Laboratori Nazionali di Frascati

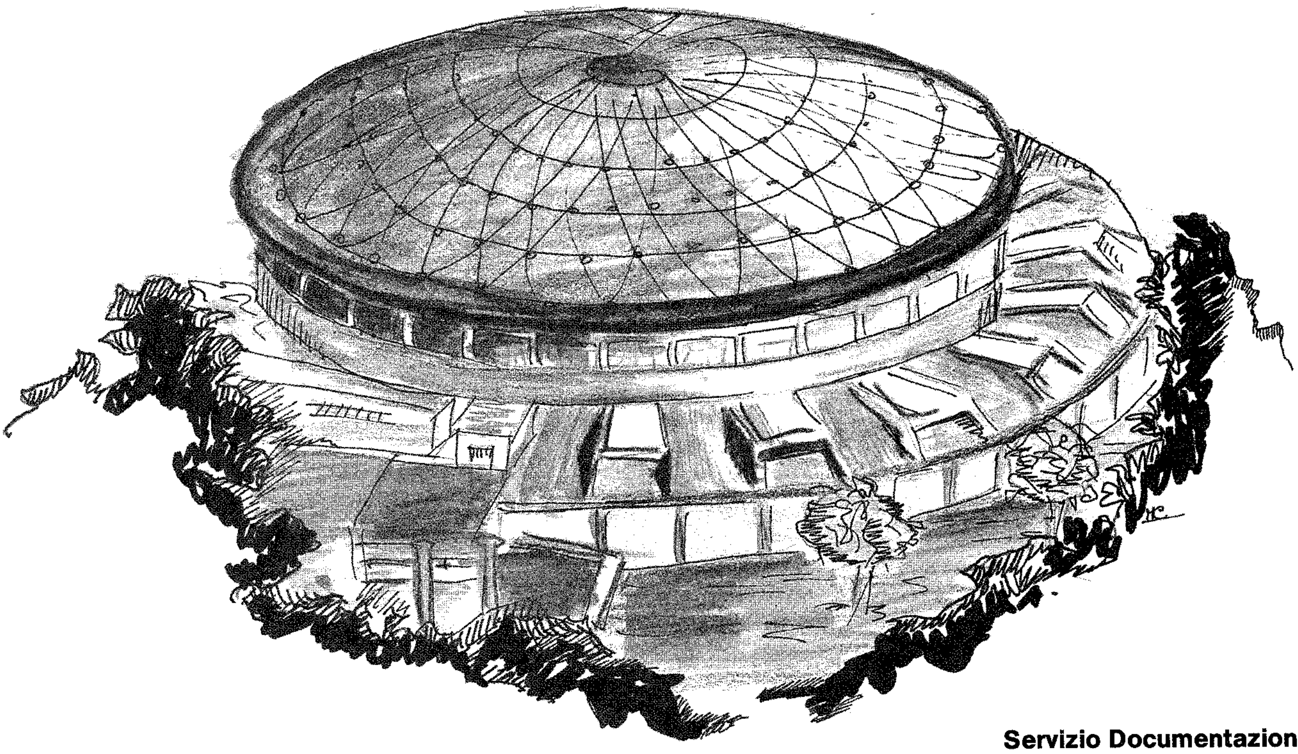
LNF-90/044(P)
5 Giugno 1990

C. Guaraldo:

ANTINUCLEON - NUCLEUS PHYSICS: EXPERIMENTAL OVERVIEW

Invited talk presented at the
First Workshop on Intense Hadron Facilities and Antiproton Physics
October 23-25,1989, Torino, Italy

To be published as a dedicated volume of the series
"Atti delle Conferenze" by the Italian Physics Society



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ANTINUCLEON - NUCLEUS PHYSICS: EXPERIMENTAL OVERVIEW

Carlo Guaraldo
Laboratori Nazionali di Frascati , C.P. 13, I - 00044 Frascati, (Roma), Italy

ABSTRACT

We review the more recent experimental results concerning antiproton and antineutron interaction with nuclei. We discuss some significant measurements with the aim to underline discrepancies from the current models and to indicate perspectives for future researches.

