POSSIBILITY OF UNUSUAL ANTIPROTON ANNIHILATION ON NUCLEI

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We give indications in favour of an antiproton annihilation by two nucleons inside a nucleus. The decay is investigated in the frame of a statistical model. It is shown that this process can lead to a substantial increase of the strange particle yield.

Introduction. For the last two years, there have been predictions for the outcome of the $\bar{p}$ annihilations on nuclei [1–3], based on the assumption that the basic mechanism is the (point-like) annihilation of the impinging $\bar{p}$ with a *single* nucleon, producing pions, like in free space, each of which initiates a cascade inside the nucleus. In particular, these calculations were aimed at describing the background, on which hopefully would be superimposed signals of more exotic processes, such as the formation of deeply bound antiproton–nucleus states [4].

We want to examine here the possibility of an annihilation mechanism in nuclei implying in the primary stage more than one nucleon. Such a possibility has been put forward some years ago by Rafelski [5], who suggested the picture of the growing of large quark bags. If such an extended quark–gluonic blob is formed, the production of strange mesons would be enhanced [5,6]. Rafelski [7] already pointed out that the $K\bar{K}$ production in the annihilation on deuterium is correlated with a large "spectator" high momentum tail and indicates the possibility of such a process.

We will first present arguments showing that annihilation on two nucleons is far from negligible. Secondly, we will examine the basic properties of such an annihilation, based on a phase space model. We will show that considering a conventional hadronic phase only also yields observables very similar to those obtained in Rafelski's approach.

Probable existence of $b > 0$ annihilations. We assume that, inside a nucleus, the collision of an incoming $\bar{p}$ with a nucleon leads in a first stage to the formation of a hadronic fireball with baryon number $b = 0$. After Hamer [8], we assume that everything will proceed in the hadronic phase. The fireball has a finite lifetime τ and a nonvanishing velocity β_f. Therefore, it may collide with another nucleon inside the nucleus and coalesce with it, forming a $b = 1$ fireball which eventually decays into a number of hadrons inside the nucleus.

We make an estimate of the probability of forming a $b = 1$ fireball, assuming that all the particles ($\bar{p}$, $b = 0$ and $b = 1$ fireballs) are travelling along a straight line. The relevant parameters are the $\bar{p}$ mean free path $\lambda = (\rho_0\sigma)^{-1}$ (ρ_0 is the normal nuclear matter density and σ the $\bar{N}N$ annihilation cross section [9]), τ and the $b = 0$ fireball mean free path $\lambda' = (\rho_0\sigma')^{-1}$, where σ' is the $b = 0$ fireball nucleon cross section. A little calculus leads to the following result:

$$R = \frac{P(b=1)}{P(b=1)+P(b=0)}$$

$$= \frac{\mu}{(\lambda-\mu)\lambda'} \, \frac{-\lambda e^{-l/\lambda} + \mu e^{-l/\mu} + \lambda - \mu}{1 - e^{-l/\lambda}}, \qquad (1)$$

where $P(b)$ is the probability of forming a fireball with baryon number b and where $\mu^{-1} = \Lambda^{-1} + \lambda'^{-1}$, $\Lambda = \gamma_f\beta_f\tau$. In this formula, l is the longitudinal thickness

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Table 1
Relative probability of forming a $b = 1$ fireball.

p_{lab}	$\sigma' = \sigma$		$\sigma' = \sigma/3$	
(GeV/c)	τ = 0.3 fm/c	τ = 1 fm/c	τ = 0.3 fm/c	τ = 1 fm/c
0.4	0.18	0.43	0.07	0.20
0.7	0.19	0.44	0.07	0.21
1.1	0.20	0.45	0.08	0.22
2.0	0.22	0.49	0.09	0.24

of the nucleus seen by the incoming antiproton. In general, $l/\lambda, l/\mu \gg 1$, and eq. (1) simply reduces to

$$R = \Lambda/(\Lambda + \lambda'), \qquad (2)$$

for most of the impact parameters.

With $\sigma \approx 44$ mb/β ($\beta = \bar{p}$ velocity), $\lambda \approx 1.36 \times \beta$ fm. For the σ' cross section, we assume the same value as σ, since both processes involve the collision of two nonstrange hadronic objects leading to many open channels (in table 1, we also consider a value three times smaller). The crucial quantity is the fireball lifetime τ. As a guide, we may consider the lifetime ($\approx$ 1 fm/c) of the g (1690) resonance, which is almost as heavy as a ($\bar{p}p$) system and which decays predominantly into 4 pions. Optical model description of the $\bar{p}p$ annihilation [10–12] would indicate a somewhat smaller lifetime. We have used two indicative values of τ: 0.3 and 1 fm/c. With these values, the calculated ratio R in a nucleus like ^{208}Pb (actually, this ratio does not depend very much on the size of the system) is given in table 1. As one can see, the probability of forming a $b = 1$ fireball is quite sizeable, even for a small lifetime of the $b = 0$ fireball. These figures would be somewhat lowered if short range correlations were taken into account, because it is then improbable to find two nucleons very close to each other. On the other hand, this effect is counterbalanced by the range for the annihilation process.

