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ANTIPROTON-NUCLEUS INTERACTION AT INTERMEDIATE ENERGIES

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ABSTRACT

The more recent experimental results in antiproton-nucleus physics from CERN, KEK, Serpukhov and ITEP are reviewed. Some typical experiments are discussed with the aim to underline the capabilities of the antiproton in investigating Nuclear Physics properties and the agreement between the intranuclear cascade (INC) models and the main bulk of data. Recent theoretical developments, beyond and refining the INC models, such as the "clan picture" and the "trawling effect", are examined. Special attention is reserved to those experimental "cases" which can not be explained within the conventional framework, indicating the possible evidence of unusual annihilations. The physical meaning of unusual (multinucleon) annihilations is recalled. Reactions which can favour multinucleon annihilations, specifically Pontecorvo reactions, are examined. The theoretical models which deal with multinucleon annihilations are recalled, together with the specific signatures, in particular strangeness enhancement. Finally, all the possible experimental evidences, up to now, of unusual annihilations are reported and discussed. In particular, the recent measurement of strangeness production from annihilation on a complex nucleus, performed at ITEP, is here reported for the first time.

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1. - INTRODUCTION

The last results from LEAR at CERN^(1+6,8+18,23+30), which cover a broad field of scientific items; the recent data from USSR (Serpukhov, ITEP)^(7,22) and Japan (KEK)⁽¹⁹⁺²¹⁾; the theoretical efforts in refining the conventional intranuclear cascade (INC) models^(31,32), demonstrate a diffused interest in investigating the interaction of intermediate energy antinucleons with nuclei.

The specific properties of antinucleons, in particular the dominant phenomenon, i.e. the ability to annihilate in nuclear matter delivering relevant energy in a well defined region of space and time, offer ample possibilities for studying a variety of nuclear phenomena, as well as nuclear matter excitation processes. Indeed, the annihilation of intermediate energy antiprotons takes place at the nuclear surface with a single proton or neutron. The annihilation is dominated by the emission of many pions which are frequently reached via intermediate mesonic resonances. Between two and eight pions, on average five (three out of them charged) are produced. The created pions cascade through the nucleus, interacting with the nucleons and ejecting few of them. Their energy being in the region (100+300 MeV) of the Δ resonance, most of the pions have short range and consequently much energy is transferred to the nucleus. Due to the collision of pions, deltas and nucleons the net result of the cascade is thus the emission of pions, fast protons and other particles. In the same time, pions which have not interacted ("primordial pions") will be found in the final state as a high energy tail. Therefore, inclusive pion spectra show a typical two-bump structure, with a low energy peak essentially due to pions from Δ decay and scattering and a second high energy peak, which characterizes primordial pions. After the cascade, the residual nucleus, still with some excitation energy, evaporates few particles, mainly neutrons.

The whole scheme can be made quantitative by the so called intranuclear cascade models (INC) in which the cascade is viewed as a succession of binary collisions, such as:

with probabilities following the experimental cross sections.

Even though the bulk of the present experimental results is indeed consistent with the scenario of the intranuclear cascade described by the current models⁽³³⁺³⁹⁾, however the number of "cases" which can not be explained in the conventional framework, indicates the possible evidence of unusual annihilations. This is a specific problem of Nuclear Physics, since looking at these "unusual" annihilations one investigates precisely *if* and *how* nuclear matter influences the $\bar{N}N$ annihilation mechanism. We call "unusual" these phenomena considering as a deviation from the standard scenario a "delocalization" of the annihilation site, which can be pictured as an annihilation on two (or more) nucleons (*multinucleon annihilations*).

This paper pursues the following aims:

- to recall the topics recently investigated by intermediate energy antiprotons on nuclei discussing some characteristic experimental results (Sect. 2);
- to examine how new calculations have dealt with features such as: properties underlying inelastic collisions of elementary particles (*clan behavior*); role of local variations of nuclear density throughout the developing of the intranuclear cascade (*trawling effect*) (Sect. 3); and, finally,
- to recall the physical meaning of unusual annihilations and to report and discuss all the actual experimental evidences (Sect. 4).

2. - RECENT MEASUREMENTS ON ANTIPROTON-NUCLEUS INTERACTION

2.1. The field of researches.

Together with the bulk of CERN results, products of advanced or completed analyses of the first generation of LEAR experiments, we report here data from Serpukhov, ITEP and from KEK, at some higher energies. While the first LEAR data were mainly inclusive measurements, the last ones are also exclusive and cover a broad variety of scientific items, as it appears from this list in which the LEAR number of the experiment, or the name of the laboratory where it was performed, are also reported:

Elastic scattering of antiprotons on light nuclei (d, ^3He , ^4He)

- PS 184, ref. (1)
- PS 179, ref. (2)

Reaction and break up cross sections on ^3He and ^4He

- PS 179, ref. (3, 4)

Measurement of correlations between the emitted particles

- PS 179, ref. (5, 6)
- Serpukhov, ref. (7)

Charged particle multiplicities

- PS 179, ref. (5, 6)
- PS 171, ref. (8)

Determination of the ratio $\sigma(\bar{p}n)/\sigma(\bar{p}p)$ from antiproton annihilation on ^3He and ^4He

- PS 179, ref. (9, 10, 11)

Light nuclei production

- PS 186, ref. (12, 13)
- PS 179, ref. (14)

Strangeness production

- PS 179, ref. (15, 16, 17)
- PS 183, ref. (18)
- PS 171, ref. (8)
- KEK, ref. (19, 20, 21)
- ITEP, ref. (22)

Heavy hypernuclei

- PS 177, ref. (23, 24)

Neutron spectra

- PS 183, ref. (25)

Antiproton induced fission

- PS 177, ref. (26)
- PS 183, ref. (25, 27)
- PS 186, ref. (28, 12)

Yields of residual nuclei

- PS 186, ref. (29, 30)

Here we discuss two of the above results, and precisely *correlation measurements between emitted particles and yields of residual nuclei*, which are for some aspects emblematic of the kinds of problems which one is faced when investigating antinucleon-nucleus interaction and, in the same time, show clearly the possibilities offered by the use of a probe such as antiproton in exploring Nuclear Physics properties.

2.2. Correlation measurements

It is quite possible that the correlations between the numbers of emitted particles of different kind are more sensitive to the details of the $\bar{N}A$ interaction mechanism compared to the inclusive characteristics. Unfortunately, only few correlations were experimentally studied. We discuss here the PS 179 streamer chamber results using 180 MeV antiprotons on Ne⁽⁶⁾ and the Serpukhov results using 5.2 GeV antineutron on Ta⁽⁷⁾. The first experiment measured the correlation between the average number of π^- and the overall charged-tracks multiplicity M ($\pi^\pm$ plus nuclear fragments): see fig. 1. The second experiment gave the plots of the number of emitted protons versus the number of π^+ and the number of π^- : see fig. 3. The CERN results have been compared with the predictions of a recent model of Cugnon *et al.*⁽³¹⁾, based on the so called "*clan picture*" (see Sect. 3.1), which retains all the basic premises of the INC calculations. The Serpukhov data were compared with the predictions of the last version of the INC model of Iljinov⁽³²⁾ which, in particular, gives a description of the elementary $\bar{N}N$ interaction in a wider energy region ($E_{\bar{N}} \leq 10$ GeV).

The two measurements exhibit a singular feature: the PS 179 results⁽⁶⁾ present a "striking" behavior in comparison with what, in principle, one might expect from the INC mechanisms, *but* they are fully explained within the model of Cugnon *et al.*⁽³¹⁾. On the contrary, the Serpukhov data show a "normal" trend, but they can *not* be explained by the calculations⁽³²⁾.

