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Role of mesonic resonances in antiproton annihilation on nuclei

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The implications of η and ω production in antiproton-nucleus annihilation are examined by means of a simplified cascade scheme. The intranuclear absorption of the pions "hidden" in the resonances is predicted smaller than the average pion absorption measured by experiment. It is also pointed out that the reaction $\omega N \rightarrow \Lambda K$ might be a significant source of Λ production in antiproton-nucleus interactions. The possibility of studying η-nucleus interactions is examined.

The annihilation channels make an important part of the antiproton-nucleus interaction at low energy, e.g., in the low energy antiproton ring (LEAR) regime. Usually, the following mechanism is assumed: the incident antiproton annihilates on a single nucleon (generally at the nuclear periphery), producing pions; some of them leave the nucleus without interacting, the others being scattered or absorbed by the nucleus, through a spallation process, followed by evaporation and/or fission for heavy targets. The most sophisticated description of this dynamical scheme is embodied by the so-called intranuclear cascade (INC) model (supplemented by evaporation). The general agreement with experiment is fair,[1–4] although the data are sometimes of low accuracy. But possible deviations are interesting, as they may signal a departure of the annihilation process from the conventional picture.

In the nuclear medium, the intranucleon distance is hardly larger than characteristic lengths for hadronic sizes and processes; this suggests that the INC may be only a first approximation. In particular, it is well known that $\bar{p}N$ annihilation produces mesonic resonances rather copiously.[5] For broad resonances such as $\rho, f, b, \ldots,$ with a lifetime of ~ 2 fm/c or less, the assumption of instantaneous decay is probably a quite reasonable and legitimate simplification. But, to the contrary, some of the pions which are observed as decay products in free space $\bar{p}p$ annihilations are in fact first produced in the form of long-lived resonances, mainly η and ω. Their decay length is larger than the internucleon distance, and therefore their evolution involves interaction with the nuclear medium. Here we want to analyze the implications of their presence in two respects: (i) the influence on the pion multiplicity, a quantity which is currently attracting attention;[6,7] (ii) the possibility of studying the interaction of these resonances with nuclear matter. Let us consider the formation and the interactions of η and ω.

The inclusive production rates for $\bar{p}p$ are

$$\langle \eta \rangle = 0.07 \pm 0.01, \quad \langle \omega \rangle = 0.28 \pm 0.11 \ . \tag{1}$$

The first value is for annihilation at rest,[8] while the second[9] one refers to $\bar{p}$'s from rest to ~ 700 MeV/c; these rates do not seem to vary much with energy.[9] The η spectrum seems roughly compatible with a thermal spectrum ($T = 110$ MeV), forced to smoothly vanish at the $\eta\pi\pi$ kinematical limit, supplemented with a contribution of the $\eta\rho$ and $\eta\omega$ channels.[10] Nothing is known about the ω spectrum (we assume in the following a similar dependence). It is not known either whether the η or ω events have special (e.g., topological) properties or not.

We study a simple model for the propagation of the resonances, assuming that they can decay or disappear through the reactions

$$\eta N \rightarrow \pi N \ , \tag{2a}$$

$$\omega N \rightarrow \pi N \ . \tag{2b}$$

We make a numerical simulation of this model. We first choose an impact parameter for the antiproton and determine its penetration by providing it with a mean free path as usual. At the annihilation point, a resonance is formed with the experimental frequency and goes away in a direction which is picked up at random in the annihilation frame, and with a momentum which is consistent with the spectrum already discussed. The nuclear radius is taken from the systematics of Ref. 11. If L is the length of the resonance straightline trajectory inside the nucleus, the reaction and decay probabilities are given by

$$P_i = \frac{\lambda}{\lambda_i}(1 - e^{-L/\lambda}), \quad i = r, d \ , \tag{3}$$

where

$$\lambda_r = \frac{1}{\rho\sigma}, \quad \lambda_d = \frac{1}{\beta\gamma\tau}, \quad \frac{1}{\lambda} = \frac{1}{\lambda_d} + \frac{1}{\lambda_r} \ . \tag{4}$$

Two assumptions underlie our simulation: (1) the global process does not disturb the nuclear medium very much; (2) the elastic scattering of the resonance does not meaningfully alter the reaction probability. The reaction cross section σ is obtained by detailed balancing the $\pi^- p \rightarrow \eta(\omega) n$ reactions.[12]

Influence on pion absorption. The reaction probability is given in Fig. 1(a) as a function of the mass number A for 608 MeV/c $\bar{p}$'s and in Figs. 1(b) and 1(c) as a function of the $\bar{p}$ momentum for the ^{12}C and ^{238}U cases, respectively. To relate this with the pion absorption, it is interesting to define the absorption probability of the "equivalent" pions, i.e., those which are contained initial-