The decay of the fireballs. Annihilation is a drastic rearrangement of hadronic matter, with an appreciable number of open channels. This suggests quite naturally the application of statistical methods. We will assume that both the $b = 0$ and $b = 1$ fireballs decay statistically into stable hadrons. Our treatment does not rely on thermodynamical considerations relevant to extended systems. Rather, it is based on the idea that, due to the finite fireball mass, the constraints of energy–momentum conservation must be significant, but that, provided the constraints are verified, the decay is governed by phase space. Former studies relying on the statistical bootstrap [13–15] have shown that such an approach reproduces the general properties of low momentum purely pionic $N\bar{N}$ annihilations [8,16–18]. Application is extended here to other channels.

The differential decay width from state i to one final state f is given by [19]

$$d\Gamma_f = \frac{(2\pi)^{4-3n}}{2\sqrt{s}} |T_{if}|^2 \delta^4(P_i - P_f) \prod_{j=1}^{n} \frac{d^3p_j}{2e_j}, \qquad (3)$$

where $s = P_i^2$ is the available (squared) CM energy, where $P_f = \Sigma_j p_j$ is the total four-momentum vector and where $e_j = (p_j^2 + m_j^2)^{1/2}$. The quantity T_{if} is the invariant transition matrix element which, in principle, depends upon the m_j's and other invariants associated with the initial and final states. As usual in statistical models, we assume that T_{if} does not depend very much upon the final states. Therefore, the rate for many observables obtained from eq. (3) by integrating over many final states variables is dominated by the magnitude of the available phase space. For instance, the rate for a given multiplicity can be written (aside from spin and isospin factors) as [19]

$$f_n(\sqrt{s}; m_1, ..., m_n) = C^n R_n(\sqrt{s}; m_1, ..., m_n), \qquad (4)$$

where R_n is the invariant momentum space integral

$$R_n(\sqrt{s}; m_1, ..., m_n) = \int \delta^4(P_i - P_f) \prod_{j=1}^{n} \frac{d^3p_j}{2e_j}. \qquad (5)$$

For equal masses, formula (4) is obtained in the frame of the statistical bootstrap for the case of the linear chain of cluster decay [15].

This method has been used [16] to predict relative multiplicity frequencies in multipion annihilations. We extend below the application of the procedure to channels containing a $K\bar{K}$ pair in the case of $b = 0$ and to more various states of $b > 0$. In principle, a different parameter C could be introduced for each type of particles π, K, N, Y (Λ, Σ or Ξ). We have tried – and succeeded – to work with a single parameter.

The parameter C in (4) has the dimension of (mass)$^{-2}$ (in units $\hbar = c = 1$). To fix a priori the order of magnitude of C, an analogy is made with the non-

Table 2
Pion multiplicities (in %) in $\bar{p}p$ at rest (pionic channels).

n_π	Experiment [20]	Model
2	0.38 ± 0.03	0.36
3	7.8 ± 0.4	5.7
4	17.5 ± 3.0	24.0
5	45.8 ± 3.0	37.4
6	22.1 ± 1.5	24.9
7	6.1 ± 1.0	6.9
8	0.3 ± 0.1	0.7
$\langle n_\pi \rangle$	5.01 ± 0.23	5.05

invariant version of the statistical model, where the factor is V/h^3, V being the "interaction volume" and h, the Planck constant; this suggests that [13]

$$C_0 = \pi r^2/h^2 = 1/4\pi m^2 \tag{6}$$

is the standard, where the characteristic hadronic mass m may be the pion mass, and where r is the corresponding Compton wavelength. We shall take

$$C = \lambda C_0 \, . \tag{7}$$

Applying the model to $\bar{p}p$ annihilation at rest (b = 0 fireball), we find that the value $\lambda = 1.60$ gives the correct mean pion multiplicity and a reasonable division between the various pion multiplicities (see table 2). At the same time, the predictions for kaonic channels are good (see table 3). The total rate of kaonic annihilations is predicted 4.5% in agreement with the experimental result (4.6 ± 1.6)% [22].