1. - INTRODUCTION

We shall overview in this paper the more recent experiments in antinucleon-nucleus physics at intermediate energy (≤ 6 GeV/c) .The majority of data come from antiproton beams, but preliminary results obtained with antineutrons are also available.

Our aim is to examine the general features of annihilation process in nuclear matter, underlining the aspects that can be understood in terms of a conventional Intranuclear Cascade (INC) picture. In the same time, we focus our attention towards eventual discrepancies from predictions, trying to identify their possible sources and to indicate new perspectives. Inclusive proton cross sections and correlation measurements will be example of such investigation. Looking for scarcely explored fields, we shall then point out the study of heavy mesons production and interaction with nuclei, stressing the many implications: from low energy interaction cross sections, to strangeness production. Heavy mesons may also play a direct role in determining pion multiplicities and the distribution of residual nuclei after annihilation.

2. - RECENT ANTIPROTON-NUCLEUS RESULTS

A consistent set of measurements on antiproton-nucleus interaction is actually available. Three laboratories have recently dealt with antiproton nuclear physics: CERN (LEAR), KEK and ITEP (Moscow).

The momentum interval interested by the experiments ranges from 0 up to 4 GeV/c. LEAR results come from seven experiments (in parenthesis the name of the spokesman): PS 171 (Klempt), PS 177 (Polikanov, Rey-Campagnolle), PS 179 (Piragino), PS 183 (Smith), PS 184 (Garreta), PS 186 (von Egidy), PS 187 (Di Giacomo).

KEK results come from Miyano experiment.

ITEP data have been taken by the group of Dolgolenko with the bubble chamber DIANA

The physics with antiprotons has produced the list reported below of recent published results.

Elastic and inelastic scattering from light nuclei

- G. Bruge et al., ref. (1).
- M.- C. Lemaire et al., ref. (2).
- G. Bruge et al., ref. (3).
- Yu. A. Batusov et al., ref. (4).

Pion multiplicities

- F. Balestra et al., ref. (5).
- F. Balestra et al., ref. (6).
- J. Riedlberger et al., ref. (7).
- E. D. Minor et al., ref. (8).

Inclusive pion spectra

- P.L. Mc Gaughey et al., ref. (9).
- P.L. Mc Gaughey et al., ref. (10).
- F. Balestra et al., ref. (5).
- F. Balestra et al., ref. (11).
- F. Balestra et al., ref. (6).
- J. Riedlberger et al., ref. (7).
- E.D. Minor et al., ref. (8).

Proton spectra

- P.L. M. Gaughey et al., ref. (9).
- P.L. Mc Gaughey et al., ref. (10).
- E. Aslanides et al., ref. (12).
- F. Balestra et al., ref. (6).

- J. Riedlberger et al., ref. (7).
- P. Hofmann et al., ref. (13).

Neutron spectra

- A. Angelopoulos et al., ref. (14).

Gamma spectra

- T.A. Armstrong et al., ref. (15).
- T.A. Armstrong et al., ref. (16).

Reaction and break up cross sections on light nuclei

- F. Balestra et al., ref. (17).
- F. Balestra et al., ref. (18).
- F. Balestra et al., ref. (19).
- G. Bendiscioli et al., ref. (20).

Correlation measurements between emitted particles

- F. Balestra et al., ref.(5)
- F. Balestra et al., ref.(6).

Determination of the annihilation ratio $\sigma(\bar{p}\,n)\,/\,\sigma(\bar{p}\,p)$

- F. Balestra et al., ref. (21).
- F. Balestra et al., ref. (22).
- F. Balestra et al., ref. (6).

Light nuclei production

- F. Balestra et al., ref. (11).
- W. Markiel et al., ref. (23).
- P. Hofmann et al., ref. (13).

Strangeness production

- S.J.H. Parkin et al., ref. (24).
- F. Balestra et al., ref. (25).
- F. Balestra et al., ref. (26).
- F. Balestra et al., ref. (27).
- G.A. Smith et al., ref. (28).
- J. Riedlberger et al., ref. (7).
- K. Miyano et al., ref. (29).

