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Two-body exit channels in $\bar{p}$-p and $\bar{p}$-nucleus annihilations

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Our previous model is used and improved to estimate branching ratios for $B=0$ ($\bar{N}N$) and $B=1$ ($\bar{N}NN$) annihilations. Particular emphasis is put on the two-body exit channels. It is pointed out that relative values of two-body exit channel branching ratios in $B=1$ annihilations are largely model independent. Nuclear effects in $\bar{p}$-nucleus annihilation at rest are estimated.

The increasing amount of experimental data on $\bar{p}$-nucleus annihilation at the Low Energy Antiproton Ring (LEAR) seems to indicate that the annihilation is not very much influenced by the surrounding medium,[1] perhaps simply because the annihilation takes place at the surface of the nucleus, where the density is low. However, physicists are looking for unusual annihilations. In fact, there is some indication that the annihilation process may directly involve two (or perhaps more) nucleons. This possibility was raised by several theoreticians.[2-5] But, the first encounter of this kind of events is to be found in Ref. 6, which dates far back in the pre-LEAR era. In this work, the authors report on the observation of $\bar{p}d \to p\pi^-$ events with typical two-body kinematics. This obviously indicates that both nucleons in the deuteron are directly involved in the process (denoted as a $B=1$ annihilation). In a previous work,[4] hereafter referred as I, we emphasized the expected sizable probability of $B=1$ annihilations in $\bar{p}$-nucleus interactions and we indicated, using a simple phase space model, that in $B\neq0$, the strangeness producing channels are enhanced compared to ($\bar{p}p$ or $\bar{p}n$) $B=0$ events. Here, we want to present specific predictions for some strangeness producing channels, especially the two-body channels. Some of them are presently under experimental study.[7] For this, we have refined a little bit our model, described in I, at the light of the current investigations of the annihilation mechanism at the quark level.[8-10]

In I, we used a simple version of the statistical model. The branching ratio for a final state of n pions in $\bar{p}p$ annihilation is given, apart from an overall normalization factor ensuring $\sum_i f_i = 1$, by

$$f(n\pi) = (\lambda_\pi C_0)^{n-2} R_n(\sqrt{s}; nm_\pi) , \quad (1)$$

where $n \geq 2$, $\sqrt{s}$ is the available c.m. energy, and R_n is the statistical bootstrap phase space integral[11] involving n particles of mass m_π. The dimensionless parameter $C_0 = (4\pi m_\pi^2)^{-1}$ corresponds more or less to the reference volume available to the interacting system and λ_π is an adjustable parameter. For K-producing channels, we write

$$f(K\bar{K}, l\pi) = \beta(\lambda_K C_0)^l R_{l+2}(\sqrt{s}; m_K, m_K, lm_\pi) , \quad (2)$$

for $l \geq 0$. A good fit of $\langle n \rangle$, $\langle l \rangle$, and the $K\bar{K}$ branching ratio is obtained with $\lambda_\pi = 1.4$, $\lambda_K = 1.8\lambda_\pi$, $\beta = 0.4$ (see Table I). It turned out that $\lambda_K/\lambda_\pi \approx 1$ with $\beta = 1$ is sufficient to guarantee the right $K\bar{K}$ branching ratio.[4] The main effect of using $\beta = 0.4$ is to give a much better value of $\langle l \rangle$, the average pion multiplicity in strange particle channels. The value of β smaller than one is to be associated with the reduction of rates for a heavy flavor quark, assuming, however, a larger interacting volume for strangeness pro-

TABLE I. Branching ratio (in percent) for several purely pionic (n) and $K\bar{K}$ plus pionic (l) channels in $\bar{p}p$ annihilations as calculated from Eqs. (1) and (2). Case (a) corresponds to $\lambda_\pi = 1.4$, $\lambda_K = 1.4$, $\beta = 1$; case (b) to $\lambda_\pi = 1.4$, $\lambda_K = 1.8\lambda_\pi$, $\beta = 0.4$.