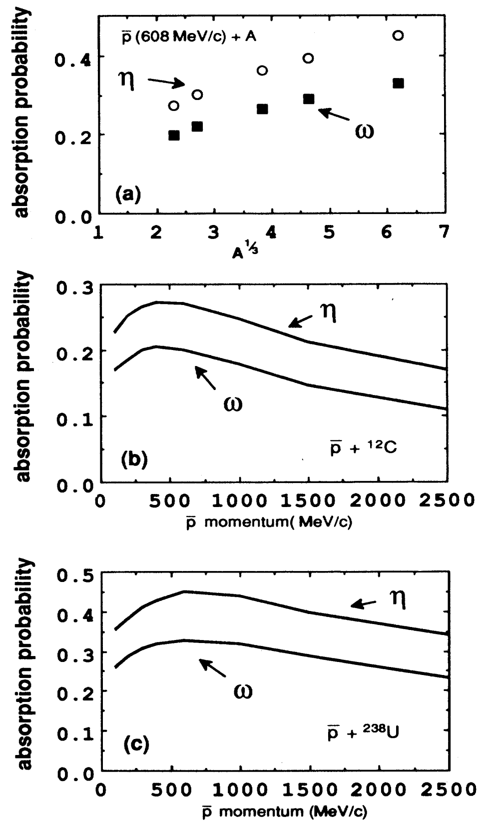

FIG. 1. Absorption probability of η, ω (per resonance) vs target mass number at $\bar{p}$ momentum 608 MeV/c [part (a)] and vs $\bar{p}$ momentum for ^{12}C [part (b)] and ^{238}U [part (c)] targets.

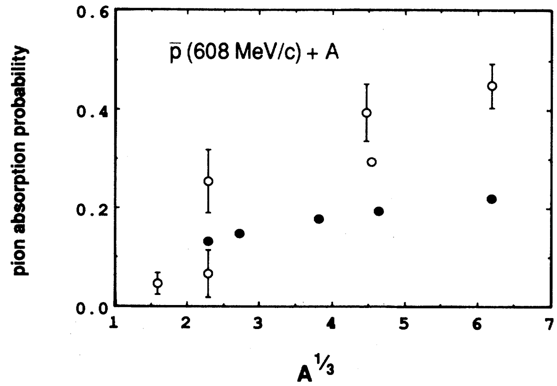

FIG. 2. Absorption rate per annihilation pion (at $\bar{p}$ momentum 608 MeV/c). Open circles: F_π, experiment [Eq. (7)]; filled circles: f_π, our calculation for the pions in η and ω [Eq. (6)].

ly in the resonances. Their multiplicity is given by

$$\langle n_\pi \rangle = 2.90\langle \omega \rangle + 2.22\langle \eta \rangle \ , \tag{5}$$

where the coefficients represent the mean number of pions from the decay of the resonances. The absorption rate per such pion is then given by

$$f_\pi = \langle n_\pi \rangle^{-1}[1.90\langle \omega \rangle P_r(\omega) + 1.22\langle \eta \rangle P_r(\eta)] \ . \tag{6}$$

In Fig. 2, we compare it with the global experimental absorption

$$F_\pi = 1 - \langle N_\pi \rangle / \langle N_{\text{prim}} \rangle \ , \tag{7}$$

where N_π is the experimental pion multiplicity and N_{prim} is the primordial pion multiplicity (any pion issued from the annihilation, free or contained in resonances), calculated from $\bar{p}p$ and $\bar{p}n$ data. Clearly, pions "hidden" in resonances suffer less absorption than "real" pions.

In order to quantify the effect of resonances on pion absorption, we have to also consider the creation of resonances by rescattering of primordial pions $[\pi N \rightarrow \eta(\omega) N]$. Let us call $P_c(\eta)$ $[P_c(\omega)]$ the probability for creation of an $\eta(\omega)$ by a pion. This can be evaluated in a way similar to P_r and P_d [Eq. (3)]. Then the variation of the pion final multiplicity, entailed by the role of the resonances is given (in first order in creation and annihilation) by

$$\Delta N_{\text{fin}} = \langle n_\pi \rangle (F_\pi^{(0)} - f_\pi) + (\langle N_{\text{prim}} \rangle - \langle n_\pi \rangle) \times [1.22 P_c(\eta) + 1.90 P_c(\omega)] \ , \tag{8}$$

where $F_\pi^{(0)}$ is the average absorption probability for a free pion. The latter is not known, but can be replaced in terms of F_π. Noticing that one should have

$$\langle N_\pi \rangle = \langle N_{\text{prim}} \rangle (1 - F_\pi^{(0)}) + \Delta N_{\text{fin}} \ , \tag{9}$$

one readily gets, with the use of Eq. (7)

$$\Delta N_{\text{fin}} = \frac{\langle N_{\text{prim}} \rangle \langle n_\pi \rangle}{\langle N_{\text{prim}} \rangle - \langle n_\pi \rangle} (F_\pi - f_\pi) + \langle N_{\text{prim}} \rangle [1.22 P_c(\eta) + 1.90 P_c(\omega)] \ . \tag{10}$$

