Antiproton Physics»
T. Bressani, F. Iazzi and G. Pauli (Eds.)
SIF, Bologna 1990

N.P. Conference Proceedings. [illegible]
"Intense Hadron Facilities and
Antiproton Physics"
T. Bressani et al,
SIF, Bologna (1990)

MODELS FOR ANTIPROTON ANNIHILATION ON NUCLEI

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ABSTRACT

The intranuclear cascade model for antinucleon annihilation on nuclei is reviewed. The transition of an evaporation to a multifragmentation regime for the target response is discussed. Models for the annihilation on several nucleons and possible signatures are examined. The present experimental data are shortly discussed from this point of view. The possibility of studying mesonic excitations in nuclear matter through annihilation on nucleus is briefly investigated. The interest of the 1-10 GeV range is particularly emphasized.

1. INTRODUCTION

In this review, we will present the status of our understanding of the phenomena and observations associated with annihilation of antinucleons on atomic nuclei. We will elaborate on the reasons to go on with the study of these processes. We can summarize them as follows : (i) the antinucleon annihilation is a unique and peculiar way to deliver negative baryon number, excitation energy, multipion excitations (and mesonic or baryonic, perhaps exotic, resonances) to the nucleus. (ii) it allows new (unusual) annihilation mechanisms. We will pay much attention to the possible signature of these mechanisms. In particular we will critically examine strangeness production in this perspective. Finally, we will draw attention on the interest of the one to ten GeV antiproton energy range.

2. REVIEW OF THE N$\overline{\mathrm{N}}$ ANNIHILATION DATA

2.1. Sketch of the experimental data

We refer to recent reviews of the subject for detailed information.[1,2] We just here remind the main aspects. At rest and low energy, the most important results can be summarized as follows :

(a) the annihilation cross-section is very large and involves many final states ;

(b) the annihilation leads to the formation of 5 pions on the average, with a large dispersion, however ;

(c) the pions show a thermal spectrum, which can be characterized by a temperature of $T \cong 110$ MeV ;

(d) the final states containing strange particles amount to 5 % of the total annihilation cross-section.

2.2. Statistical vs dynamical picture

The bulk of experimental data for $\overline{\mathrm{N}}$N annihilation is consistent with the formation of an intermediate state with B=0 quantum number and ~ 2 GeV excitation energy within a volume of typical hadronic size, which decays in many possible mesonic final states according to available phase space :

$$\overline{\mathrm{N}}\mathrm{N} \rightarrow (\mathrm{M})^* \rightarrow n\pi.$$

There are however some systematic deviations from this simple picture, the most prominent of which is the so-called suppression of strangeness production.[3] One is forced to introduce a hindrance factor $h \approx \frac{1}{6}$ in the statistical model in order to comply with the observed strange particle yield, which would otherwise be of the order of 30 %. This hindered strangeness production is not proper to $\overline{\mathrm{N}}$N only, but seems to be present in all low energy hadronic physics. It has been substantiated by Dosch and Gromes[4], who describe meson production as arising from a Schwinger mechanism for $q\bar{q}$ creation in a chromoelectric field. This naturally introduces a q-mass dependence in the transition matrix element in addition to the trivial dependence in the phase space integral embodied by the statistical model.

The search for deviations from the statistical picture has not been very much successful. To be short, the only indications are : (i) the so-called annihilation graphs are probably dominant ; (ii) the effective interaction is probably mediated by a color singlet gluon-like exchange. This does not give much light on the structure of the intermediate state : is it alike a meson of which it has the quantum numbers or does it have a much more complex structure ? We do not have any answer yet. (iii) the decay of (M)* goes predominantly through a succession of two-body decays into, at each step, the channel with the lowest Q-value. This feature is responsible for the production of η and ω-mesons with a rate of ~ 0.07 and ~ 0.30, respectively.

3. RESPONSE OF THE NUCLEUS TO ANTINUCLEON ANNIHILATION

3.1. The conventional picture

The antinucleon annihilation on a nucleus is conventionally viewed as follows : the antinucleon annihilates on a single nucleon, basically at the nuclear surface, giving birth to a few pions, with the same properties as in free space. The pions can rescatter in the target. The complicated process of the annihilation and of the subsequent multiscattering process is usually handled by the Intranuclear Cascade (INC) model which, in fact, simulates the successive collisions between pions and nucleons. This model gives a satisfactory description of the gross features of the experimental data, mainly p, π, d,... inclusive cross-sections, but also some correlation data (see refs. 2, 5 for a review).

