye, and J. Vandermuelen, Nucl. Phys. **A500**, 701 (1989).
[26]Particle Data Group, Phys. Lett. B **204**, 1 (1988).
[27]High-Energy Reactions Analysis Group, CERN Report CERN-HERA 83-01, 1983 (unpublished).
[28]High-Energy Reactions Analysis Group, CERN Report CERN-HERA 83-02, 1983 (unpublished).
[29]K. Kikuchi and M. Kawai, *Nuclear Matter and Nuclear Reactions* (North-Holland, Amsterdam), 1968.
[30]W. Brenig, Nucl. Phys. **13**, 333 (1959).
[31]E. Oset, L. L. Salcedo, and D. Strottman, Phys. Lett. **165B**, 13 (1985).
[32]K. Miyano *et al.*, Phys. Rev. C **38**, 2788 (1988).
[33]G. T. Condo, T. Handler, and H. O. Cohn, Phys. Rev. C **29**, 1531 (1984).
[34]F. Eisele *et al.*, Phys. Lett. **60B**, 297 (1975).
[35]W. G. Gibbs, in *Proceedings of the Intersections Between Particle and Nuclear Physics (1986, Lake Louise, Canada),* AIP Conf. Proc. No. 150, edited by Donald F. Geesaman (AIP, New York, 1986), p. 505.
[36]D. E. Kharzeev and M. G. Sapozhnikov, JINR Report E4-88-930 (Dubna), 1988.
[37]P. Gregory *et al.*, Nucl. Phys. **B102**, 189 (1976).
[38]S. C. Phatak and N. Sarma, Phys. Rev. C **31**, 2113 (1985).
[39]S. C. Phatak and N. Sarma, Phys. Rev. C **36**, 864 (1987).
[40]S. J. Brodsky, in *Physics at LEAR with Low Energy Antiprotons,* edited by C. Amsler, G. Backenstoss, R. Klapisch, C. Leluc, D. Simon and L. Tauscher (Harwood, Academic, Chur, Switzerland, 1988), p. 317.
[41]C. M. Ko and R. Yuan, Phys. Lett. B **192**, 31 (1987).
[42]C. B. Dover and P. Koch, Invited talk at the Conference on Hadronic Matter in Collision, Tucson, Arizona, 1988 (unpublished); Brookhaven National Laboratory Report 1988 BNL-42105.
[43]T. Bressani *et al.*, Europhys. Lett. **2**, 587 (1986).
[44]J.-P. Bocquet *et al.*, Phys. Lett. B **182**, 146 (1986).