According to the well established mechanism of "pionic" energy transferring along the intranuclear cascade, via Δ formation and absorption, assuming that high multiplicity events, and hence in general high multiplicity of ejected nucleons, are due to a higher deposited energy from pions, one might expect a *decreasing* number of (survived) final pions at high M: see, for instance, fig. 2, taken from ref. (40).

The experimental trend found by PS 179 experiment apparently contradicts this general conclusion, since the average number of π^- is an *increasing* function of the *overall* multiplicity, for high M values (see fig. 1). However, nothing *unusual* is underlying this result, as shown by Cugnon *et al.*⁽³¹⁾. Their (modified) clan picture reproduces in fact beautifully this behavior, as a *direct consequence of charge conservation* handled exactly at each step of the cascade (and not only on the average, as usually done).

To check this feature, the model was run in picking *at random* the charge of each pion (and assuming that the values of probability for the target nucleon being a proton or a neutron stayed constant and equal to their initial values, throughout the emission process: which corresponds not to take into account the depletion of the target). The result is shown in fig. 1, open dots: in this case the agreement with experiment is totally lost. The difference between the two cases clearly shows that the correlation observed at high M is a result of the constraint and has no dynamical content.

The fact that the increasing of the average number of π^- at high M has to do with charge conservation through the process can be easily demonstrated.

The overall multiplicity M of the reaction products is given by:

$$M = M_f + n_{\pi^+} + n_{\pi^-} \quad (1)$$

where M_f is the nuclear fragment multiplicity (proton, deuteron, triton,...) and $n_{\pi^\pm}$ are the pion multiplicities.

The *total* net charge Q can be written as:

$$Q = q_{\pi^+} - q_{\pi^-} + Z_f + Z_{res} \quad (2)$$

where Z_f is the fragment charge and Z_{res} is the charge left to the nucleus.

Then:

$$Q \geq q_{\pi^+} - q_{\pi^-} + Z_f \quad (3)$$

Moreover, being

$$M_f \leq Z_f \quad (4)$$

one has, *a fortiori*,

$$Q \geq q_{\pi^+} - q_{\pi^-} + M_f = n_{\pi^+} - n_{\pi^-} + M_f \quad (5)$$

Consequently,

$$n_{\pi^-} \geq n_{\pi^+} + M_f - Q \quad (6)$$

that is:

$$n_{\pi^-} \geq \frac{M - Q}{2} \quad (7)$$

The average pion multiplicity must be an *increasing* function of M at high M values.

In the Serpukhov experiment the trend of the distribution of the emitted protons is a *decreasing* function of the final pions but, at the high energy of the experiment, the specific prediction of the recent model of Iljinov⁽³²⁾ differs markedly from the experimental result (see fig. 3). The inclusion in the calculation of an effect such as trawling which, owing to the deeper penetration of the high energy antineutron, should be particularly strong in this case (see Sect. 3.1), not only increases the discrepancy, but also fails the trend of the distribution. In other terms, a cascade model which deals with conventional $\bar{N}N$ annihilation mechanism is *not* able to reproduce the data. This can be a hint of the influence of nuclear matter and thus an evidence of unusual annihilation. We shall come back to this result in Sect. 4.

2.3. Yields of residual nuclei.

Studying the properties of residual nuclei produced in the inelastic $\bar{N}A$ interaction is important since these properties contain the main information about the interaction between the multipion system formed in the $\bar{N}N$ annihilation and a nucleus: *Multipion-Nucleus Interaction (MPNI)*. In this *MPNI* "uniformly heated" highly excited nuclei are produced effectively.

The number of nucleons A and protons Z and, also, the momentum $\vec{P}$ and the angular momentum $\vec{I}$ of the residual nucleus can be expressed by the relations⁽³²⁾:

$$\begin{aligned} A &= A_t + q_{\bar{N}} - \sum_1^{N_c} q_i^c & Z &= Z_t + e_{\bar{N}} - \sum_1^{N_c} e_i^c \\ \vec{P} &= \vec{P}_{\bar{N}} - \sum_1^{N_c} \vec{p}_i^c & \vec{I} &= \vec{I}_{\bar{N}} - \sum_1^{N_c} \vec{i}_i^c \end{aligned} \quad (1)$$

where: q baryonic number; N_c number of cascade particle;
 e charge; $\vec{P}, \vec{p}_i$ momentum; $\vec{I}, \vec{i}_i$ angular momentum.

As shown in fig. 4, a result of cascade calculations⁽³²⁾ is that the residual nuclei have a wide distribution in excitation energy E^* that extends up to E^* close to their total binding energy. During the cascade stage, the target nucleus loses a large number of nucleons ΔA . Finally, when the cascade is over, the residual nuclei acquire large values of momentum P and angular momentum I . According to relations (1) these wide distributions are directly determined by the fluctuations in the number of particles of the cascade. The large momentum $\vec{P} \cong 1 \text{ GeV}/c$ allows the experimental detection of the recoil nucleus and the large angular momentum $\vec{I} = 30\hbar$ suggests the possibility of revealing the phenomenon of population of high spin isomeric states.

The subsequent decay mechanism of the residual nucleus is determined by the excitation energy it acquired.

a) *Moderate excitation ($E^* \leq 2 \text{ MeV/nucleon}$).*

The best decay mechanism is the successive emission (evaporation) of particles from the compound nucleus and fission. Weak *MPNI* (namely, pions which leave the nucleus without scattering, charge-exchange channels of elementary πN interactions, nucleon knock-out via quasi-free scattering) give rise to isotopes neighbouring the target nucleus (small ΔA and ΔZ). The products of deep spallation of the target nucleus in deep inelastic *MPNI* constitute the second vast region of the formed isotopes.

Due to these processes a wide spectrum of residual nuclei are produced far from the target nucleus and far from the β -stability line, as seen in the PS 186 experiment^(29,30). According to the calculations^(32,38,39) the mass regions of the observed nuclides ($60 < A < 95$ for Mo targets; $110 < A < 160$ for ^{165}Ho target) correspond to products of evaporation of not too hot residual nuclei. Fig. 5 and 6 show the good agreement between experimental mass distributions⁽²⁹⁾ and INC model results^(32,38) for the case of stopped antiprotons in ^{95}Mo and ^{98}Mo targets. This agreement confirms the main features of *MPNI* described by the model and in particular shown in Fig. 4.

b) *Excitation close to the total binding energy of the nucleus ($E^* \geq 5 \text{ MeV/nucleon}$).*

In this highly excited nuclear matter there can occur a *phase transition* of the liquid-gas type. Its specific signal is the multiple production of nuclear fragments (of the order of C or O) resulting from the explosive decay of the residual nucleus, a feature referred to as *multifragmentation*. Needless to stress the conceptual significance of this phenomenon: it is important to understand how a nucleus loses its cohesion as to understand the origin of its self-boundedness. The properties of this phase transition should bear some relationship with the saturating properties of nuclear forces and the nuclear surface tension⁽⁴¹⁾.

Unfortunately, the experimental method of induced radioactivity applied in the PS 186 experiment was not sufficiently sensitive or applicable in the mass regions where multifragmentation takes place: $10 < A < 50$ for Mo targets and $10 < A < 100$ for the ^{165}Ho target. Therefore, no experimental evidence is up to now available about this relevant physical process induced by antiprotons. It is noteworthy to underline that studying the break up of a

nucleus using antiprotons is much more than an alternative way compared to the most common tools, namely high energy proton-induced reactions and intermediate energy heavy ion reactions. Heavy ions give rise, intrinsically, to a more complicated dynamical path⁽⁴¹⁾. Furthermore, both high energy protons and heavy ions are subject to an other difficulty, namely the fact that many impact parameters are mixed in the observation. This is not the case for antiproton annihilation at rest, for instance, where the initial system is always "prepared" in the same way⁽⁴¹⁾.