- K. Miyano et al., ref. (30).
- K. Miyano et al., ref. (31).
- V.V. Barmin et al., ref. (32).

Heavy hypernuclei

- J.P. Bocquet et al., ref. (33).
- J.P. Bocquet et al., ref. (34).

Antiproton induced fission

- J.P. Bocquet et al., ref. (35).
- A. Angelopoulos et al., ref. (14).
- T.A. Armstrong et al., ref. (15).
- W. Markiel et al., ref. (23).
- T.A. Armstrong et al., ref. (16).
- H. Machner et al., ref. (36).

Yields of residual nuclei

- E.F. Moser et al., ref. (37).
- E.F. Moser et al., ref. (38).
- T. von Egidy et al., ref. (39).

3. - RECENT ANTINEUTRON-NUCLEI RESULTS

Antineutron data are scarce in absolute due to lack of antineutron beams. Recent results come from LEAR and from Serpukhov and cover a momentum interval from 0 up to 6 GeV/c.

At LEAR, a dedicated experiment, PS 178 (spokesman Bressani), has prepared an antineutron beam and started a systematic programme of antineutron physics. A second LEAR experiment, PS 173 (Walcher), has obtained antineutron data as secondary research line of the scientific programme. At Serpukhov, an experimental programme with a 12 GeV/c antideuteron beam has allowed to obtain, by stripping on the hydrogen atoms of the bubble chamber LYUDMILA (Baranov) an antineutron beam of 6 GeV/c. We report also here the first CERN results obtained using antineutrons, the data of Besh and collaborators with the well known GARGAMELLE bubble chamber.

Below, the preliminary results of a still unexplored antineutron physics programme are reported:

Antineutron production on nuclei

- T Bressani et al., ref. (40).

Correlation measurements between emitted particles

- H.J. Besh et al., ref. (41).
- V. F. Andreev et al., ref. (42).
- V.F. Andreev et al., ref.(43).

Pion multiplicities

- V.F. Andreev et al., ref. (42).
- V. F. Andreev et al., ref. (43).
- T. Bressani et al., ref. (44).

Annihilation cross sections

- W. Brückner et al., ref. (45).
- M. Agnello et al., ref. (46).

4. - ANTINUCLEON-NUCLEUS ANNIHILATION: GENERAL FEATURES AND OPEN PERSPECTIVES

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. The annihilation of intermediate energy antiprotons takes place essentially 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. The created pions (on average five) cascade through the nucleus, interacting with the nucleons and directly ejecting some of them. Their energy being, on average, in the region of the Δ resonance ($100 \div 300$ MeV), most of the pions have short range and consequently energy is transferred to the nucleus via deltas excitation, interaction and decay. As net result of the cascade, secondary and "primordial pions" (those which have not interacted), fast nucleons and heavier particles (d,t,α..) emitted in a quasi-spallation process can be found in the final state. After the cascade, the heated residual nucleus evaporates few particles, mainly neutrons. This sequence of reactions is embodied in the INC models(47÷ 54), in which the cascade is viewed as a succession of binary collisions.

It is well know that INC calculations can be considered, on the whole, successful as far as the general features of data are concerned: see the recent reviews of Cugnon and Vandermeulen(55) and Guaraldo(56). This confirms the underlying elementary multipion dynamics in nuclear matter. Beyond the standard version of the INC models, more refined approaches(57÷ 59) have taken into account the non-linear effect of the local reduction of the nuclear density and explained fairly well, to give an example, the nuclides chart after antiproton annihilation at rest on heavy nuclei$^{(57)}$. Moreover, by handling exactly charge conservation at each step of the cascade (in contraddistinction with the standard code, which disregard isospin degrees of freedom)$^{(58)}$, it has been solved the apparent puzzling correlation between the average number of π^- and the total number of charged prongs experimentally found in $\bar{p}$ Ne annihilation @ 600 MeV/c$^{(6)}$.

