B>0 ANNIHILATION*

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We analysed the experimental data on strange particle production in antiproton nucleus annihilations. Following the standard conventional annihilation picture we account for the dominant reaction channels in order to calculate the cross sections observed. The experimental data on single strangeness production are reproduced by the calculations and account for the annihilation on a single nucleon followed by subsequent rescattering proceeding in the hadron phase. The contribution of the discussed process underestimates the experimental results on double strangeness production by an order of magnitude. One of the possible explanation for this discrepancy may be related with the B>0 annihilation.

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1. Introduction

A considerable interest has been attached recently to the antiproton annihilation on nuclei and especially for the strangeness production. Since the strangeness was suggested by Rafelski [1] as an obvious signature for the quark gluon plasma a number of experimental studies have been performed on hadron–nucleus and heavy ion collisions in order to search for genuine strangeness enhancement. The advantage of the antiprotons for producing the high temperature and high nuclear density phenomena is the possibility to release their entire energy in the very specific volume.

Annihilation on more than one nucleon (B>0 annihilation) can also produce KY and $K\bar{K}$ pairs and the total strange particle yield is higher in this channel than in the B=0 annihilation. For B=1 annihilation at rest Cugnon *et al.* [2] predicted that strange particles are produced at a rate of 0.17 compared to 0.04 for the B=0 annihilation.

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Within a more conventional picture the strangeness production is investigated by means of a cascade model where the annihilation is considered to occur on a single nucleon (B=0) and the production of both nonstrange and strange mesons is followed by the sequent rescattering of these particles on the residual nuclear nucleons. Detailed study by Cugnon *et al.* [3] and Gibbs and Kruk [4] on single strangeness production established that the experimental data are consistent with the conventional annihilation picture. It was found that the dominant contribution to the strangeness production is due to the antiproton annihilation on a single nucleon followed by a rescattering of a secondary particles ($\bar{p}N \to MX$, $MN \to KY$). For antiproton induced reactions we hope that multiple strangeness reactions are more sensitive to the reaction process. The double strangeness production is likely to be an effective tool to study the reaction mechanisms and to search for high-temperature and high nuclear density phenomena [5].

In the frame of conventional annihilation picture we analyzed single and double strangeness production in antiproton–nucleus collisions. Our goal is to estimate the contribution of the B>0 annihilation to the experimental data.

2. Single strangeness production

We made the calculations by means of the three dimensional cascade model COMIC described in detail in Ref. [6]. In order to analyze the experimental data on strange particle production measured with Xenon Bubble Chamber DIANA at ITEP accelerator [7]. We consider antiproton annihilation on a single nuclear nucleon. Following the model by Vandermeulen [8] we suggest the $\bar{p}$+N annihilation is proceeded exclusively via two meson creation

$$\bar{p} + N \to M_1 + M_2 , \tag{1}$$

where M_1, M_2 are two mesons (π, ω, ρ, η, K, K^*) of total strangeness zero. In order to calculate the rescattering of nonstrange annihilation meson on nuclear nucleon M + N → Y + K we assume the meson resonance-nucleon cross section to be equal the pion-nucleon one at the same collision energy. To calculate the hyperon production in η-nucleon collision the relations based on SU(3) symmetry was applied.

In Tab. I, II the experimental and calculated inclusive and two-particles production yields are presented. The calculated strangeness yields are in good agreement with the experimental data.

TABLE I

Percent rates of particles produced in p̄Xe annihilations at rest.

	exp.	model
Λ	2.46 ± 0.30	2.27
K^0_s	2.14 ± 0.23	2.10
Σ^0	0.16 ± 0.09	0.24

TABLE II

Percent rates of two-particles states produced in p̄Xe annihilation at rest.

	exp.	model
$\Lambda\ K^0_s$	1.25 ± 0.30	1.30
$\Lambda\ K^+$	0.76 ± 0.20	0.94
$K^0_s\ K^0_s$	0.28 ± 0.11	0.27
$K^0_s\ K^-$	0.48 ± 0.21	0.39
$K^0_s\ K^+$, $K^0_s\ \Sigma^+$	0.24 ± 0.08	0.29
$K^+\ K^-$, $K^+\ \Sigma^+$	0.43 ± 0.3	0.52

3. K^+K^+-production in p̄ +Xe annihilations

The experimental data on K^+K^+ production in p̄Xe annihilations were obtained at ITEP facility by DIANA Collaboration [9]. The antiproton momenta cover the region from 0 to 900 MeV/c. Different reaction mechanisms were analysed in order to reproduce the experimental data. Namely we study the contributions of the direct K^+K^+ production as well as two-body and cascade reactions.