Table I gives the values of ΔN_{fin} (obtained with the experimental values of F_π) as well as the global number of absorbed pions. One sees that the explicit introduction of resonances *decreases* the absorption. (Note, however, the inconclusive results for ^{12}C, due to the existence of two contradictory measurements[1,13] of $\langle N_\pi \rangle$ for this case.) Therefore this effect could not help to correct the lack of absorption observed in some models.[2,6]

The possibility to study η-nucleus interactions. Because

TABLE I. Estimate of the change in final pion multiplicity (ΔN_{fin}) due to the presence of mesonic resonances. For comparison, the number of absorbed pions, extracted from experiment, is also given.

	^{12}C (Ref. 1)	^{12}C (Ref. 12)	^{89}Yt (Ref. 1)	^{98}Mo (Ref. 1)	^{238}U (Ref. 1)
ΔN_{fin}	0.161 ± 0.077	-0.065 ± 0.057	0.256 ± 0.069	0.137	0.289 ± 0.054
$N_{\text{abs}}^{\text{exp}}$	1.29 ± 0.32	0.33 ± 0.24	2.00 ± 0.29	1.50	2.27 ± 0.23

of the huge antiproton annihilation cross section and the copious resonance production, the use of antiproton beams is a potentially interesting tool to study resonance-nucleus interactions. A rate of 10^7-10^8 interactions will easily be attained in the near future. The first question is how many resonances can be detected. This is given by Fig. 3. In Fig. 3(a), we give the number of resonance absorptions [Eqs. (2a) and (2b)] and creations [$\pi N \rightarrow \eta(\omega)N$]. Taking account of the possible decay inside the nucleus, we obtain the number of resonances escaping from the nucleus [Fig. 3(b)]. The case for ω is largely dominated by decay (since at least one of the decay pions is very likely to rescatter, only the surviving ω's are counted); for η, we find that the net effect of the nuclear interactions on the final abundance is small. We have made a calculation to get an idea of a possible effect of a modification of the $\eta N \leftrightarrow \pi N$ cross sections in the nuclear medium. The multiplication of these cross sections by a factor 3 gives a sizable effect, which goes in the direction of a smaller final abundance [see Fig. 3(b)].

Recently, it has been suggested[14] that the ηN interaction could be sufficiently strong and attractive to guarantee the existence of η-bound nuclear states in medium-weight and heavy nuclei. So far, they have not been detected. This may be due to a renormalization of the ηNN^* coupling constant[15] or to unfavorable kinematical conditions.[16] Indeed, one needs to create an η with low momentum inside the nucleus to have a chance to build this possible bound state. The most favorable case with a pion beam is at the proximity of the threshold (≈ 750 MeV/c), the yield of slow η's falling rapidly when the pion momentum rises. We look briefly at the situation with $\bar{p}$ beams as a source of η particles. With the available beams nowadays, $\bar{p}$ annihilation delivers slow η's ($p \leq p_F$) at essentially the same rate per incident particle as a 750 MeV/c pion beam, but the yield of slow η's stays fairly constant over a broad band of incident momenta ($\sim 0-1000$ MeV/c). The difficulty lies in the detection of the η nuclei. The lifetime is rather short, so that it would be difficult to isolate the decay products from the other ejectiles. We found that the reaction $\eta N \rightarrow \pi N$ generates high-energy ($p \geq 1$ GeV/c) protons; these protons, however, are indicative of the presence of η and not only of its possible bound states. Furthermore, the estimated rate does not significantly rise above the one expected from the extrapolation of the measured proton spectrum.[1]

Another possible signal of the presence of η nuclei is given by the mesonless decay $\eta NN \rightarrow NN$. The signature of such events is a concentration of events in the scatter plot $d^2\sigma/dE\, d\cos\theta$, E being the value of the invariant mass of pp pairs and θ the laboratory angle between the proton momenta, around $E = m_\eta$, $\cos\theta = -1$. From a comparison with the output of an intranuclear cascade calculation,[6] which fits the inclusive spectra,[1] we find that a possible signal will be lost in the background of the pairs of protons produced in the cascade process.