	Branching ratio			Branching ratio	
n	(a)	(b)	l	(a)	(b)
2	0.51	0.51	0	0.44	0.17
3	7.0	6.7	1	2.3	1.6
4	25.9	25.8	2	2.2	2.8
5	35.3	35.1	3	0.4	1.0
6	20.5	20.5	4	0.01	0.06
7	5.0	5.0			
8	0.5	0.5			
9	0.02	0.02			
Sum	94.6	94.3		5.4	5.7
$\langle n \rangle$	4.90	4.90		1.49	1.85
$\langle n \rangle_{exp}$	5.01 ± 0.23 (Ref. 20)		$\langle l \rangle_{exp}$	~ 1.95 (estimated from Ref. 13)	
$\langle n+l \rangle$	4.72	4.73			

ducing channels. According to recent theoretical investigations,[8-10] the reduction could be due to topologically different annihilation diagrams of s quarks in the final state compared to u and d quarks.

The extension of this model to $B=1$ annihilation is made by the following formulas:

$$f(\mathrm{N},n\pi)=(\lambda_\pi C_1)^{n-1}R_{n+1}(\sqrt{s};m_\mathrm{N},nm_\pi)\ , \tag{3}$$

$$f(\mathrm{NK\bar{K}},l\pi)=\beta(\lambda_\mathrm{K}C_1)^l R_{l+3}(\sqrt{s};m_\mathrm{N},m_\mathrm{K},m_\mathrm{K},lm_\pi)\ , \tag{4}$$

$$f(\mathrm{YK},l\pi)=\beta(\lambda_\mathrm{K}C_1)^l R_{l+1}(\sqrt{s};m_\mathrm{Y},m_\mathrm{K},lm_\pi)\ , \tag{5}$$

$$f(\Xi\mathrm{KK},k\pi)=\beta^2(\lambda_\mathrm{K}C_1)^k R_{k+3}(\sqrt{s};m_\Xi,m_\mathrm{K},m_\mathrm{K},km_\pi)\,. \tag{6}$$

In these equations, Y is an hyperon (either Λ or Σ), $n\geq 1$, l, and $k\geq 0$. The factor β^2 in (6) is in keeping with the above discussion on the reduction for s-quark production. As in I, the quantity C_1 is related to C_0 by $C_1/C_0=1.31$. This value does not result from a fit, but is chosen as in the fireball model, by assuming the interaction volume in proportional to the mass of the initial system.[12]

The predictions of this model for two-particle modes and for the global types are given in Table II. The global contribution of strange channels is reinforced compared to the calculation of I. The rates for two-particle channels were not given in I.

From Eqs. (1) and (2) we obtain

$$\frac{f(\mathrm{K\bar{K}})}{f(\pi\pi)}=\beta\frac{W_\mathrm{KK}}{W_{\pi\pi}}\frac{p_\mathrm{K}}{p_\pi}\ , \tag{7}$$

where the p's are the c.m. momenta (entering in the R_2 integrals), and where the W's are isospin factors, not explicitly written down previously. Similarly we obtain from Eqs. (3) and (5):

$$\frac{f(\Lambda\mathrm{K})}{f(\mathrm{N}\pi)}=\beta\frac{W_{\Lambda\mathrm{K}}}{W_{\mathrm{N}\pi}}\frac{p_\Lambda}{p_\mathrm{N}}\ , \tag{8}$$

$$\frac{f(\Sigma\mathrm{K})}{f(\mathrm{N}\pi)}=\beta\frac{W_{\Sigma\mathrm{K}}}{W_{\mathrm{N}\pi}}\frac{p_\Sigma}{p_\mathrm{N}}\ . \tag{9}$$