The inclusive pion spectrum can also be computed in the assumption of uniform phase space distributions. The prediction turns out rather close to the observed spectrum. It is also reasonably akin to a Boltmann spectrum with T = 105 MeV. This is definitely lower than the temperature obtained in several models for the transition from the quark–gluon plasma to the hadron phase.

The b = 1 fireball. Encouraged by the fit obtained for b = 0 we translate its application to the b = 1 case. The possible final states contain, in addition to a baryon in one of the various possible states (N, Λ, Σ or Ξ), a system of mesons of opposite strangeness.

It is interesting in this context to recall two types of experimental observations: Bizzarri et al. [23] have observed for annihilations at rest in deuterium the clear three-body process $\bar{p}d \to \pi^- p$ and, in addition, various $\Lambda K\pi$'s channels which do not seem to be entirely consistent with K rescattering. Oh et al. [24] have observed, for annihilation on deuterium in flight containing an $K\bar{K}$ pair, a long tail in the momentum distribution of the spectator proton.

The main question for the application of the model is the dependence on the baryon number. On the basis of a result obtained in the frame of the statistical bootstrap model [25], that the proper volume of a particle (or cluster) must be proportional to its mass, we have put

$$C(b=1)/C(b=0) = (1.5)^{2/3} \, . \tag{8}$$

Table 3
Kaonic channels in $\bar{p}p$ at rest [21] (branching ratios × 10^3)

Final state	Columbia	CERN	Model predictions for $K\bar{K}\pi$'s (all charge states)	
K^+K^-	1.1 ± 0.1	0.96 ± 0.08	$K\bar{K}$	2.96
$K^0\bar{K}^0$ (K_SK_L)	0.71 ± 0.10	0.80 ± 0.05		
$K^0_SK^0_S\pi^0$	0.73 ± 0.10	0.78 ± 0.06	$K\bar{K}\pi$	17.9
$K^0K^\pm\pi^\mp$	4.25 ± 0.55	4.25 ± 0.20		
$K^0_SK^0_S\pi^+\pi^-$	2.01 ± 0.26	1.95 ± 0.23	$K\bar{K}2\pi$	19.4
$K^0_SK^0_L\pi^+\pi^-$	2.41 ± 0.36	2.26 ± 0.45		
$K^0_SK^\pm\pi\pi^0$	4.47 ± 0.53	4.69 ± 0.55		
$K^0_SK^0_S\pi^+\pi^-\pi^0$	1.49 ± 0.22	1.10 ± 0.14	$K\bar{K}3\pi$	4.5
$K^0_SK^\pm\pi^\mp\pi^+\pi^-$	0.59 ± 0.08	0.71 ± 0.07		
$K^0_SK4\pi$	~0	~0	$K\bar{K}4\pi$	0.2

Table 4
Predicted branching ratios for $\bar{N}NN$ annihilation ($\sqrt{s} = 3M_n$)

Channel type	Percentage	$\langle n_\pi \rangle$
$N\pi$'s	88.5	4.73
$N\pi$	5.2×10^{-2}	
$NK\bar{K}\pi$'s	2.7	1.16
$\Lambda K\pi$'s	2.9	2.51
$\Sigma K\pi$'s	5.5	2.32
$\Xi KK\pi$'s	0.4	0.39
all	100	4.42

Table 4 gives the relative rates for the final states of the different types. The novel feature of the results is an enhancement of strange channels. On the one hand, the fraction of channels containing a $K\bar{K}$ pair is somewhat reduced compared to the b = 0 case, but on the other hand the channels with one hyperon take up a substantial fraction of the total rate. We predict that 8.8% of the b = 1 annihilations will produce a hyperon. The average number of kaon (S = 1) per annihilation is predicted to be 0.12 compared to 0.05 in the case b = 0. [It is still larger with a b-independent C, cf. eq. (8).]

Let us come back to the experimental results for $\bar{p}d$ annihilation. Bizzarri et al. [23] mention that the behaviour of the "spectator" proton in multipion final states can be interpreted as a superposition of that expected from the deuteron wave function (~84%) and a smooth background (~16%) extending up to the maximum momentum kinematically allowed. Studying $\bar{p}d \to \Lambda K\pi$'s events, these authors have shown that at least a large fraction of these events cannot be described by K^+ rescattering but have to be considered as "three-body annihilations" (b = 1 in our terminology).