The theoretical predictions⁽³²⁾ for multifragmentation are rather explicit. Accompanying the many-body break up of the hot nucleus into light fragments, in moderately hot nuclear systems ($3 \leq E^* \leq 5$ MeV/nucleon), "quasi-evaporation" (i.e. the break down into a large residual nucleus and one or two small fragments or nucleons) and "quasi-fission" (i.e. the break down into two fragments with approximately equal masses) can be observed⁽⁴²⁾. This gives a characteristic U-shaped inclusive mass distribution which can be seen in fig. 6. At higher excitation energies ($E^* \geq 5$ MeV/nucleon) the multifragmentation takes place and the mass spectrum decreases exponentially for light fragments with increasing A .

In order to study multifragmentation of nuclei by antiprotons it is then necessary to measure the yield of residual nuclei in the mass region $10 < A < 50$ if the target is, for example, Mo. An initial energy of antinucleons $E_N \equiv 100+200$ MeV is, evidently, most favorable for production of hot thermalized nuclei. According to Iljinov⁽³⁰⁾ the yields of fragments produced by a 180 MeV antiproton would increase by a factor 2+3 compared with the one at rest shown in fig. 6.

3. - RECENT THEORETICAL CALCULATIONS IN ANTIPROTON-NUCLEUS INTERACTION

A substantial contribution in understanding the new bulk of antinucleon-nucleus results has come from recent *ad hoc* developed theoretical models, the success of which is striking in some cases, while in other ones more accurate experiments or more refined or better established theoretical efforts are still needed in order to draw definite conclusions.

We want to mention here two out of them, and precisely:

- *Negative binomial analysis of multiplicity distributions.*
- *Trawling effect in intranuclear cascade.*

3.1. Negative binomial multiplicity distribution

Recently, it has been discovered by the UA5 collaboration⁽⁴³⁾ that charged particle multiplicity distributions in high energy $\bar{p}p$ collisions closely follow a negative binomial (NB) form. Further analyses at different energies (from a few tens to a few hundreds GeV c.m. energy) and for various systems ($\bar{p}p$, pp , πp , e^+e^- , ...) seem to establish the general validity of the NB distribution both for total multiplicities and for restricted intervals of pseudorapidity^(44,45). It is not clear yet whether this universal property is a signature of a peculiar aspect of the underlying dynamics or not. Anyway, some arguments and observational

facts support the idea^(45,46) that the existence of NB distribution is linked to an underlying cascade process in which primary objects ("*ancestors*") are created independently and subsequently generate the final particles (see fig. 7). Each of the observed particles belongs to one of N clans; each clan is initiated by an ancestor and contain n_c particles. A NB distribution is obtained if N is a *Poisson* variable (*independent clans*) and if n_c follows a *logarithmic* law.

The possible existence of similar properties at lower energy in nuclear processes has been analyzed by Cugnon⁽⁴⁷⁾. Specifically the ability of the INC dynamics to develop NB distributions was investigated. It has been shown that the antiproton-nucleus interaction, especially at rest, is a good system for observing NB distributions, since the latter liberates a few pions which are expected to cascade more or less independently inside the nucleus (see fig. 7). In fact, excellent best fits by NB distributions of the charged particle multiplicities measured in $\bar{p}$ -annihilation in emulsion, both at rest and at 300 MeV/c by PS 179 experiment⁽⁴⁸⁾ were obtained⁽⁴⁹⁾ (fig. 8). A comparison with INC calculations gives a result⁽³⁸⁾ remarkably close to the fit mentioned above. Thus the picture of clan formation, the ancestors being the interacting pions, seems to emerge both from the model calculation and from experiment.

At a more detailed analysis, however, the "original" clan picture applied to low energy $\bar{p}A$ interaction is physically unsatisfactorily, in two respects:

- 1) the number of ancestors is larger than the number of interacting pions. For instance, applied to the ^{20}Ne results at 608 MeV/c of PS 179 experiment⁽⁶⁾ one finds $N = 6.36$, larger than the overall number of primordial pions ($\cong 5$);
- 2) clans with zero prongs are excluded.

In the new clan picture recently developed by Cugnon et al.⁽³¹⁾, not only the number of ancestors in *Poissonian*, but also the number of secondaries (size of the clan) follows a *Poissonian* distribution (*Compound Poissonian model*). This is largely supported by the results of the INC model, as demonstrated by the authors. The model has been applied to the recent correlation and multiplicity measurements of PS 179 experiment⁽⁶⁾.

The correlation measurements were beautifully reproduced, as a direct consequence of charge conservation, as shown in Sect. 2.2 (see fig. 1).

The same excellent agreement is displayed by the model while handling the multiplicity distributions measured in Ne at various energies⁽⁵⁾ (see fig. 9). As far as the specific aspects of the new model are concerned, now - differently from the standard NB - the number of ancestors is found in agreement with the average number of pions from $\bar{N}N$ annihilation.

In conclusion, the Compound Poissonian model seems more suitable in reproducing low energy antinucleon-nucleus data, while the standard NB is better in situations where there is a large reservoir for particle production, as in high energy particle physics.

3.2. Trawling effect in intranuclear cascade

The trawling effect⁽³²⁾ is a non-linear effect due to the local reduction of the nuclear density during the development of the intranuclear cascade. One more assumption underlying the standard version of the cascade model is that the number of cascade particles N_c is much less

than the number of nucleons A_t in the target nucleus: $N_c \ll A_t$, i.e., during the evolution of the cascade the properties of the target nucleus remain unchanged. For πA and NA interaction this condition is violated at energies $E_{\pi,N} \equiv 3+5$ GeV^(45,46), when multiple pion production becomes dominant: more and more nucleons are involved. Owing to the knock out of nucleons by fast secondary particles, the low energy component of slower cascade particles passes through the lower density region and leaves the nucleus without rescattering (*trawling* of a nucleus). In other words, these particles suffer much fewer collisions compared with the standard cascade. In the $\bar{N}A$ reactions the trawling effect can be essential also at low energies, since the annihilation channel of multipion production is the basic channel of the $\bar{N}N$ interaction. As a result, the inclusion of the trawling effect leads to the suppression⁽³²⁾ of the low energy part of inclusive proton spectra⁽⁵²⁾ and of the tail of the distribution in the number of charged particles⁽⁴⁸⁾ (see fig. 10), in excellent agreement with the experimental results.

Perhaps the most striking success of the trawling is obtained in analysing some of the properties of residual nuclei after $\bar{p}$ -annihilation. The trawling effect decreases the number of collisions between slow cascade particles and intranuclear nucleons and hence alters the characteristics of the thermalized residual nuclei. As a result, the yield of nuclei with extremely large excitation energies decreases and so do the number of nucleons ΔA carried away from the nucleus and the momentum of residual nuclei $\vec{P}$ (see fig. 4). If now one compares the experimentally obtained⁽²⁹⁾ isotope chart of nuclides, with given numbers of neutrons N and protons Z (see fig. 11), with the results of the calculations by the cascade model⁽³⁰⁾, taking or not into account the trawling effect, the isotopes predicted by trawling are the same ones found in the experiment, while the isotope chart predicted by the standard cascade looks significantly different (see fig. 12).

Still studying residual nuclei, the contribution of trawling towards a fundamental phenomenon such as *multifragmentation* could be easily checked. In fact, the yields of such explosive events would display a difference of about one order of magnitude with and without the trawling effect (see fig. 6).