Importance of resonances in lambda production. Let us mention another possible consequence of η and ω production and interaction in $\bar{p}$ nucleus annihilation. Reactions such as

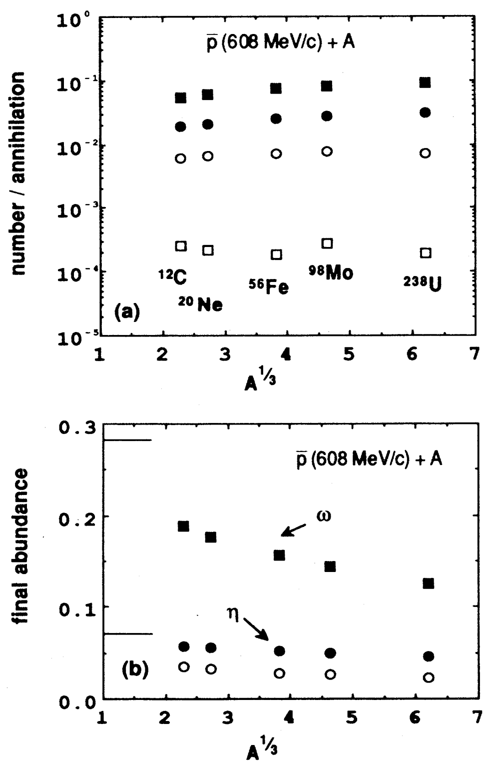

FIG. 3. (a) Number of resonances absorbed (filled symbols) and created by pion rescattering (open symbols) per annihilation event versus target mass number ($\bar{p}$ momentum 608 MeV/c); square, ω; circles, η. (b) Final abundance of resonances versus target mass number. The primordial abundances [Eq. (1)] are indicated by the horizontal segments. For η the filled circles refer to the normal calculation; the open ones to the case when the cross sections are multiplied by 3.

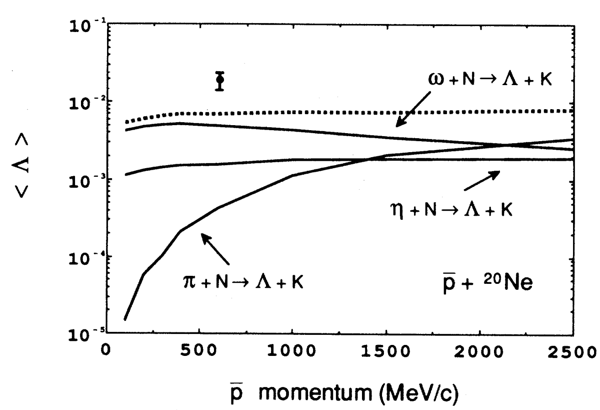

FIG. 4. Estimate of the mean number of Λ hyperon produced in ^{20}Ne per $\bar{p}$ annihilation by the indicated processes (full curves); the dotted curve gives the sum of the three contributions. The measurement of Ref. 21 is indicated by the dot.

$$\eta N \rightarrow \Lambda K \ , \tag{11a}$$

$$\omega N \rightarrow \Lambda K \ , \tag{11b}$$

can increase the strange particle yield, a matter under present debate.[7,17,18] We make an estimate of Λ production rate as follows. We assume that the reactions $\pi N \rightarrow \pi N$, ηN, and ΛK mainly proceed through N^* formation, with N^* partial widths proportional to the c.m. momentum, and apply detailed balance; we have

$$\frac{\sigma(\eta N \rightarrow \Lambda K)}{\sigma(\pi N \rightarrow \Lambda K)} = \frac{p_\pi^*}{p_\eta^*} \ , \tag{12}$$

at a given c.m. energy; a similar relation holds for ω. In Fig. 4 we show the mean number of Λ expected per annihilation in ^{20}Ne as the result of: (a) primordial pion rescattering ($\pi N \rightarrow \Lambda K$); (b) production by η (11a); (c) production by ω (11b). For the sake of comparison, the Λ yield for direct production in the annihilation vanishes at ~ 600 MeV/c (since it is below the $p\bar{p} \rightarrow \Lambda\bar{\Lambda}$ threshold) and amounts to ~ 0.02 at 4 GeV/c, according to Ref. 19. One sees that at low $\bar{p}$ momenta the ω-induced production dominates. The total contribution of the three mechanisms amounts to about half of the experimental value; production by resonance thus appears as a possible process competing with annihilation on two nucleons, another mechanism which has been proposed as a source of hyperon production, in $\bar{p}$ nucleus annihilation. Since an average yield $\langle \Lambda \rangle \approx 0.05$ per multinucleon annihilation is predicted in the literature,[20] a frequency of $\sim 20\%$ for this kind of process could account for the remaining discrepancy in Fig. 4. A more detailed examination of the characteristics of the different processes is clearly needed.

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