According to the INC model, the antinucleon-nucleus annihilation can be viewed as a multispallation process followed by ordinary evaporation, as sketched in figure 1. For a few tens of fm/c, the pions scatter on nucleons, ejecting some of them. After this process is over, the remaining excitation energy (about 150 MeV for a nucleus like ^{98}Mo) is more or less thermalized and will be released by evaporation of light particles.

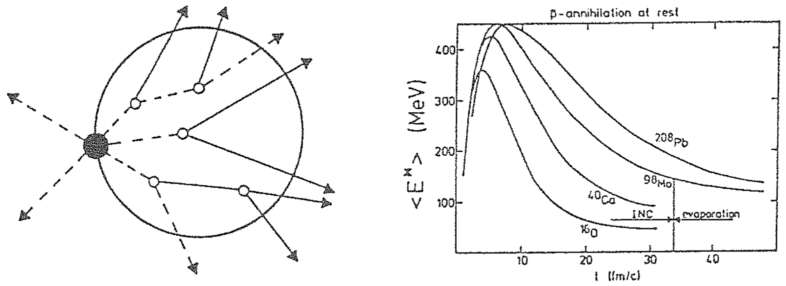

Fig. 1 : Left : schematic representation of the interaction between the pions (dotted lines) issued from the annihilation site (heavy dots) with the nucleons (full lines). Right : time evolution of the target excitation energy after antiproton annihilation at rest on various nuclei.

In other words, on the average, the process is not as violent as it is sometimes assumed. In any case, at low energy the annihilation does not "fire" all the nucleus in spite of the fact that the inclusive p and π cross-sections does show high energy tails characterizable by high "temperatures". This point has been discussed repeatedly in the literature.[2,6,7] It is established that the Maxwellian tails of the spectra arise from the thermal spectrum of the primordial pions but do not imply at all the formation of large size thermalized hot sources.

3.2. Transfer of energy

An important quantity which controls the evolution of the nuclear system is the energy (W_{tr}) transferred from the pion to the baryon system. If E_0 is the energy released in the annihilation and if W_π is the final energy of the emitted pions, one has

$$E_0 = W_\pi + W_{tr} \ . \tag{1}$$

Experimentally, neither W_{tr} nor W_π is measured. The accessible quantity is

$$W_{\tilde{\pi}} = W_{\pi^+} + W_{\pi^-} + W_\gamma = W_{\pi^\pm} + W_\gamma \ , \tag{2}$$

where W_γ indicates the energy carried by the γ-rays, coming from π^0 decays. There is only one direct measurement of $W_{\tilde{\pi}}$.[8] It is shown in Table I along with the INC prediction of ref. 9. For U there is a good agreement, but not for ^{12}C, in which case the experimental value of W_{tr} is incredibly small.

Table 1 : Values of the energy transfer (in MeV) after antiproton annihilation at rest.

	$W^\pm$	W_γ	W_{tr} (ref. 8)	W_{tr} INC (ref. 9)
$\bar{p}$ ^{12}C	1081	709	75 ± 53	220*
$\bar{p}$ U	971	505	447 ± 42	450

*extrapolated from a calculation for ^{16}O.

Another related quantity is the final pion multiplicity. Some data are given in Table 2 for typical systems along with the INC predictions. There is some discrepancy between the counter experiments and the bubble chamber experiments (see refs. 10, 11 for a discussion of this point). On the theoretical side the dispersion in the predictions is due to different treatments of the pion absorption and to medium effects on this pion absorption.[11,12] The agreement between theory and experiment is fair. However, we want to stress here that there are some intriguing features. The INC seems to overestimate the pion yield for antiproton annihilation whereas it underpredicts the yield for the antineutron case of ref. 13. In any case, it should be emphasized that further careful measurements are required to clarify the situation of the experimental pion multiplicities.