About the role of trawling in intranuclear cascade some similarity can be found with *percolation* models⁽⁵³⁺⁵⁵⁾: the evolution of the nucleus will depend very much on the "damage" caused by fast processes. Beyond a certain percentage of "voids" created in the medium, the system breaks into many clusters of small size (percolation transition $\leftrightarrow$ multifragmentation). Below this fraction one has normal evaporation from cascade.

4. - UNUSUAL ANNIHILATIONS

4.1. Reaction which can favour multinucleon annihilations

Hunting for processes which can favour multinucleon annihilations can start from investigating, preferentially, the ensemble of *reactions which present intrinsically a typical two- (or more-) body nature*. As early as 1956, just half a year after the discovery of the antiproton,

Bruno Pontecorvo was the first who realized⁽⁵⁶⁾ that there must exist unusual annihilation processes ("extraordinary" annihilations, as dubbed by Pontecorvo) forbidden on a free nucleon but allowed on nucleons bound in nuclei.

Such are annihilation reactions (*Pontecorvo reactions*) with only one meson in the final state (*one-meson annihilations*), for example:

$$\bar{p} + d \rightarrow \pi^- + p \quad (1)$$

$$\bar{n} + {}^3\text{He} \rightarrow \pi^+ + d \quad (2)$$

or annihilations without any meson at all (*mesonless annihilations*), for example:

$$\bar{p} + {}^3\text{He} \rightarrow p + n \quad (3)$$

$$\bar{n} + {}^3\text{He} \rightarrow p + p \quad (4)$$

These reactions are strictly forbidden in $\bar{N}N$ annihilation in vacuum by charge and baryonic number conservation.

The influence of nuclear matter on the annihilation mechanism can manifest itself in many ways. For instance, in a mesonless annihilation, alongside a more or less "conventional" process in which all pions are absorbed, there may exist the mechanism of *direct interaction* of the produced fireball with the surrounding nuclear matter, *skipping the stage of pion production*. This possibility seems plausible in the light of arguments⁽⁵⁷⁾ according to which the $\bar{N}N$ fireball lives long enough to interact with an other nucleon before decaying into pions. Then, in particular, following the first suggestion of Rafelski⁽⁵⁷⁾, the initial fireball, enriched with gluons and $q\bar{q}$ pairs, can "melt" the surrounding nuclear matter and create inside the nucleus a bubble of *quark-gluon plasma*.

4.2. Interest in Pontecorvo reactions

Studying multinucleon annihilations, and in particular Pontecorvo reactions, has straightforward implications.

Antinucleon absorption on a two-nucleon pair reminds the well known dominant process of pion absorption in nuclei, which is also of two-body nature, since absorption on a single nucleon is very suppressed due to the nucleon large momentum (~ 500 MeV/c) required. But there is a significant difference between pion-nuclear absorption and Pontecorvo reactions: in antiproton annihilation the delivered energy is seven times larger, which means a correlation radius correspondingly reduced, and hence the peculiar possibility of investigating *short range correlations in nuclei*.

Moreover, taking for instance in consideration the simplest reaction, $\bar{p}d$ absorption, a standard triangular rescattering diagram, in which in the beam vertex (see fig. 13) is created a

pair of mesons and one is absorbed on the second nucleon, is intrinsically suppressed, since it involves the rare process of meson absorption on one nucleon, in comparison with the corresponding quark diagram (see fig. 14), in which the impinging antiquarks annihilate on quarks of both the target bags. In the case of mesonless annihilations three quarks can be directly involved. More generally, one can therefore claim that such an investigation can be essential in clarifying the role of *multi-quark configurations*.

We want also to mention the sensitivity of Pontecorvo reactions to *high momentum components of the nuclear wave function*, where quark gluon degrees of freedom may play an important role⁽⁵⁸⁾. More generally, the high momentum tail of the nuclear wave function is related to the problem of the behavior of *highly excited nuclear matter*. Indeed, in the diagram of fig. 13, the rescattering process can not conserve energy-momentum for all on-shell particles at each step, the degree of virtuality of the particles in the intermediate state being considerable ($\geq m_N$). Consequently, the nuclear amplitude must be sensitive to small internucleon distances.

An other strong motivation is the already mentioned search for *new quark degrees of freedom* (quark-gluon plasma)^(59,60). Moreover, according to Brodsky⁽⁶¹⁾, in studying the two-nucleon absorption of $\bar{p}$ in deuterium, it is possible to test *the basic QCD dynamics in the intermediate momentum transfer domain*, using the so called "reduced amplitude" formalism.

Finally, following a recent suggestion of Cugnon and Vandermeulen⁽⁶²⁾, we point out the role that multinucleon processes, and two-nucleon annihilation in particular, can play in extending our comprehension of the charge conjugation concept. The pure charge conjugation (in the Dirac sense) appears at the quark level. In Fig. 15 a) and b) are shown, respectively, the quark diagrams of the $B=0$ reaction $\bar{p}p \rightarrow \pi^+\pi^-$ and of the $B=1$ reaction $\bar{p}d \rightarrow \pi^-p$. The Pontecorvo reaction is characterized by one additional $\bar{q}q$ annihilation, but the relevant point is that the annihilation on two nucleons allows a grouping of $\bar{q}q$ annihilations different from that active in $\bar{p}p$ annihilation. One antiquark can indeed annihilate on a quark of one bag while the remaining ones can interact with the other bag. In other terms, if antiquarks are introduced in a nuclear medium (under the form of an antibaryon) their evolution is not necessarily dictated by charge conjugation at the bag level if more than one nucleon is involved in the process.

4.3. Signatures of unusual annihilations

The properties of the system which represents the minimal departure from the standard annihilation, i.e. the fireball with $B=1$, have been studied by Cugnon and Vandermeulen⁽⁶³⁾ under the simplest assumption, namely that its decay is governed by phase space. The basic premise of this approach is that antiproton annihilation is a complicated process, which, therefore, can be handled by a statistical model. In fact, the main features of $\bar{N}N$ annihilation both at rest and in flight are largely consistent with such an assumption. The model used is a microcanonical approach, in the sense that energy and baryon number are conserved exactly. The most important prediction is a considerable *enhancement of strange particles* production for $B=1$ annihilations compared with $B=0$ (see Table I). This is a pure consequence of phase space, since the threshold for ΛK production in $B=1$ is below that for the $K\bar{K}$ channel.

In a different framework, the same conclusion was previously drawn by Rafelski⁽⁶⁴⁾ in discussing the properties of quark-gluon plasma. In that case, the main process in producing an enhancement of $s\bar{s}$ pairs is gluon-gluon interaction more than light quarks annihilation (see Fig. 16).

More subtle signatures of unusual mechanisms can also be looked for. It is obvious that the complicate rearrangement of quarks in the course of annihilation can be disturbed by the proximity of other nearby nucleons. Compared to free space annihilation, the distribution of the emitted pions can, in principle, be altered. The average numbers are more or less fixed by the energy released, but the *widths of the total charged pion multiplicities* may be affected by the multinucleon process.

Moreover, if some "delocalization" of the annihilation site occurs, the *spectrum of "primordial" pions* - which is a high temperature thermal one - can be affected, in the sense that a *high energy tail* might appear.

Finally, an other predicted characteristic of a multinucleon annihilation is a typical *tail of high energy protons*^(59,60), associated to strangeness production.