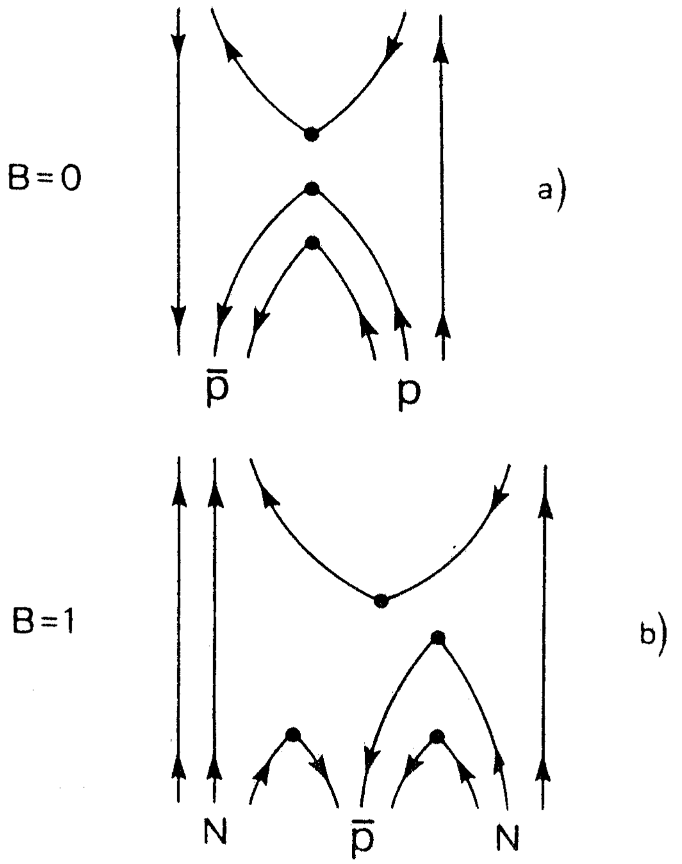

FIG. 1 - Evoluation of antiquarks in annihilation processes. a) $\bar{p}$p annihilation (B=0); b) two-nucleon $\bar{p}$ annihilation (B= 1).

Sic stantibus rebus, it might rise the belief that in antinucleon-nucleus physics, no room is left for new phenomena, in a deeper knowledge of nuclear matter. In the following Sections, we intend to examine some significant experimental results with the aim to underline the "weak points" of conclusions often too easily drawn. Discrepancies with predictions indeed can be found.

They can be ascribed essentially to three sources: a) quality of data, still too scarce, and/or incomplete and limited to inclusive cross sections; b) quality of the INC model which, as properly underlined by Cugnon and Vandermeulen$^{(59)}$, is still a rather crude model for the quantum multiple scattering problem; c) real "unusual" effects, like multinucleon annihilations, which are, by definition, totally absent in the actual theoretical treatment based only on well established processes.

The latter point finds a clearer definition at the quark level, in which, for instance in the simplest case of two-nucleon annihilation, one impinging antiquark annihilates on a quark of the bag of one nucleon and the two others antiquarks annihilate on quarks of an other bag (see Fig. 1). This phenomenon has straightforward implications in studying the role of multiquark configurations, and in searching new quark degrees of freedom in nuclear matter (quark-gluon plasma), which are examples of frontier problems in modern nuclear physics. For a discussion on the physical meaning of multinucleon annihilations, see ref.$^{(56)}$.

We shall also discuss a rather unexplored field which has been opened by antiproton annihilation on nuclei. It is the investigation of interaction of heavy mesons with nuclei. The interaction of heavy mesons (ρ,η,ω,..) with nucleons and nuclei has been usually studied producing mesons by high energy particles. Following this technique, meson-nucleons interaction cross sections were measured in a rather wide energy range (1÷ 10 GeV). Antiproton annihilation is indeed a rich source of all kind of mesons and meson resonances: together with pions, 32% of all $\bar{p}p$ annihilations at rest results in ρ production, 11% in ω production, 7% in η production. Moreover, approximately 5% of all annihilations at rest give $\bar{K}K$ production (a percentage which increases with energy): out of them, about 30% come from the decay of strange resonances $\bar{K}^*K^*$. For FWHM greater than about 100 MeV, i.e. for life times less than about 2fm/c, the evolution of a resonance does not generally imply an interaction with the nuclear medium. But for long-lived species, like η,η',ω, the annihilation spots can be regarded as localized "heavy-meson factories" - on the surface of the nucleus or deep in nuclear matter - offering powerful tools of investigation. Firstly, they allow a study of heavy meson-nucleus cross sections in the low energy range, inaccessible using the traditional technique for producing mesons. Moreover, also as a consequence of the low energy involved, there are speculations that quasi-stable meson-nucleus states may be formed.

