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Medium effects in antiproton annihilation on nuclei. A phase space approach

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A phase space model for meson production in antiproton–nucleon annihilation in flight is proposed and shown to be very successful. The distortion of phase space when annihilation occurs inside a nucleus is studied, assuming that the meson masses are changed inside nuclear matter. Modifications of particle multiplicity are calculated.

Statistical models have been applied to antiproton–proton annihilation for a long time, justified by the fact that, considered inclusively, annihilation into pions displays statistical properties. A version including channels containing a $K\bar{K}$ pair has been used [1] for annihilation at rest. We present here a version for annihilation in flight, extending the set of "stable" mesons to $\{\pi, \eta, \eta', \omega, K, \bar{K}\}$. All the other mesons (of short lifetime) are assumed to decay without distorting the phase space of the stable mesons. The different treatment applied here to the two vector mesons, ρ and ω, is justified by the difference of an order of magnitude of their widths. As for φ production, it is neglected by reference to the OZI rule.

The basic premise of our approach is the assumption of uniform population of phase space. This is justified by experimental results. For example, even at 4.6 GeV/c incident antiproton momentum [2] the angular distribution of the pions in the CM system does not deviate much from isotropy and is anyway forward–backward symmetric, except for the highest energy pions. Similarly, in antiproton–proton interactions at 7.2 GeV/c [3], the angular distribution of the ω meson in the $\omega\pi^+\pi^-$ channel is practically uniform, whereas in the $\bar{p}p\omega$ channel it is sharply peaked.

The underlying picture of our model is that the annihilating antinucleon–nucleon system forms an intermediate state, a "compound" or fireball with zero baryon number which subsequently decays into a number of channels, in a way essentially governed by phase space. The cross sections for the different final states are given by

$$\sigma_i = b_i \sigma^* , \tag{1}$$

where σ^*, the cross section for fireball formation, is taken here equal to the empirical total annihilation cross section. The branching ratios b_i at CM energy E are given by

$$b(E; n\pi, p\eta, q\eta', r\omega) = N g_\eta^p g_{\eta'}^q g_\omega^r (\lambda C_0)^{n+p+q+r-1} \times R_{n+p+q+r}(E; nm_\pi, pm_\eta, qm_{\eta'}, rm_\omega) \tag{2a}$$

for non-strange channels; for channels containing a $K\bar{K}$ pair by

$$b(E; K\bar{K}, n\pi, p\eta, q\eta', r\omega) = N\beta_s g_\eta^p g_{\eta'}^q g_\omega^r (\lambda_s C_0)^{n+p+q+r+1} \times R_{n+p+q+r+2}(E; 2m_K, nm_\pi, pm_\eta, qm_{\eta'}, rm_\omega) . \tag{2b}$$

The production of two $K\bar{K}$ pairs is also considered, although the contribution is small:

$$b(E; KK\bar{K}\bar{K}, n\pi, p\eta, r\omega) = N\beta_s^2 g_\eta^p g_\omega^r (\lambda_s C_0)^{n+p+r+3} \times R_{n+p+r+4}(E; 4m_K, nm_\pi, pm_\eta, rm_\omega) . \tag{2c}$$

In relations (2), N is an overall normalization factor, $g_{\eta'}$, $g_{\eta'}$, and g_ω are statistical weights (with respect to g_π taken equal to 1), β_s is the hindrance factor associated to strangeness production, $C_0 = (4\pi m_\pi^2)^{-1}$ is the dimensional parameter of the model and the quantities R are the invariant momentum space integrals of ref. [4]. A version with common features has been applied to protonium decay [5], taking account in that case of P-, C- and G-parity conservation laws and initial state interactions typical of annihilation at rest. These refinements are not necessary for annihilation in flight, where many partial waves contribute.

The parameters λ and λ_s determine the mean pion multiplicity in non-strange and strange channels respectively. As the antiproton momentum increases, some peripheralism sets in progressively. This, among other features, manifests itself by the fact that the experimental pion multiplicity does not increase as fast as predictions with a fixed value of λ foresee. We account for this behaviour in our model by allowing for a smooth energy dependence of λ

$$\lambda(E) = \lambda(E_0)\exp[-A(E-E_0)] , \qquad (3)$$

where E_0 is equal to $2m_N$.