We note, however, that these ratios are much less dependent upon a particular model than the ones indicated in Tables I and II. In particular, we could consider a much more complicated description for multiparticle production, but, provided we assume that the $B=0$ and $B=1$ annihilation systems *first* decay in two-body channels (with also resonances), we would also obtain Eqs. (7)–(9). The only assumption behind these equations is the same reduction factor β for s-producing two-body channels. This seems quite reasonable in view of the corresponding quark diagrams.[10] Fitting the experimental value[13] of $f(\mathrm{K^+K^-})/f(\pi^+\pi^-)$ at rest ($\sim\frac{1}{3}$, which is also the observed value at low momentum), one finds $\beta\approx 0.33$, which is not far from the value quoted previously. We remind the reader that the latter was obtained essentially by fitting the total strangeness yield and the associated pion multiplicity $\langle l\rangle$. We finally predict

$$R_1^d=\frac{f(\bar{\mathrm{p}}\mathrm{d}\to\Sigma^-\mathrm{K}^+)}{f(\bar{\mathrm{p}}\mathrm{d}\to\mathrm{p}\pi^-)}=\beta\frac{\mathrm{p}_\Sigma}{\mathrm{p}_\mathrm{N}}\ , \tag{10a}$$

$$R_2^d=\frac{f(\bar{\mathrm{p}}\mathrm{d}\to\Lambda\mathrm{K}^0)}{f(\bar{\mathrm{p}}\mathrm{d}\to\mathrm{p}\pi^-)}=\tfrac{3}{2}\beta\frac{\mathrm{p}_\Lambda}{\mathrm{p}_\mathrm{N}}\ . \tag{10b}$$

We can also make predictions for p̄-nucleus annihilations, with the assumption that the nucleus just provides a statistical sample of $T=1$ and $T=0$ pairs of nucleons. It turns out that the $\Sigma\mathrm{K}/\mathrm{p}\pi$ ratio is independent of the isospin: $R_1^A=R_1^d$. For the $\Lambda\mathrm{K}/\mathrm{p}\pi$ ratio, one gets

$$R_2^A=\frac{f(\bar{\mathrm{p}}A\to\Lambda\mathrm{K}^0)}{f(\mathrm{p}A\to\mathrm{p}\pi^-)}=\beta\frac{\mathrm{p}_\Lambda}{\mathrm{p}_\mathrm{N}}\left[\frac{6Z}{2Z+3(N-1)}\right]\ , \tag{11}$$

where Z and N are the proton and neutron numbers of the target. Numerically, one has

$$R_1^d=R_1^A\approx 0.29,\quad R_2^d\approx 0.45\ ,\qquad R_2^A\approx 0.30\frac{6Z}{2Z+3(N-1)}\ . \tag{12}$$

Using the experimental value[7] of $f(\bar{\mathrm{p}}\mathrm{d}\to\mathrm{p}\pi^-)=(28\pm 3)\times 10^{-6}$, and our theoretical value of R_1^d, we predict $f(\bar{\mathrm{p}}\mathrm{d}\to\Sigma^-\mathrm{K}^+)=(7.8\pm 0.8)\times 10^{-6}$. No signal has been detected at the moment, the 90% confidence limit being[7] $\sim 8\times 10^{-6}$. The closeness of our prediction claims for an improvement of the experimental result.

Following our idea of I, we assume that the $B=1$ annihilation is a two-step process, i.e., that first the antiproton annihilates on a nucleon and since it has a finite lifetime, the fireball fuses with another nucleon, provided the latter is close enough. For at rest annihilation, the concept of range should be substituted to the one of lifetime. If we denote by P_0 the probability of having the primary annihilation, and P_1 the probability for the subsequent fusion, then the respective probabilities for $B=0$ and $B=1$ annihilations are given by

$$P_{B=0}=P_0(1-P_1),\quad P_{B=1}=P_0P_1\ . \tag{13}$$

The quantity P_1 can tentatively be ascribed to be

$$P_1=C\int f\left[\frac{r}{a}\right]n_{12}(\mathbf{r})d^3r\ , \tag{14}$$

where $n_{12}(\mathbf{r})$ is the nucleon density at distance $\mathbf{r}$ apart from the first annihilating nucleon. The quantity a stands for the range of the two-nucleon annihilation and f is a function normalized to unity. Below, it will be taken as a

TABLE II. Branching ratio (in percent) for several channels in $B=1$ annihilations. Same conventions as in Table I.