The interaction of meson resonances with nuclear matter is significant also towards other relevant aspects of annihilation dynamics: (a) in evaluating the strangeness production in $\bar{p}$-nucleus annihilation, taking into account their rescattering ; (b) in considering the features of the absorption process of the pions "hidden" in a resonance, compared to the absorption of "free" pions. The point (b) has a direct influence on pion multiplicities and on the distribution of residual nuclei after annihilation.

5. - INCLUSIVE NUCLEON SPECTRA

The gross features of inclusive nucleon spectra after $\bar{p}$- nuclei annihilation are understood by INC models. However, we discuss this topic since, also in this emblematic case of a measurement which belongs–one might say "by definition" – to the first stage of any scientific programme, even in this rather rough way of exploring the intrinsic complexity of the annihilation process, nevertheless room is left for not trivial problems. Also at the LEAR energy. As for the pion spectra, one can distinguish in a proton spectrum two components: a low energy bump and a high energy tail, corresponding to different dynamics and different time scales. The most significant proton spectra are provided by the results of the LEAR experiments PS 179 (on Ne) (5,6), PS 184 (on ^{2}H, ^{6}Li, ^{12}C, ^{63}Cu, ^{208}Pb, ^{209}Bi) (12), PS 187 (on ^{12} C and ^{238} U)(9,10), all @ 600 MeV/c; moreover, of experiments PS 185 (on ^{14}N)(7) and PS 186 (on ^{12}C,^{40}Ca, ^{63}Cu, ^{92}Mo, ^{98}Mo,^{238}U)(13), both using stopped antiprotons. At these energies, fast nucleons are due, essentially, to direct ejection from primordial pions, but also to Δ inelastic scattering, after "true" pion absorption. To the energy transfer to the baryon system contribute also pions rescattered after isobars decay and pions colliding with nucleons. Of the initial energy, most is carried away by fast nucleons and by pions which escape from the nucleus. The remaining excitation is progressively randomized and, in a second stage, released under the form of evaporated nucleons.

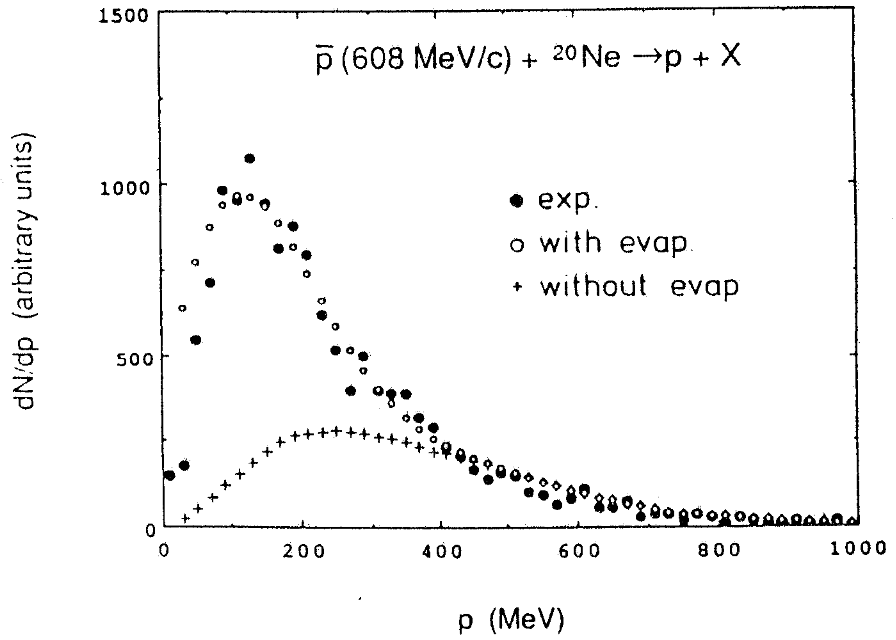

FIG. 2 - Proton momentum spectrum for $\bar{p}$ annihilation events on ^{20}Ne target. Exp. points: ref. (6). Calculation: ref. (59).