Furthermore, a different value for λ and λ_s is demanded by experiment, but their difference decreases when the annihilation energy increases. We have taken the form

$$\lambda_s(E) = \lambda(E) + [\lambda_s(E_0) - \lambda(E_0)] \times \exp[-B(E-E_0)] . \qquad (4)$$

The parameter β_s is kept independent of the antiproton momentum. The increase of strange meson production thus comes from the opening of phase space only. Finally the choice $g_\eta = g_{\eta'}$, has been made for simplicity. On the other hand, in order to reproduce correctly the η and ω multiplicities, we were forced to keep g_η and g_ω as free parameters. It turned out that a good agreement was achieved with $g_\eta = \frac{1}{2}$ and $g_\omega = 3$, which correspond to their spin statistical factor relative to the π (if one considers as in ref. [6] that the $s\bar{s}$ content ($\sim 50\%$) of the η reduces by half its formation probability). However, these parameters can be viewed as dynamical parameters controlling the production rates of η's and ω's, like β_s controls K production.

To compare the model output with the data, we use a definite prescription to distribute the different charge distributions among a definite number of π's and K's. For the case of a pair of πs (K's) the isospin statistical ratio $\pi^0\pi^0/\pi^+\pi^- = \frac{1}{5}$, $(K^0\bar{K}^0/K^+K^- = 1)$ is used, while for the case of more than two partners, relative weights of the form $(n_+!n_0!n_-!)^{-1}$ are used.

With the values of g_η and g_ω cited above, the fitting procedure is performed by varying the parameters $\lambda(E_0)$, $\lambda_s(E_0)$, β_s, A and B. The best values are $\lambda(E_0) = 1.15$, $\lambda_s(E_0) = 1.95$, $\beta_s = 0.30$, $A = 0.40\ \text{GeV}^{-1}$ and $B = 0.36\ \text{GeV}^{-1}$. With these values, we achieve a good fit of cross sections for 18 exclusive channels (15 of antiproton–proton, 3 of antiproton–neutron), where a sufficient set of data exists in the momentum range up to 6 GeV/c.

The results are displayed in figs. 1–3. The overall agreement is striking. The energy dependences are rather easy to understand. The gradual decrease in low multiplicity channels is due to the smooth decrease of the annihilation cross section and to a progressive opening of phase space. The increase in high

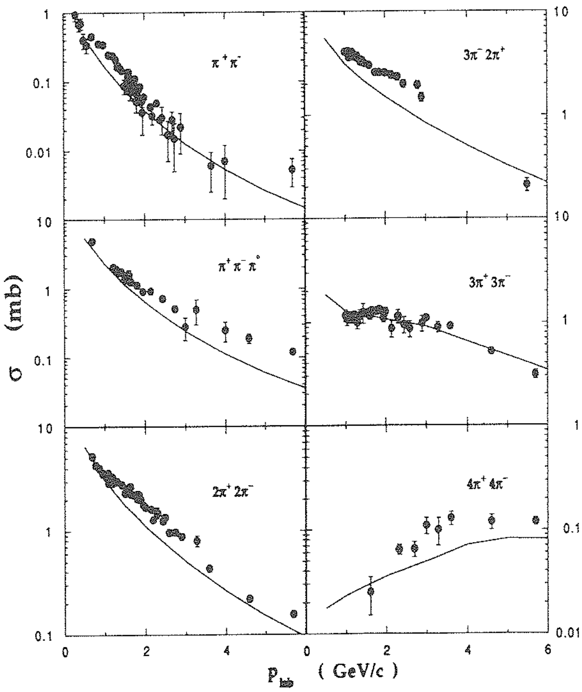

Fig. 1. Cross sections for $\bar{p}p$ and $\bar{p}n$ annihilations into various channels, indicated in the boxes. The lines correspond to the output of our model.