Table 2 : Pion multiplicities

		$<\pi^\pm>$	$<\pi^+>$	$<\pi^0>$	$<\pi^\pm>$ INC	$<\pi^+>$ INC
at rest	$\bar{p}\,^{12}C$ (ref. 8)	2.86		1.81		
	$\bar{p}\,U$ (ref. 8)	2.57		1.36	2.7	
0-600 MeV/c	$\bar{p}\,^{12}C$ (ref. 38)	2.3	1.01		3.0-2.9	1.32-1.21
	$\bar{p}\,^{12}C$ (ref. 34)	2.9	1.33			
	$\bar{p}\,U$ (ref. 33)	1.8	0.69		2.45-1.9	0.89-0.78
	$\bar{n}\,Fe$ (ref. 13)	3 ± 0.3			2.75	

3.3. The fate of the nucleus

As we have indicated in fig. 1, at 600 MeV/c, about 75 % of the energy transferred to the baryon system is carried away by rapid particles (p, n, d, t,...). The remaining part E*

$$W_{tr} = W_{ej} + E^* \ , \tag{3}$$

which amounts to ~ 150 MeV for a medium weighted target is dissipated by evaporation. This spallation plus evaporation regime, embodied by the INC model, can explain the distribution of the mass residues as shown in fig. 2. The latter has been measured by the PS186 collaboration.[14,15] For medium heavy nuclei, the target can lose a large number of nucleons (~ 40 for ^{98}Mo e.g.), but in all cases, there exists a heavy remnant, of a size smaller but comparable to the one of the target.

The spallation plus evaporation process is not unique in nuclear physics. It also occurs in high energy proton-induced reactions and, more commonly, in intermediate energy heavy ion interactions. One of the most important issues in this context is to know whether this spallation plus evaporation regime does disappear or not when the parameters of the system are varied.

The common idea[16] is that the spallation plus evaporation regime holds if excitation energy per particle $E^*/A \lesssim 3$ MeV. Above this value, the multifragmentation is expected to set in. In this regime, the nucleus decays in several pieces of similar size, but all much smaller than the original

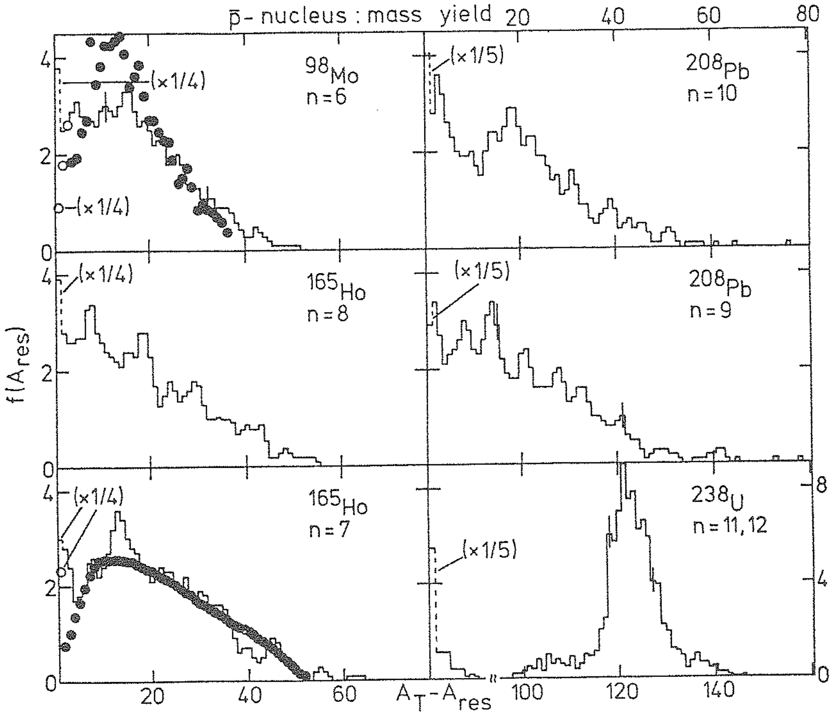

Fig. 2 : Histograms : INC predictions for the residual mass distribution after antiproton annihilation at rest on several targets (n denotes the principal quantum number of the annihilation state). The dots indicate the data of refs. 14, 15. Adapted from ref. 9.

target. The transition between the evaporation to the multifragmentation regime may reveal critical aspects, akin to those of the percolation transition.