Channel	Branching ratio (a)	Branching ratio (b)	$\langle n\rangle$ (or $\langle l\rangle$, or $\langle k\rangle$) (a)	$\langle n\rangle$ (or $\langle l\rangle$, or $\langle k\rangle$) (b)
Nπ	0.0738	0.0678	1	1
Nπ's	86.6	79.7	4.57	4.57
NK$\bar{\mathrm{K}}\pi$'s	3.2	4.5	1.07	1.45
ΛK	0.033	0.012	· · ·	· · ·
ΛKπ's	3.3	5.7	2.40	2.88
ΣK	0.097	0.0356	· · ·	· · ·
ΣKπ's	6.5	10.1	2.23	2.68
ΞKKπ's	0.4	0.1	0.35	0.52
Sum	100	100	4.22	4.14

Gaussian or a uniform distribution on a sphere of radius a. The "coupling constant" C can then be determined by fitting the "observed" value[6,14] of P_1 in the annihilation on a deuteron. In that particular case, n_{12} is the square of the normalized deuteron wave function. For the case of a uniform medium of baryon density ρ,

$$n_{12}=\rho(1-\nu_{12}) , \tag{15}$$

where ν_{12} is the so-called correlation function. For the latter, we used the nuclear matter calculations of Ref. 15, but similar results are obtained by other authors.[16] For ρ, we used the baryon density at the average annihilation distance (from the center) at rest. This turns out to be[17,18] of the order $\sim 0.1\rho_0$. We calculated P_1 for several values of a. Note that $a \approx 1$ fm is an upper limit and, that $a \approx 0.5$ fm is probably more reasonable.[19] It should be noted that $B=1$ annihilations are sensitive to short range correlations for $a<0.5$ fm only. One can see from Table III that the $B=1$ annihilation rate is at the most of a few percent. The very reason is that the antiproton annihilates in a region of the nucleus where the density is as small as in the deuteron.

Let us finally comment on the values of the ratios (8) and (9). Here again, we tried to make an estimate of the nuclear effects, mainly the absorption of the particles. For simplicity, we used a constant mean free path picture assuming that either of both particles crosses the nucleus. For a typical nucleus (of radius ~ 5 fm), we found, summarizing all the effects (for $N=Z$)

$$R_1^A \approx P_1 \times 0.29 \times 3.5, \quad R_2A \approx P_1 \times 0.36 \times 3 , \tag{16}$$

TABLE III. Value of the integral entering in Eq. (14) for the deuteron case and the nuclear case, respectively. The last column gives the value of P_1 in the nuclear case. The letters G and U refer to Gaussian and uniform f functions. See text for detail.

		Integral (d)	Integral ("nucleus")	P_1 (nucleus)
	$a=1$	0.19	0.016	0.01
G	$a=0.75$	0.13	0.016	0.013
	$a=0.5$	0.045	0.015	0.03
	$a=1$	0.155	0.016	0.01
U	$a=0.75$	0.05	0.015	0.03
	$a=0.5$	0.016	0.015	0.10

where the last enhancement factor translates the fact that the proton and the pion are interacting more strongly than the strange particles do.

We have made definite predictions for branching ratios in $B=1$ annihilations. Besides the direct evidence of $B=1$ annihilations, ΣK and ΛK measurements in $\bar{\text{p}}$-d would be very interesting because they would be helpful to test our ideas about the $B=1$ annihilation process, and more importantly, to measure the degree of the hindrance factor (β) for strangeness production. Similar measurements in $\bar{\text{p}}$ nucleus could bring information on the $B=1$ annihilation rate (P_1) in nuclei.

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