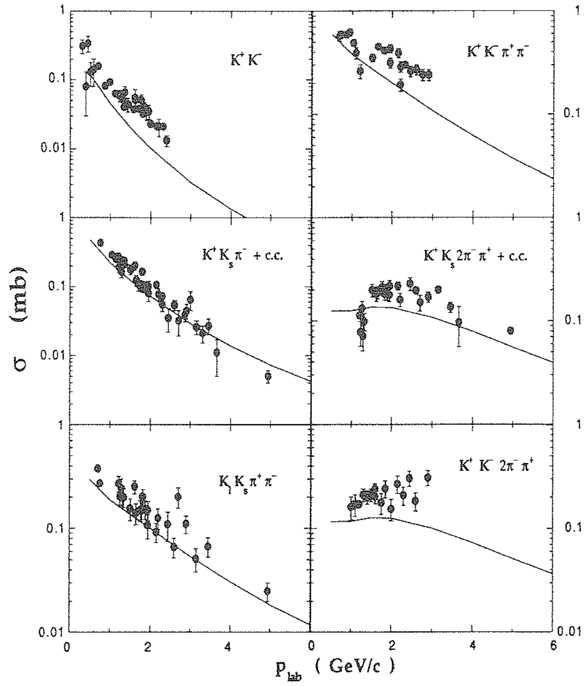

Fig. 2. Same as in fig. 1 for the indicated channels.

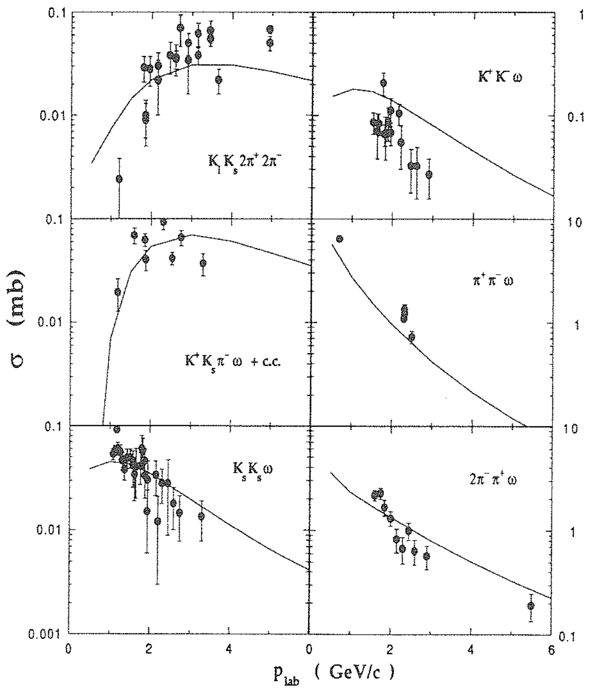

Fig. 3. Same as in figs. 1 and 2.

multiplicity channels or in channels with heavy particles is caused by a smooth threshold effect.

Having demonstrated that antinucleon–nucleon annihilation in free space is dominated by phase space, we turn to the interesting problem of the possible modifications when annihilation occurs inside a nucleus. The first question to be addressed is to know whether particle multiplicities, *prior to rescattering*, are modified, due to the nuclear environment. Here, we investigate the most trivial effects one can think of.

The first one concerns the available energy E. Inside nuclear medium, both the nucleon and the antiproton have potential and kinetic energy. One may admit that the antiproton has a constant (kinetic+potential) energy. The target nucleon energy is equal to its binding energy, i.e. a few tens of MeV at the most. Compared to free space, the total available energy is lowered by this amount. The effect is thus practically negligible.

The second most obvious effect comes from the distortion of phase space. There are stronger and stronger indications [7–12] that the meson masses are modified when they are embedded inside a nuclear medium. Most studies along these lines are based on Nambu–Jona-Lasinio models, which related the mass modification to partial restoration of chiral symmetry inside nuclear matter. Unfortunately, the predictions of these models cannot be taken at the quantitative level, since: (i) these models are not renormalizable; (ii) they then imply a regularization procedure, which is arbitrary to some extent; (iii) the definition of some meson fields is not unique in these models [8,12]. Nevertheless, although there are differences between the results of the various groups, even on the sign of the mass modification, all of them agree roughly on the order magnitude of the modification of the meson masses inside nuclear matter. In view of this situation, instead of using the results of one or the other group, we prefer to adopt a general and pragmatic approach. We assume that the masses of the mesons of interest (here π and K primarily) may be lowered (this is the most likely modification) by some reasonable amount and we look at the corresponding changes of the particle multiplicities within the model described above. Our main results are contained in fig. 4. The π multiplicity is not charged significantly when the π mass is decreased by