4.4. Experimental evidences for unusual annihilations

The very observation of a Pontecorvo reaction is already an evidence of a $B > 0$ event. But as far as specific branching ratios are concerned, to compare predictions with data is a hard job. In all generality the yield Y of a reaction including multinucleon processes can be written as:

$$Y = \sum_{B=0}^{A-1} P_B R_B D_B \quad (1)$$

where B is the baryonic number of the annihilation fireball, P_B is the rate of formation of the fireball, R_B is the branching ratio for the decay into a specific channel and D_B represents the distortion due to the subsequent cascades.

At present, no model which deals with all the above quantities does *not* exist. The model of Cugnon and Vandermeulen⁽⁶³⁾ is the only one to give specific predictions for strangeness producing channels and especially two-body channels⁽⁶⁵⁾, but it is unable to predict the formation frequency of the fireball, a part simple geometrical estimations⁽⁶⁶⁾. The more difficult task is the evaluation of the coefficient D_B , which requires an elaborate cascade calculation. For the $\bar{p}d$ reaction this difficulty could be overcome by taking advantage of some experimental evidences⁽⁶⁷⁾ which can be used to deduce the $B = 1$ component of annihilations. But for the mesonless annihilations - never explored experimentally - and, more generally, for the $\bar{N}A$ case, the problem is totally open.

As a consequence, as far as the strangeness signature is concerned, one has to follow, for the moment, and *indirect* way: namely, to see whether experimental data involving strangeness can, or not, be understood in terms of pure $B=0$ annihilations. At this regard, moreover, one has

also to take into account the distortion that a strange particle yield necessarily suffers passing through a nucleus. This is not the case of K^+ , which scatters only elastically.

The list of the possible experimental evidences for not conventional annihilations contains, at present, the following cases:

- 1) *Measurement of the one-meson reaction $\bar{p}d \rightarrow \pi^- p$: refs. (8,18,68).*
- 2) *Measurement of the increasing of the ratio K^+/π^- in nuclear matter: ref. (18).*
- 3) *Measurement of the strangeness enhancement in $\bar{p}$ -annihilation on complex nuclei: refs. (8,15,17,19+21, 22).*
- 4) *Measurement of a high energy tail in the inclusive proton momentum spectrum from $\bar{p}d$ annihilation under strangeness trigger: ref. (67).*
- 5) *Hypernuclei formation in $\bar{p}$ -annihilation on heavy nuclei: ref. (23,24).*
- 6) *Correlation measurements between emitted particles: ref. (5,6,7).*
- 7) *Measurement of a high energy tail in the primordial pion spectrum: ref. (6,52).*

1) Measurement of the reaction $\bar{p}d \rightarrow \pi^- p$

There is an old measurement of Bizzarri *et al.*⁽⁶⁸⁾ with 6 bubble chamber events and a measured b.r. of $(0.9 \pm 0.4) \cdot 10^{-5}$ and a recent measurement at LEAR of PS 183 experiment⁽¹⁸⁾ giving a b.r. of $(2.8 \pm 0.3) \cdot 10^{-5}$. An other LEAR group has recently communicated⁽⁸⁾ a measurement of the $\bar{p}d \rightarrow \pi^- p$ yield: $(1.4 \pm 0.7) \cdot 10^{-5}$, somewhat lower than the value of ref. (18). As said above, in this case exists a theoretical prediction, since an assumed frequency of about 10% for $B=1$ formation from the data of ref. (67), allows to the Cugnon and Vandermeulen model⁽⁶⁵⁾ to predict a b.r. of $3 \cdot 10^{-5}$, in fair agreement with the experimental result of ref. (18). It is noteworthy to mention that a recent elaborated calculation by Kondratyuk and Sapozhnikov⁽⁶⁹⁾, in the framework of the classical triangle rescattering diagram, with a realistic Paris deuteron wave function and a realistic dipole form factor, misses the experimental result of about one order of magnitude.

2) Measurement of the ratio K^+/π^- in nuclear matter

A measurement of K^+ abundance takes advantage, in principle, of the fact that the yield is practically unchanged by the cascade process. Therefore an eventual enhancement in p-nucleus interaction would indicate the presence of unusual annihilations. Unfortunately, there are no measurements available up to now. More easier to measure is the ratio K^+/π^- using a spectrometer, since it does not require a measurement over a large solid angle. However the result might be distorted by two competitive effects: π^- absorption and, for large nuclei, where $N > Z$, π^- production. These problems might be overcome by using $N = Z$ nuclei and/or measuring the $K^+/(\pi^- + \pi^+)$ ratio. The only measurement up to now performed using the spectrometer of P183 experiment⁽¹⁸⁾, has shown an effective, although modest, enhancement in K^+/π^- ratio passing from Hydrogen to Uranium: 2.2% to 3%.

3) Strangeness enhancement in $\bar{p}A$ annihilation

In antinucleon-nucleus annihilation, strangeness production is enhanced, due to the effect of the medium, beyond the level expected on the basis of "direct" production in first order antinucleon-nucleon annihilation.

In dealing with unusual annihilation, some specific physical quantities involving strangeness are of interest. In particular, for antiproton momenta below about 1 GeV/c, hyperon production (Λ , Σ) in $\bar{p}$ -nucleus annihilation involves necessarily two or more nucleons, whereas kaon production can be generated on a single nucleon. Therefore, ratios like:

$$R = \frac{\Lambda}{K_s^0} \quad (1)$$

are indicative of the relative importance of many-nucleon processes.

Four experiments, two at CERN, PS179⁽¹⁵⁺¹⁷⁾ and PS183⁽¹⁸⁾, one at KEK⁽¹⁹⁺²¹⁾ and one at ITEP (Moscow)⁽²²⁾, have dealt recently with inclusive neutral strangeness production from complex nuclei in a broad momentum range (0+4 GeV/c). The relevant quantities, i.e. the ratios Λ/K are reported in Table II, together with the corresponding values from $\bar{p}p$ and $\bar{p}d$ annihilation.

In the ITEP case⁽²²⁾, since these data appear here for the first time, due to the courtesy of soviet colleagues, it is worthy to give some more detail. Strangeness is generated by a 1.05 GeV/c antiproton beam in the 700 litres Xenon Bubble Chamber DIANA. These preliminary data concern two energies: at rest and at an average value of 0.55 GeV/c (0.3+1.05 GeV/c). An overall number of $2 \cdot 10^5$ pictures were collected, 25% out of them scanned looking for events with strange particles of the type:

$$\Lambda \rightarrow \pi^- p \quad K_s^0 \rightarrow \pi^+ \pi^- \quad K_s^0 \rightarrow \pi^0 \pi^0. \quad (2)$$

About 700 events with strangeness were found and are reported, without corrections, in Table III, distributed along the various production reactions. The Λ detection efficiency turned out to be 50%, the K_s^0 detection efficiency 88%.

What is significant in this experiment, in comparison with the other ones, is that not only multiple Vees (as in the Japanese experiment) but also neutral decay mode are reported.

In order to compare the ratios Λ/K_s^0 found in the ITEP measurement with those obtained in the other experiments, one can select from Table III the inclusive Λ events and the inclusive K_s^0 events in the channel $(\pi^+\pi^-)$. Taking into account the relative detection efficiencies, the obtained values are reported in Table II.

Three significant observations can be drawn from Table II:

- 1) the ratio Λ/K_s^0 – i.e., the specific parameter connected directly to many-particle effects – is, in complex nuclei, about *one order of magnitude greater* than the corresponding value from $\bar{p}p$ or $\bar{p}d$ annihilation at the same momentum;
- 2) the ratio is independent on the incident momentum: the value is 2.2 at 0.55 GeV/c and 2.4 at 4 GeV/c;
- 3) the ratio is independent on the target mass: the value is 2.2 in Xe, 2.3 in Ne, 2.4 in Ta.