Clearly, antiproton annihilation at low energy pertains to the undercritical regime. A simplest way to get overcritical is to increase the antiproton energy, as suggested in fig. 3. A more refined analysis, based on a percolation model (see ref. 5 for detail) shows that the transition might occur around 600-800 MeV incident energy.

As in ref. 5, we want to stress the advantages of studying the multifragmentation transition by means of antiprotons. They are summarized in Table 3. The most important of them is the fact that annihilation allows to deliver a sizeable excitation energy without transferring much momentum and angular momentum. Furthermore, the excited system is more sharply defined (in the heavy ion case there is mixing of target and compound nucleus excitations) and the dynamics is better understood.

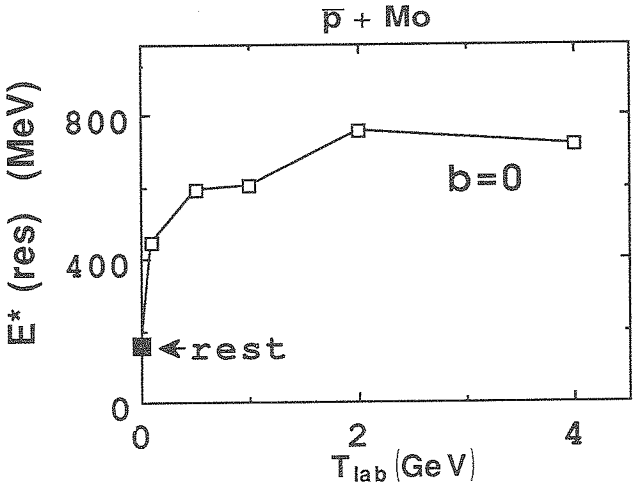

Fig. 3 : Residual excitation energy delivered to a Mo target after antiproton annihilation as a function of the kinetic energy of the antiproton.

Table 3 : Comparison between antiproton and heavy ion beams for the study of multifragmentation

	antiproton	heavy ions
critical energy	~ 1 GeV	~ 200 MeV/A
momentum transfer	small	large
angular momentum transfer	small	large
definition of the fragmenting system	good	~ rather bad
mixing of various sources	no	~ yes

Let us finally mention that another appealing way to go into the overcritical regime is provided by antideuteron annihilation.[17,18]

4. UNUSUAL ANNIHILATIONS

4.1. B≥1 annihilations

It was already proposed a long time ago[19] that an antiproton can be absorbed on two or more nucleons at the same time in a nucleus. However, we have to stress that this process cannot be clearly

$$\sigma(s) = \frac{1}{2}\,\sigma(Y) + 2\sigma\left(K_S^0\right) \qquad (5)$$

is much less sensitive to the detail of the dynamics (in particular of strangeness exchange processes). The primordial (annihilation) contribution accounts for a large part of the experimental value and the rescattering is sufficient to account for the remaining part in the Ta case and but overshoots the Ne value. (3) The high Λ/K_S ratio comes from strangeness exchange which reshuffles s-quarks from $\overline{K}$'s into hyperons through the exothermic reactions $\overline{K}N \to Y\pi$.

In conclusion, up to now, the occurrence of B=1 annihilation seems to be proved for $\bar{p}d$ only. We note however that few experiments have been performed and that the PS177 experiment[31] has not been analyzed from this point of view at least. Another signature could be provided by the rates of the reactions $\bar{p}\,{}^3He \to pn$ and $\bar{n}\,{}^3He \to pp$ [3,35], which should be measured in the future.

5. HADRONIC EXCITATIONS IN NUCLEI

The $\bar{p}p$ system being an important source of mesons, mesonic resonances and hyperons, it could be considered as an alternative tool for studying hadron-nucleus interactions. We just here comment of some aspects of this question.

(a) Search for hadronic nuclear bound states

The most obvious candidate is the Λ-particle, due to its strong attractive interaction with the nucleons. Apparently, the PS177 experiment at LEAR has already observed the formation of an hypernucleus after $\bar{p}$-annihilation at a rate of the order of 10^{-4} which allows to make lifetime and perhaps spectroscopic studies.