The kaon production in the direct antiproton collision with bound nuclear nucleon is considered in the reaction

$$\bar{p} + N \to K + K + \overline{K} + \overline{K}\,. \quad (2)$$

The reaction threshold for free p̄p annihilation corresponds to antiproton momentum of 668 MeV/c in the case of $K^+K^+K^-K^-$ production. Four kaons production in antiproton-nucleus annihilation at bombarding energies below the free p̄N-threshold is due to the internal nuclear motion. In the single-particle density approach we use the nucleon momentum distribution $\rho(q)$ describing the available momentum components in a nucleus.

Direct particle production is usually described by means of the First Collision Model (FCM). In the frame of FCM we consider that kaons are produced in the first collision on the incident proton with the nuclear nucleon and give the Lorentz-invariant differential cross section by

$$E\frac{d^3\sigma_{\bar{p}A\to KK\overline{K}\overline{K}X}}{d^3p} = N_1 I_s \int d^3q\ \rho(q) E' \frac{d^3\sigma_{\bar{p}N\to 4K}(\sqrt{s})}{d^3p'}\ , \qquad (3)$$

where $\rho(q)$ is the groundstate momentum distribution, N_1 is the first chance collisions number, I_s accounts for final isospin state of interest, $\sqrt{s}$ is the invariant energy of the incident antiproton–nucleon system and primed indices denote the K momentum and energy in this $\bar{p}$+N system, q is the nuclear nucleon momentum. $d^3\sigma_{\bar{p}N\to 4KX}(\sqrt{s})/d^3p$ stands for the elementary differential cross section of $KK\bar{K}\bar{K}$ production in collision of antiproton with free nucleon.

The cross section of the reaction (1) was calculated by phenomenological way

$$\sigma_{\bar{p}N\to 4K}(\sqrt{s}) = b(\sqrt{s} - \sqrt{s_o})^{1/2}\ , \qquad (4)$$

where s and s_o are the collision and threshold invariant energy in GeV respectively. For antiproton momenta below 1 GeV we adjust the parameter b=5.26 μb/GeV$^{1/2}$ from PS202 (JETSET) experimental data on $\phi\phi$ and 4K-production in $\bar{p}$p annihilations [10].

The first chance collision number N_1 was calculated by the approach of Glauber and Matthia [11]. For low antiproton momenta and in the case of annihilation at rest the approach trends to $N_1 = A^{2/3}$ following the assumption on the antiproton annihilation at the nuclear surface.

Obviously the 4K-production cross section in $\bar{p}$A annihilations strongly depends on the function ρ(q) describing the nuclear nucleon momentum distribution. We use a Fermi gas model for the nucleus in which nucleons are supposed to be bound and moving with Fermi-type momentum distributions characterized by the Fermi momentum q_F. The Fermi momentum is roughly constant for target nuclei heavier than Ni, and close to the corresponding value $q_F = h(3\ \pi^2\rho_0)^{1/3} = 270$ MeV/c in infinite nuclear matter with density $\rho_0 = 0.17$ fm^{-3}.

In order to describe the deep inelastic nuclear reactions with high momentum transfer one need to take into account the extreme momentum component in the nuclear wave function, possibly generated by two-body dynamical correlations. To produce four kaons at bombarding energy far below the free $\bar{p}$N threshold we need to incorporate the high momentum component. In our calculations we use the double-gaussian function suggested by Geaga *et al.* [12, 13].

In Tab. III we show the calculated cross sections for K^+K^+-production in $\bar{p}$Xe annihilations at various antiproton momenta. The results are performed for Fermi-gas model as well as for high momentum single nucleon distribution (HEC). For HEC calculations we use two values of parameter γ: 0.07 and 0.15.

TABLE III

The K^+K^+-production cross sections (μb) in $\bar{p}$Xe annihilations calculated by means of FCM.

$p_{\bar{p}}$ (MeV/c)	Fermi	HEC 7 %	HEC 15	Exp.
100		0.044	0.12	
200		0.260	0.36	
300		0.440	0.61	
400	0.07	1.580	1.71	25.8
600	9.60	9.900	10.30	
800	28.30	29.100	30.00	64.5
1000	45.20	45.800	46.00	90.3

Noticeably, the FCM calculations underestimate the experimental results. The disagreement is most significant at low antiproton momenta.

In order to analyze K^+K^+ production in $\bar{p}$A annihilations in the framework of the two-body mechanism we consider the following reaction channels

$$\bar{p} + N_1 \to K + \overline{K}^*, \tag{5}$$

$$\overline{K}^* + N_2 \to K + \Xi, \tag{6}$$

$$\bar{p} + N_1 \to K^* + \overline{K}^*, \tag{7}$$

$$\overline{K}^* + N_2 \to K + \Xi, \tag{8}$$

$$K^* \to K + \pi, \tag{9}$$

$$\bar{p} + N_1 \to K + \overline{K} + \pi, \tag{10}$$

$$\pi + N_2 \to K + Y. \tag{11}$$

We account for all final combinations of produced particle in order to evaluate the production rate for K^+K^+ pairs.