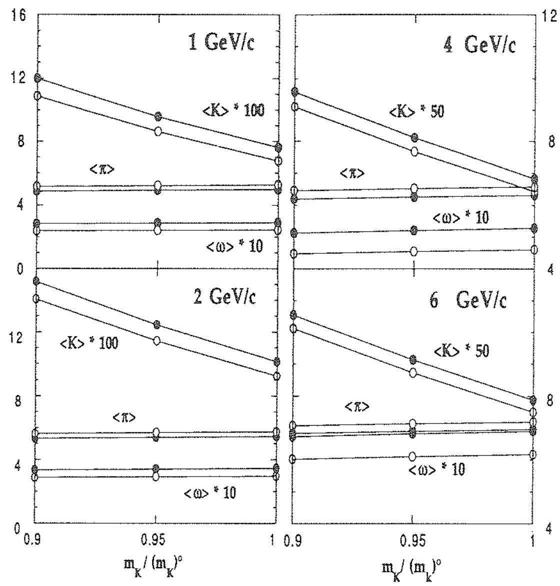

Fig. 4. π, K and ω average multiplicities in annihilation at 1, 2, 4 and 6 GeV incident $\bar{p}$ momentum for different assumptions for the π and K masses in the nuclear medium. The K mass is varied between 0.9 and 1.0 times its free space value. The full and open dots correspond respectively to 1.0 and 0.8 times the free space value for the π mass. Note the change of scale from the left to the right parts of the figure. Note also the various factors multiplying the K and ω multiplicities in order to fit inside the boxes.

20% (difference between full dots and open dots in fig. 4). In fact, the antinucleon–nucleon system decaying largely into relativistic pions, the situation for the latter is very much akin the one of a statistical system of massless particles, except for the highest multiplicities. The latter are enhanced by a lowering of the π mass. As a consequence, the fraction of the strange channels is reduced. The change of the ω abundance has the same origin.

More interestingly, the modification of the K mass has a marked influence on the average K multiplicity. Diminishing the K mass increases the importance of the strange channels substantially, for the same reason as discussed above. One can show that, in the limit of vanishing π mass (and neglecting ω and η production), the following approximate relation holds

$$m_K \frac{\partial\langle K\rangle}{\partial m_K} \approx -\frac{8m_K^2}{3E^2} \times (1-\langle K\rangle)\langle K\rangle\overline{\ell(\ell+1)(\ell+2)}\,, \qquad (5)$$

where $\langle K\rangle$ is the kaon multiplicity and ℓ is the number of π's accompanying the $K\bar{K}$ pair. Formula (5) embodies the qualitative physical dependence upon the parameters. Furthermore, it is correct semiquantitatively: it predicts the LHS to be equal to ~0.3, 0.5, 0.8 and 1.0 at 1, 2, 4 and 6 GeV/c respectively, whereas the exact calculation yields 0.5, 0.6, 0.55 and 0.55. Fig. 4 shows that, under a given modification of m_K, the π multiplicity is changed significantly less than for the K and the ω multiplicity is only slightly decreased. In fact, one can show that, if at most one ω or one $K\bar{K}$ pair is produced, the following relation holds:

$$m_K \frac{\partial\langle \omega\rangle}{\partial m_K} = -\frac{\langle\omega\rangle}{1-\langle K\rangle} m_K \frac{\partial\langle K\rangle}{\partial m_K}\,. \qquad (6)$$

This indicates that at 4 GeV/c the ω multiplicity is lowered by 0.03 when the mass of the K is diminished by 10%, in agreement with fig. 4.

We have considered a decrease of the masses. Had the masses to be increased, the effects would be reversed, for the range of the mass modification considered here.

The range of densities probed by antiproton annihilation is rather limited at low momentum. But in central collisions at 4 GeV/c, the antiproton annihilates, on the average, at a point where the density is 0.8 times normal nuclear matter density. The possible size of meson mass modification at this density is around the value envisaged in fig. 4. According to ref. [11], it might even be larger (~30%), but the issue is not settled yet.

The most important of our results, for a possible experimental check, is the enhancement of strangeness production. K abundances are not modified by the rescattering process (this is not true for $\bar{K}$). However, other possible sources of strangeness enhancement have been proposed [13,14] and the scarce experimental data (at low momentum and for light target masses) seems rather to indicate an hindrance of strangeness production [15]. Further data are needed to draw any reliable conclusion.

In summary, we have worked out a successful phase space model for particle production in antiproton–nucleon annihilation. We have studied the distortion of the phase space when annihilation occurs inside nucleus. The most important changes are coming from the K mass modification. The expected size of the latter is large enough to yield detectable effects.

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