The existence of this target evaporative component is one of the most characteristic feature of low energy $\bar{p}$–nucleus annihilation. At the same time, the prediction of the low energy component in inclusive proton spectra is one of the most successful effort of INC calculation and therefore a validity check of the dynamics of multipion nucleus interaction (MPNI) included in the models. In light nuclei (C, Ne) the evaporative component appears as a low energy bump in the *proton* spectrum. In heavy nuclei, more rich in neutrons, in the de–excitation stage mostly *neutrons* are released. In the Uranium case, the nucleus undergoes fission, but the process is preceeded by a significant evaporation. Fission and evaporation then become competitive.

At LEAR, the only experimental apparatus able to measure low momentum protons (≤ 250 MeV/c) was the streamer chamber of PS 179 experiment(6). In Fig. 2, the heavy fragments spectrum (most protons) is shown. A characteristic low energy evaporative bump is clearly displayed. In the same figure, the prediction of the INC model of Cugnon and Vandermeulen(59) is also reported. In such a case, there is some difficulty in comparing theory with experiment. In fact the streamer distinguishes protons from heavy fragments, while the model does not introduce easily a reliable fragmentation process. The importance of the evaporation component is then seen in the striking discrepancy of predictions from experiment when the evaporative process is not taken into account (see Fig.2).

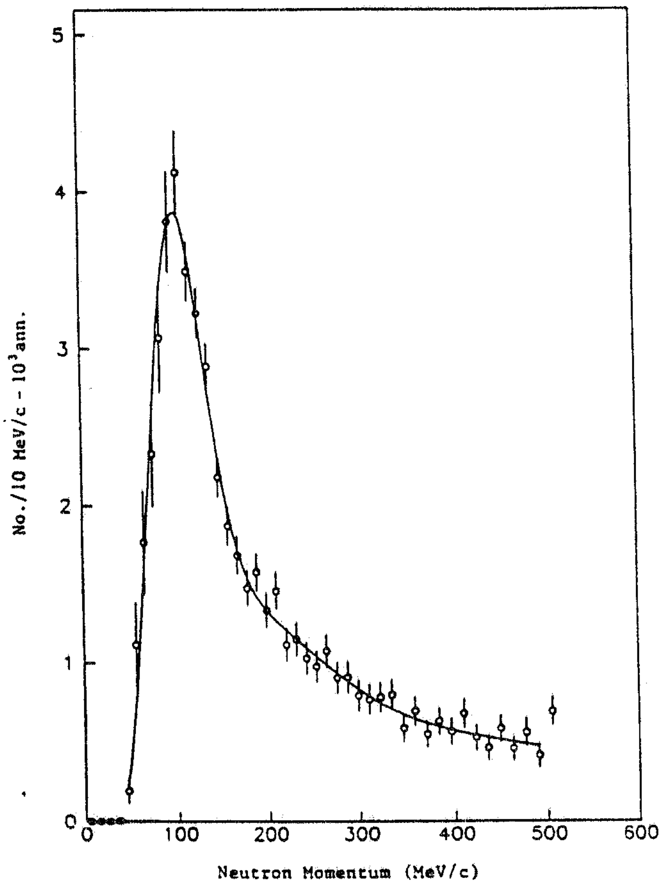

FIG. 3 - Observed neutron momentum spectrum from $\bar{p}$ annihilation at rest in Uranium, ref. (14).

For heavy nuclei, the evaporation component has been measured directly as neutron spectra[(14)], or indirectly looking for the yield of residual nuclei[(36)] which, in the case of Uranium, is the distribution of fission fragments (practically all reaction products are due the fission)[(36)]. The experiment PS 183 [(14)] has measured 5.77 neutrons per annihilation at rest on an Uranium target .The spectrum, peaked in the low momentum region, is shown in Fig. 3.