Another candidate is the η meson, since it is produced with a reasonable rate (0.07) in the annihilation and since the ηN interaction is attractive (the 1440 MeV N* has a decay width in the ηN channel), but the situation is unclear. The η meson can be captured on two nucleons, which will broaden quite well the possible η-nucleus bound states.

(b) Study of hadron-nucleus interaction

Let us point out some problems which have only been partly attacked. The long lifetime resonances produced in the annihilation (η,ω) can affect pion multiplicities, which are usually evaluated as assuming uncorrelated pions issued from the annihilation. In fact, the correlated pions in η's and ω's are more protected against absorption, but the net effect is rather small.[32] On the other hand, they favour associated production, since $\eta N \to \Lambda K$ and $\omega N \to \Lambda K$ are exothermic reactions with sizeable cross-sections.

Strange resonances (K^* and $\overline{K}^*$) are also produced. Their lifetime (~ 4 fm/c) is rather short, but long enough to allow them to interact with the nucleons before decaying. The K^*'s are produced with an appreciable rate however (actually, <K*> ≈ <K>/3). The interaction of K's and K*'s with the nucleons being not the same, the presence of K*'s can influence the strangeness production in annihilation on nuclei. This has not been studied so far.

The direct production of hadrons (η,ω,Λ,...) in the annihilation can be used to study their interaction with nuclear matter. The simplest quantity to determine is the medium hadron-nucleon cross-section. This was studied extensively at high energy in the past and can be done by means of $\overline{p}$ annihilation on nuclei at low energy. The measurement of η and ω multiplicity can give directly their interaction cross-section. An example of the sensitivity is shown in fig. 6.

Further studies are possible, including the ones dealing with the hadronization time, the role of Δ-particles (through the $\pi^{\pm}p$ invariant mass distribution e.g.[11]), the possible multi-Δ states,... In general, annihilation on nucleus is a natural laboratory for the evolution of localized mesonic excitations (hot spots) of nuclear matter.

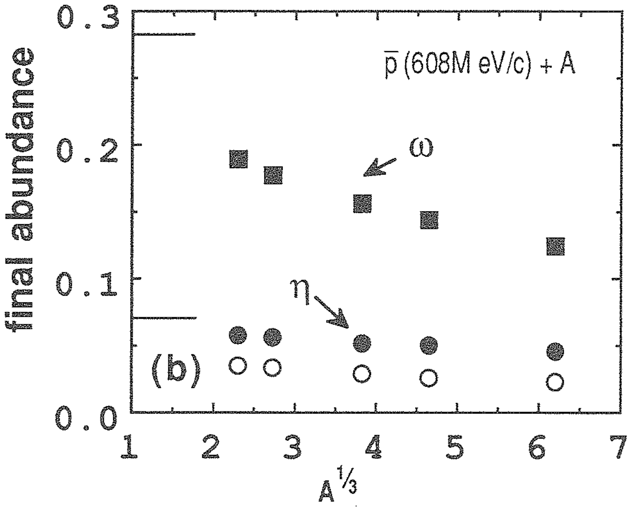

Fig. 6 : Predictions of ω and η yield after antiproton annihilation on several nuclei.[32] For η particles, the open circles correspond to a ηN interaction cross-section reduced by a factor 3.

6. CONCLUSION

We have here insisted on two currently debated aspects of antinucleon annihilation on nuclei, namely the possibility of studying the transition from evaporation to multifragmentation of the residual nucleus and the possibility of having $B \geq 1$ annihilation processes. As a conclusion, we list for these topics and for some other ones, the questions which, according to us, should be studied in the future.

(1) In the LEAR regime

- π-multiplicities
- strangeness production
- $\overline{d}$ annihilation
- hadronic resonances
- multi-Δ states,...
- hadronic bound states : η-nucleus,...
- light particle production
- fissility of heavy targets.

(2) In the GeV regime

- multifragmentation : mass yield, angular distributions, correlations
- correlated hadronic final state.
- hadronic bound states : hypernuclei, hadronic excitation : φ , f_2 , ...

(3) In the 10 GeV regime

- propagation of hot spots
- color transparency : J/ψ , φ,... production
- correlated hadronic states in the forward direction : H-particles, Λ_c,...
- production of exotic heavy fragments at large angles.

We want to thank Drs. Carlo Guaraldo and Jacques Vandermeulen for helpful discussions.

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