The rapidity of a particle is defined as

$$y = \frac{1}{2} \ln \frac{1 + \beta_L}{1 - \beta_L} \quad (3)$$

where β_L is the longitudinal component of the velocity.

Rapidity distributions of emitted particles allow to find the effective centre-of-mass systems, i.e. the effective number of target nucleons interacting in the various processes with the incoming antiproton. In the reference frame associated to the centre-of-mass of the system made up by the antiproton and a nuclear mass M , expressed in terms of nucleon mass m_N ($M = nm_N$), on which it interacts, the distribution of rapidity is centered around zero. Of course, if particles are emitted isotropically (annihilation at rest) one has always $\langle y \rangle = 0$.

The effective c.m. frame is moving in the laboratory with a velocity

$$\beta = \frac{P_{\bar{p}}}{W_{\bar{p}} + nm_N} \quad (4)$$

where $P_{\bar{p}}$ and $W_{\bar{p}}$ are the momentum and the total energy of the antiproton. The velocity β is directly obtained from the mean value $\langle y \rangle$ of the individual rapidities over a certain number of particles:

$$\beta = e^{2\langle y \rangle} - 1 / e^{2\langle y \rangle} + 1 \quad (5)$$

For instance, in the case of $\bar{p}$ -Ta annihilation @ 4 GeV/c the rapidity distribution of K_s^0 is peaked around the value $\langle y \rangle \approx 0.6$. The peak goes to $\langle y \rangle^* = 0$ in the reference frame moving in the laboratory with $\beta = 0.54$. From eq. (3) this corresponds to assume a $\bar{p} - 3N$ c.m. frame: i.e. the incident antiproton collides with an effective target of three nucleon mass in the centre-of-mass system.

The main conclusion from the data is that the rapidity distributions have $\langle y \rangle^* = 0$ in the c.m. systems constituted by $\bar{p} + (m \text{ nucleons})$ for Λ production and $\bar{p} - (n \text{ nucleons})$ for K_s^0

production, with $m > n$. In other words, Λ production requires an overall number of involved nucleons greater than that for K_s^0 production.

In Table IV the effective targets as deduced from the rapidity distributions of Λ and K_s^0 measured in KEK experiment and PS 179 experiment are reported. It is shown that to produce a Λ an effective target of $8+13$ nucleons is required, while for K_s^0 $1+3$ nucleons are necessary. It does not mean, of course, that an effective target of many nucleons represent a multinucleon annihilation. Nevertheless, it can be a good indication for favorable conditions for such a process.

The experimental behavior of the ratio Λ/K_s^0 in complex nuclei and the effective targets involved in Λ and K_s^0 production, raise two kinds of questions: the experimentally measured one-order-of-magnitude enhancement in comparison with elementary process, enhancement which can not be simply justified by geometrical scaling, is a signal of *new physics*? The different effective targets measured for Λ and K_s^0 production is a signal of *different mechanisms*?

A clear interpretation of *all* these facts is *not* existing yet. Two different theoretical approaches have dealt with the problems of strangeness enhancement and rapidity distributions. Dover and Koch⁽⁷⁴⁾ try to understand the data on strange particle production in $\bar{p}$ -nucleus interaction in terms of a conventional hadronic picture, in which strangeness is produced in first order $\bar{N}N$ processes and redistributed by a combination of direct and sequential (final state interaction) processes. The conclusion is that the main features of the data, namely the absolute cross sections for Λ and K_s^0 production, and the energy and A dependence of the ratio Λ/K_s^0 for momenta ≤ 4 GeV/c, can be understood in terms of direct (D), associated production (AP) and strangeness exchange (SE) contributions.

In particular, in Λ cross section evaluation, the SE contribution is given by processes like:

where $i = \bar{K}, \bar{K}^*$ (see Fig. 17).

In the AP term

where j can be both a pion and a meson resonance (ρ, ω, η) (see Fig. 18). The calculated value for the inclusive Λ cross section turns out to be 215 mb at 4 GeV/c⁽⁷⁴⁾, to be compared with the experimental value of 193 ± 12 mb⁽¹⁹⁾.

According to Rafelski⁽⁷⁵⁾, it is the natural fate of the annihilation process, in which quark-antiquark annihilation occurs, to proceed via a fireball of quarks and gluons. If the annihilation occurs not too far below the nuclear surface (at 3+4 GeV/c the penetration depth is about one nuclear diameter), the reaction products are contained in a narrow forward tube along which they

distribute to nuclear matter all the annihilation energy. It is then possible to postulate the formation of *supercooled quark matter* at $T \leq 60$ MeV, satisfying all the physical constraints, in particular the value of entropy per baryon, although in a range of thermodynamic parameters where one would normally find hadronic gas. The strangeness enhancement in KEK data⁽¹⁹⁺²¹⁾ and the total strangeness abundance as observed in Ta are consistent with the hypothesis of formation of quark matter. Moreover, the agreement of data with rapidity distributions computed assuming a *unique thermal source* for the emitted particles at the same temperature confirms the internal consistency of the hypothesis of a central fireball disintegrating into various particles.

In conclusion, concerning the specific problem of unusual annihilations, the situation appears rather contradictory. The Dover and Koch calculation⁽⁷⁴⁾ makes some approximations and specific assumptions, like the strong absorption limit for K and $\Sigma^\pm$ conversion. No exotic explanation, as quark gluon plasma formation or, more specifically, multinucleon annihilation, is required to explain the relevant strangeness enhancement. Of course this conclusion is not along the line of the main result of the Cugnon and Vandermeulen model⁽⁶⁶⁾, according to which clear signature of unusual annihilation is represented by a strangeness enhancement. A previous attempt by Ko and Yuan⁽⁷⁶⁾, using the same rescattering approach, failed in reproducing the experimental value, letting so opened the door to some unusual phenomena. Supercooled quark matter in the Rafelski model⁽⁷⁵⁾, formed already at 4 GeV/c, is of course at the extreme position in the scale of exotica.

4) High energy tail in inclusive proton spectrum under strangeness trigger

There is an impressive experimental result obtained years ago in an already classical experiment by Oh et al.⁽⁶⁷⁾. In $\bar{p}d$ annihilation in the 1+3 GeV/c region, they measured the proton spectrum with a trigger on $K\bar{K}$ pair.

The proton spectrum shows (see fig. 19) a marked peak at low momentum, which corresponds to the spectator proton (the average momentum inside the deuteron is ≈ 100 MeV/c). In addition, there is a long tail, which extends very far in the high momentum domain. This tail cannot be explained by the proton rescattering on K or π^0 meson. It thus should correspond to a large extent to the annihilation on two nucleons. Indeed, the followed slope corresponds to a temperature $T=160$ MeV⁽⁵⁹⁾, which confirms the emission from a nuclear region particularly heated by energy deposition.

The interesting feature is that this clear signal completely *disappears* in the background⁽⁷⁷⁾, when the $K\bar{K}$ trigger is not used (see fig. 20). In such a way a direct connection seems to be put in evidence between strangeness production and multinucleon annihilation. From the entity of the excess of events above 0.2 GeV/c one can quantify the $B = 1$ contribution in $\bar{p}d$ annihilation. This number turns out to be around 10%.

5) Hypernuclei formation

The experiment PS 177 has observed delayed fissions following $\bar{p}$ -annihilation at rest on ^{238}U and ^{209}Bi (23,24). The large lifetime ($\tau \approx 10^{-10}\text{s}$); the yields (between $8 \cdot 10^{-4}$ and $4 \cdot 10^{-3}$); the fission mode (symmetric), restrict, according to the authors, the only possible explanation to the formation of Λ -hypernuclei. For nuclei heavier than Li, the non mesonic decay

$$\Lambda + N \rightarrow N + N \quad (1)$$

should predominate. One may expect the residual nuclei to be excited to energies substantially exceeding the fission barriers in the region of Uranium and Bismuth.