According to them, about 10% of the events come from the decay of the b = 1 fireball. The branching ratio predicted in the model for the Λ (including Σ^0) events in 4.7×10^{-2} (see table 4). This leads to a prediction of a rate of 4.7×10^{-3}, while the observed rate is 3.6×10^{-3}, in quite reasonable agreement. The most frequently observed channel types contain 2 and 3 pions besides ΛK, in agreement with the value of $\langle n_\pi \rangle$ predicted in the model. As for the $\bar{p}d \to \pi^- p$ reaction, our model predicts a rate of $\sim 3 \times 10^{-5}$ while the observation is $(0.9 \pm 0.4) \times 10^{-5}$. The orders of magnitude again match.

Discussion. We have given indications which tend to show that occurrence of annihilations inside nuclei implying two (and perhaps more) nucleons is a likely event. Available data for $\bar{p}d$ annihilation is consistent with such a scheme.

The model that we consider here is based on kinematical constraints operating in a pure hadronic phase. The most important consequence is the prediction that strangeness production is favoured in $b > 0$ compared to b = 0 annihilations. This is essentially due to the fact that the transformation of a nucleon into a hyperon requires only 35 to 50% of the energy necessary to create a kaon. In this perspective it is interesting to compare our results with those obtained in refs. [6,26], where the authors assumed that the annihilation gives rise to the formation of a quark–gluon blob. It is convenient here as in ref. [27] to consider the ratio $\bar{R}$ of the antistrange quark to the total antiquark content of the produced particles. In the quark–gluon phase, one has

$$\bar{R} = \bar{s}/\bar{q} = \tfrac{1}{4}\sqrt{\pi/2}\,(m_s/T)^{3/2} \exp[(\mu - m_s)/T] \, , \tag{9}$$

where m_s is the mass of the strange quark. For zero chemical potential and $m_s/T \approx 1$ to 2, one has $\bar{R} \approx 0.12$. For a non-zero baryon density ($\mu \neq 0$), this ratio is somewhat larger. Experimentally, annihilation at rest gives (by using pion and kaon multiplicities) $\bar{R} = 0.009$. This result is accounted for in our model (see tables 2 and 3). The small value reflects the large difference between pion and kaon masses. If, on the other hand, a quark–gluon model is applied to fit the $\bar{N}N$ annihilation data, it is then necessary to assume that the strange quark density is not saturated, by a fraction $F \approx 0.1$–0.2 [26].

When we consider b = 1 annihilation in our model, we find a ratio

$$\bar{R} = \frac{f(NK\bar{K}) + f(\Lambda K) + f(\Sigma K) + 2f(\Xi KK)}{\langle n_\pi \rangle + f(NK\bar{K})} = 0.027 \, .$$

This is a substantial increase from the b = 0 case. For b = 2, we find $\bar{R}$ = 0.037. We recall that these results are obtained with the assumption that the strangeness production is saturated in a b = 1 hadronic fireball.

This is not completely sure, even if we have shown that this holds for $b = 0$.

Let us now come to the possible observation of $b > 1$ annihilations. The difficulty is that the properties of the annihilation may be distorted by the subsequent cascade initiated by the products of the annihilation. Fortunately, the $(S = -1)$ kaons do not interact very strongly with the nucleons, and they can scatter elastically only. Therefore the $(S = -1)$ content is preserved by the intranuclear cascade. On the other hand, at the energies covered by LEAR, the energy of the annihilation pions is not sufficient to produce kaons through $\pi N \to \Lambda(\Sigma)K$ reactions with significant rate. An experimental strangeness production cross section larger than the one corresponding to the ratio $\bar{R} = 0.009$ of the $\bar{N}N$ annihilation would signal a $b > 0$ annihilation. Let us remark that a $b = 1$ annihilation rate of the order of 25% would yield an observed average $\langle \bar{R} \rangle \approx 0.015$, i.e. substantially larger than the $b = 0$ ratio. Another signal is the presence of a high energy tail in the proton spectrum. Indeed, $b = 1$ annihilations produce protons with a temperature of $T \approx 110$ MeV. The nucleus is not completely transparent to such protons, but ~30–50% of them would emerge out of medium heavy targets like Ca or Ag. These protons would then be observable, since the so-called "participant" protons ejected during the cascade will have a rather lower temperature [2,3], especially at low energy. Finally, very special events, like ones showing a very fast pion and a very fast nucleon travelling in opposite directions would be an indisputable indication of a $b = 1$ annihilation.

In conclusion, we have shown, using plausible arguments that $b > 1$ annihilations inside nuclei are rather probable. Their most important property is the enhancement of the strangeness production compared to free $\bar{N}N$ annihilations. We thus arrive qualitatively at the same conclusion as the one obtained in ref. [5] assuming the formation of a quark–gluon blob. But we stress that our result only comes from kinematical constraints inside the hadron phase. The difference between the two pictures could be clarified by looking at the high energy tail of the nucleon spectra.

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