The cross sections for two kaons production were calculated by means of Two Step Model described in detail in Ref. [14, 15] as

$$E\frac{d^3\sigma_{\bar{p}A\to K^+K^++X}}{d^3p} = I_s \int\int d^3q d^3p_M F(p_M) W(p_M, A) \rho(q) E' \frac{d^3\sigma_{MN\to KX}(\sqrt{s})}{d^3p'}, \tag{12}$$

where I_s accounts for final isospin states, $W(p_M, A)$ is the probability that secondary mesons M produced in the first collision are rescattered in the target nucleus [14], $F(p_M)$ is the M-spectrum in p̄N annihilation and $\rho(q)$ is the nucleon momentum distribution. The spectrum of M-meson in p̄ N annihilation was calculated means of FCM. For secondary pion induced reactions we followed the parameterizations suggested by Cugnon *et al.* [16].

The results calculated by means of TSM with taking into account the discussed reaction channels are shown in Tab. IV. Obviously the experimental data are not reproduced by the model.

TABLE IV

The K^+K^+-production cross sections (μb) in p̄Xe annihilations calculated by means of two-step model.

$p_{\bar{p}}$ (MeV/c)	$K\overline{K}^*$	$K^*\overline{K}^*$	$K\overline{K}\pi$	Exp.
100	0.79	0.63		
200	0.81	0.69		
300	0.83	0.79	0.001	
400	0.86	0.89	0.010	25.8
600	0.89	1.18	0.130	
800	0.93	1.46	0.310	64.5
1000	0.92	1.63	0.630	90.3

The importance of the two meson annihilation process followed by the meson–nucleon rescattering ($\bar{p} + N_1 \to M_1 + M_2$, $M_i + N_2 \to K + Y$) was emphasized by Cugnon *et al.* [17].

In the case of double strangeness production it is necessary to account for both annihilation meson rescattering in nuclear environment

$$\bar{p} + N_1 \to M_1 + M_2 \,, \tag{13}$$
$$M_1 + N_2 \to K_1 + Y_1 \,, \tag{14}$$
$$M_2 + N_3 \to K_2 + Y_2 \,. \tag{15}$$

We made the calculations by means of the cascade model COMIC [6]. We analyzed $\pi\pi$ and $\omega\omega$ channels only because these reactions supply minimal and maximal contribution correspondingly to single strangeness production from two-meson annihilation. Thus other possible reaction channels contribute withing the calculated rate range. The cascade results shown in Tab. V essentially underestimate the experimental data.

Really we have no means to calculate the rate for double strangeness production in the case of B>0 annihilation. The statistical model referred to in order to estimate the influence of possible B>0 annihilation [18] is based on quite simple and free parameters assumptions. Nevertheless let us to assume that the contribution of q^6 component in the nucleus is of about 5%, that is not contradicting the estimation on the high momentum component of the nuclear wave function [19]. Assuming the strangeness suppression factor equal to 0.1 we estimate the double strangeness production in B>0 annihilation is about 500 times less than ordinary single strange particle production. This simple estimation allows us to reproduce the DIANA experimental data on K^+K^+ production but it is quite ambiguous.

TABLE V

The K^+K^+-production cross sections (μb) in $\bar{p}$Xe annihilations calculated in the frame of cascade model.

$p_{\bar{p}}$ (MeV/c)	$\pi\pi$	$\omega\omega$	Exp.
100	0.050	1.970	
200	0.052	1.770	
300	0.054	1.550	
400	0.056	1.160	25.8
600	0.041	0.072	
800	0.017	0.420	64.5
1000	0.006	0.170	90.3

4. Resume

We analysed the experimental data on single strangeness and K^+K^+ production in antiproton nucleus annihilations. We use standard conventional annihilation picture and assume the antiproton annihilates on a single nucleon and produces the mesons that are rescattered in the nuclear environment ($\bar{p}N \rightarrow MX$, $MN \rightarrow K, \Lambda X$). This approach was very successful in the analysis of the single strangeness production and allows us to reproduce both inclusive and exclusive experimental data.

We account for the dominant reaction channels in order to reproduce the cross section on double strangeness production. We also take into consideration the direct double strangeness production in $\bar{p}N$ annihilation and more complicated cascade processes.

It was found that the total contribution of the discussed reaction mechanisms underestimates the experimental results by an order of magnitude at average. One of the possible explanation for this discrepancy may be related with the B>0 annihilation.

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