Two mechanisms can lead to the hypernucleus formation:

a) Usual annihilation ($B = 0$): two-step process

$$\bar{p}N \rightarrow K\bar{K} \pi's \quad (2)$$

followed by

$$\bar{K}N \rightarrow \Lambda\pi, \quad (3)$$

and then fixation to the nucleus.

The particular interest of this process for producing hypernuclei is the kinematics⁽⁷⁸⁾. In fact the momentum distribution of the kaons peaks closely to the momentum of recoilless production of lambda particles, therefore favouring the formation of the hypernucleus. The yield Y_0 of formation of one hypernucleus per annihilation in the two-step process can be written as

$$Y_0 = B_{\bar{K}} P_{\Lambda}^A F_{\Omega} \quad (4)$$

where $B_{\bar{K}}$ is the branching ratio for kaon productions,

P_{Λ}^A is the probability of hypernucleus formation,

F_{Ω} is the fraction of the total solid angle seen by the $\bar{K}$ when interacting within the nucleus.

Following the evaluation of ref. (79) one can put

$$P_{\Lambda}^A \approx 3 \cdot 10^{-2} \quad (5)$$

Moreover $F_{\Omega} \approx 30\%$, since the $\bar{N}N$ annihilation takes place on the surface, and $B_{\bar{K}} = 0.06^{(80)}$

Therefore $Y_0 \approx 6 \cdot 10^{-4}$ (accurate within a factor of 2). This value is lower than the experimental result.

The second possible formation mechanism is:

b) Unusual annihilation ($B = 1$)

$$\bar{p} (NN) \rightarrow K\Lambda \pi's \quad (6)$$

followed by Λ fixation.

In this case

$$Y_1 = P_1 R_1 P_{\text{fix}} \quad (7)$$

where P_1 is the formation frequency of the fireball $B = 1$, R_1 is the branching ratio for the channel $K\Lambda$ in $B = 1$ decay and P_{fix} is the fixation probability.

From Cugnon and Vandermeulen⁽⁶⁶⁾.

$$P_1 \approx 10\% \quad R_1 = 4.8 \cdot 10^{-2} \quad (8)$$

P_{fix} depends on the Λ energy: a possible value can be $\approx 10\%$.

Therefore

$$Y_1 \approx 4.8 \cdot 10^{-4} \quad (9)$$

From which $Y = Y_0 + Y_1 \approx 10^{-3}$, close to the experimental result.

6) Correlation measurements between emitted particles

We come back here to the correlation measurement performed at Serpukhov using 5.2 GeV antineutrons on Ta⁽⁷⁾ discussed in Sect. 2.2. The measurement presents features which can not be explained within the framework of the conventional INC model, also in the recent version of Iljinov⁽³²⁾ (see fig. 3). It has to be noted that the cascade calculation taking into account the trawling effect describes well the experimental correlation in the case of interaction of high energy (6+20 GeV) *protons* with medium-heavy nuclei^(50,51,81). Therefore, the discrepancies seem to be connected to the annihilation process, but they cannot be explained by a model which considers only "usual" annihilations. The relevant point is that discrepancies are, seemingly, most strong in the channels of *mesonless* and *one-meson* annihilations: namely, there where, in principle, one should look for unusual annihilations.

It does not seem reasonable to draw any definite conclusions until more accurate experiments on the measurement of the correlations between protons and $\pi^\pm$ and also π^0 are performed. However, this might be the *first direct evidence* of a discrepancy from the conventional cascade mechanism, to be ascribed to an unusual annihilation.

7) High energy tail in primordial pion spectrum

If annihilation is not a point-like event, i.e. it involves a larger and at higher temperature hadronic region, the thermal spectrum of primordial pions should be affected, in the sense that a higher energy and temperature tail should appear. There are indeed two experimental evidences which support such a picture:

- the inclusive pion energy spectrum from antiproton annihilation on Uranium at 608 MeV/c (PS 187 experiment)⁽⁵²⁾ exhibits large kinetic energy values which are *far* from the thermal slope of primordial pions (see fig. 21);
- the pion rapidity distribution from antiproton annihilation on Neon at 607 MeV/c (PS 179 experiment)⁽⁶⁾ shows, if one takes into account only pions with $p_T > 400$ MeV/c, namely only primordial pions, a high rapidity component, which is not reproduced by a $\bar{p}p$ phase space calculation (see fig. 22).

CONCLUSIONS

The antiproton-nucleus interaction presents more than one specific reason of interest. The interaction between the multipion system formed in the $\bar{N}N$ annihilation and the nucleus produces "uniformly heated" nuclei. Although the process has been extensively investigated, precise questions have not been addressed yet: in particular the way through which an excited nucleus loses its cohesion. Indeed, in highly excited nuclear matter can occur a phase transition, of the liquid-gas type, of which specific signature is the multipole production of nuclear fragments (multifragmentation). The properties of this phase transition should bear some relationship with the saturating properties of nuclear forces and the nuclear tension.

Another great reason of interest is the study of the process of annihilation in itself. From the problem of if and how nuclear matter influences the elementary $\bar{N}N$ annihilation mechanism, to the search for unusual annihilations, in the sense of "true" many-nucleon annihilations.

The latter topic contains, in its turn, many fascinating suggestions at the modern frontier of Nuclear Physics. From the role of multi-quark configurations, due to the overlap of many-quark bags, to the "extreme" answer of a nucleus to a concentrated delivery of energy: with the possibility of creating a dehadronized region in which new quark degrees of freedom play a specific role (quark-gluon blobs). Typical signatures of such a kind of processes should be an enhancement of strangeness production and high energy tails in proton and pion spectra.

Multinucleon annihilations can also help to a better understanding of the pure charge conjugation concept: indeed, when antiquarks are introduced in a nuclear medium, if more than one quark-bag is involved in the annihilation, their evolution does not follow necessarily $\bar{p}p$ conjugation, since any symmetry is now lost in grouping of $\bar{q}q$ pairs.

The INC models can not-intrinsically-take into account multinucleon annihilations since they are build, by definition, only on known processes. Therefore, the experimental evidences of multinucleon annihilations appear or under specific signatures, like strangeness, or as deviations from the model predictions. The number of such signatures, or deviations, is increasing in the new experimental data and they begin to constitute a bulk of experimental confirmations from which to derive a new physics. However, the "unusual" data suffer of low statistics, precision measurements and processes never studied as, for instance, the mesonless annihilations, among the Pontecorvo reactions, and all the physics with antineutrons.

A lot of work is worthy to be performed, in particular with the next generation of experiments in the ACOL era at LEAR.

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FIGURE CAPTIONS

- Fig. 1 - Correlation between the average number of π^- and the number of charged tracks. Bars: exp. data, ref. (6), $\bar{p}$ -Ne at 180 MeV. Full and open circles: predictions of the Compound Poissonian model with and without charge conservation, ref. (31).
- Fig. 2 - Intranuclear cascade calculation for the correlation between the mean ejected nucleon multiplicity versus the ejected pion multiplicity, for 2 GeV/c $\bar{p}$ -annihilations in a nucleus of $A = 100$, ref. (40).
- Fig. 3 - Correlations between the average number of protons and the numbers of $\pi^\pm$. Dots: exp. values, ref. (7), $\bar{n}$ -Ta at 5.2 GeV. Solid and dotted lines: Iljinov model predictions with and without trawling, ref. (32).
- Fig. 4 - Iljinov model predictions, ref. (32), for the distributions of the thermalized residual nuclei in $\bar{p}$ - ^{100}Ru annihilation at 180 MeV. ΔA , number of ejected nucleons; E^* , excitation energy; $\vec{P}$, momentum; $\vec{L}$, angular momentum. Solid and dashed histograms refer to calculations with and without the trawling effect, respectively.
- Fig. 5 - Comparison between the Cugnon et al. model predictions, ref. (38), histogram, and the exp. data of ref. (29), $\bar{p}$ stopped in ^{98}Mo , dots.
- Fig. 6 - Comparison between the Iljinov model predictions, ref. (32), and the exp. data of ref. (29), $\bar{p}$ stopped in ^{95}Mo , dots. Solid and dotted lines refer to calculations with and without the trawling effect, respectively.
- Fig. 7 - Left: schematic illustration of a clan production in a high energy p-p collision. The ancestors indicated by dots are the partons produced in a hard interaction. Right: clan production in $\bar{p}$ -annihilation on a nucleus. The pion (dotted lines) originating from the annihilation fireball propagate inside the nucleus and produce ejectiles (nucleons, solid lines) which are members of the clan.
- Fig. 8 - Best fit by negative binomials (full lines), ref. (49), of the charged particle multiplicity distributions measured in $\bar{p}$ -annihilation in emulsion, both at rest (squares) and at 300 MeV/c (open dots), ref. (48).
- Fig. 9 - Multiplicity distribution of charged tracks from $\bar{p}$ -annihilation in Neon at various energies. The histograms are exp. data from ref. (5). The points are the Compound Poissonian model results, ref. (31).
- Fig. 10 - Production probability of a given number of charged particles n_{ch} in the $\bar{p}$ -annihilation in emulsion. Solid and dashed histograms refer to calculations with the Iljinov model, including or not the trawling effect, ref. (32). The dots are exp. values, ref. (48).
- Fig. 11 - Distribution of residual nuclei in ^{98}Mo after $\bar{p}$ -annihilation.
- Fig. 12 - Calculated yields of residual nuclei as functions of A and Z following the annihilation of $\bar{p}$ in ^{98}Mo , Iljinov model, ref. (30). Values in parts a) and b) were calculated with and without trawling effect, respectively.
- Fig. 13 - Triangle diagram describing the two-step mechanism of the reaction $\bar{p}d \rightarrow \pi^- p$.
- Fig. 14 - Quark flow diagram describing the reaction $\bar{p}d \rightarrow \pi^- p$.
- Fig. 15 - Evolution of antiquarks in annihilation processes. a) $\bar{p}p$ annihilation ($B = 0$); b) two-nucleon $\bar{p}$ -annihilation ($B = 1$).

- Fig. 16 - Strangeness production according to Rafelski model, ref. (64). The $s\bar{s}$ enhancement mechanism is essentially due to gg interaction more than $\bar{q}q$ annihilation ($\approx 10\%$).
- Fig. 17 - Associated production (AP) of strangeness in the rescattering model of Dover and Koch, ref. (74).
- Fig. 18 - Strangeness exchange (SE) processes in the rescattering model of Dover and Koch, ref. (74).
- Fig. 19 - High momentum spectator proton tail in $\bar{p}$ -absorption on deuterium at $1+3$ GeV/c under $K\bar{K}$ trigger. The experimental points are from ref. (67). Solid line: deuteron wave function.
- Fig. 20 - Spectator momentum distributions at $1.6+2$ GeV/c for reactions $\bar{p}d \rightarrow p_s p \bar{p} \pi^-$ (up) and $\bar{p}d \rightarrow p_s \pi^+ \pi^+ \pi^- \pi^- \pi^-$ (down) from ref. (77). The clear signal at high momenta seen under strangeness trigger (see fig. 19) completely disappeared in the background.
- Fig. 21 - High energy primordial pion and proton tails in inclusive pion and proton spectra from $\bar{p}$ -annihilation on Uranium at 607 MeV/c. Dots and crosses: exp. points from ref. (52). Full lines: primordial pion spectrum and contribution of the nucleons which have been hit only once, respectively, from ref. (41). The corresponding temperatures are indicated.
- Fig. 22 - Rapidity distribution for primordial π^- ($p_T > 400$ MeV/c) from $\bar{p}$ annihilation on ^{20}Ne at 608 MeV/c. Full and dashed line histograms represent the experimental data, ref. (6), and the $\bar{p}p$ phase space calculation, respectively.

FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5

FIG. 6

pp interaction

$\bar{N}N$ annihilation

FIG. 7

FIG. 8

FIG. 9

FIG. 10

FIG. 11

FIG. 12

$$\bar{p} + d \rightarrow \pi^- + p$$

FIG. 13

FIG. 14

FIG. 15

FIG. 16

FIG. 17

FIG. 18

FIG. 19

FIG. 20

FIG. 21

FIG. 22

TABLE I
Strangeness enhancement (Cugnon and Vandermeulen)

B	$n\pi$ (%)	$K\bar{K}$ (%)	ΛK (%)	ΣK (%)	YK (%)	Total strangeness (%)
0	95.3	4.7	---	---	---	4.7
1	82.9	3.8	4.8	8.5	13.3	17.1
2	82.0	3.7	5.3	8.9	14.2	17.9
3	80.7	3.6	5.9	9.8	15.7	19.3
4	79.0	3.3	6.8	10.8	17.6	20.9

TABLE II
Recent experimental results in $\bar{p}$ -nucleus strangeness production

$$R = \frac{\Lambda}{K_s^0}$$

Momentum (GeV/c)	p	d	^4He	Ne	Xe	Ta
@ rest			1.09 $\pm$ 0.10(17)	1.25 $\pm$ 0.19(17)	1.68(22)	
0.45 $\pm$ 0.92		0.22 $\pm$ 0.2(70)				
0.3 $\pm$ 1.05					2.2(22)	
0.6			0.94 $\pm$ 0.04(17)	2.3 $\pm$ 0.7(15)		
3.0	0.18 $\pm$ 0.04(71,72)	0.29 $\pm$ 0.04(67)				3.3 $\pm$ 1.2(21)
4.0	0.28 $\pm$ 0.04(71,72)					2.4 $\pm$ 0.3(19,20)

Table III
 $\bar{p}$ Xe strangeness production
 (ITEP, Moscow)

N	Reaction	Number of events @ rest	Number of events in flight 0.3÷1.05 GeV/c
1	$\bar{p}\text{Xe} \rightarrow \Lambda X$	62 (22K ⁺)	191 (72K ⁺)
2	$\bar{p}\text{Xe} \rightarrow \Lambda K_s^0 (\pi^+ \pi^-) X$	17	57
3	$\bar{p}\text{Xe} \rightarrow \Lambda K_s^0 (\pi^0 \pi^0) X$	6	19
4	$\bar{p}\text{Xe} \rightarrow K_s^0 (\pi^+ \pi^-) X$	67 (10K ⁺)	14 (14K ⁺ , 1 K ⁻)
5	$\bar{p}\text{Xe} \rightarrow K_s^0 (\pi^+ \pi^-) K_s^0 (\pi^+ \pi^-) X$	4	12
6	$\bar{p}\text{Xe} \rightarrow K_s^0 (\pi^+ \pi^-) K_s^0 (\pi^0 \pi^0) X$	1	5

TABLE IV
Rapidity in strangeness production

Experiment	Momentum (GeV/c)	Λ	Effective Target K_s^0
PS 179(15)	0.6	8^{+7}_{-3}	1
KEK(21)	3.0	13	3
KEK(19,20)	4.0	13	3