Fig. 4 shows the fission fragments distribution, after $\bar{p}$ annihilation at rest in ^{238}U, measured by the experiment PS 186[(36)]. It turns out that the most probable fission fragment has mass number A=106.

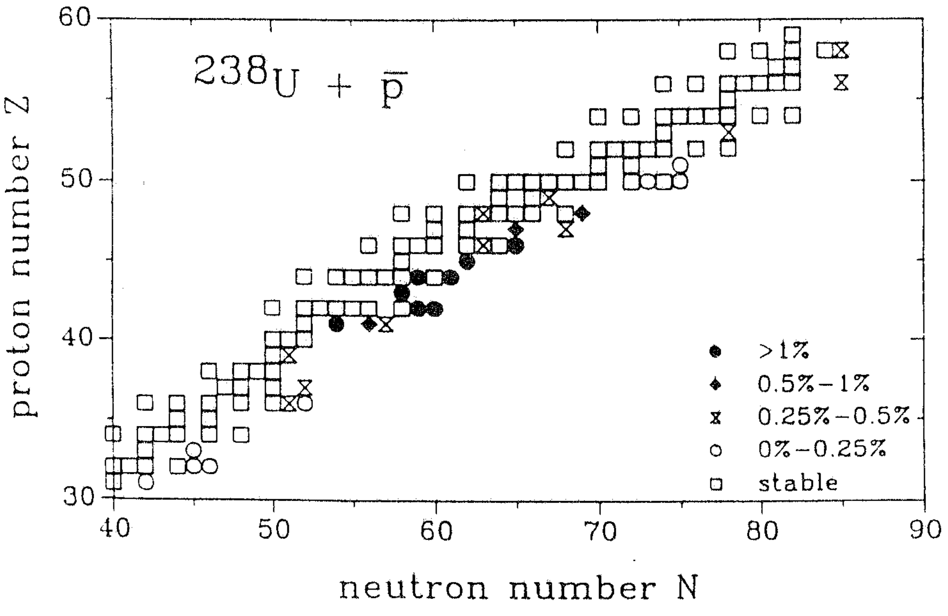

FIG. 4 - Fission fragment distribution after $\bar{p}$ annihilation at rest in Uranium: ref. (36)

If binary fission is assumed to be the underlying reaction mechanism, and neglecting particle emission following fission, fission from a system close to ^{213}Ac can be expected. This implies the removal of 26 nucleons (of which 23.7 neutrons and 2.3 protons) *prior* than the fission process. The discrepancy with the result of PS 183 experiment is probably caused by the selective trigger employed in measuring the neutron spectrum: in fact in that case only neutron events were accepted which were accompanied by a charged particle. The capability of INC models of reproducing the residual mass distribution of residual nuclei (53, 54), or the nuclides chart after p annihilation(57, 38) are significant in understanding MPNI.

The high momentum tail of the proton spectra is not equally fully understood. First of all, let's recall that, according to the existing speculations, a high energy tail should be the natural arena for unusual annihilations, the impressive signature of exotic processes, like "true" multinucleon annihilations (60), or also the formation of quark–gluon droplets (61,62).

But a foreward is necessary. The slopes of the Maxwell–Boltzman tails, which should give the "temperature" of the source, do *not* necessarily correspond to real *nuclear* temperatures. Indeed, a calculation of Mc Gaughey et al.(63) shows that only a small fraction of nucleons receive large kinetic energy. As a consequence, high nuclear temperatures probably are not attained and only limited surface regions are responsible for nucleon emission. In other words, MPNI seems much more to lead, at the energy considered, to a multi-spallation process, rather than to the heating of substantial pieces of nuclear matter. So, any conclusion about exotic effects should not forget the circumstance that, below some GeV/c of incident momentum [6 GeV/c in the case of $\bar{p}$, according to Strottman and Gibbs (64)], a real heating of the nucleus, in the direction of a phase transition, can not occur.

We shall take into consideration two experimental results, both worthy of attention for their implications. The first one, reported in Fig. 5, is the high energy tail of the proton spectrum obtained by PS 187 experiment(9). In the Figure are also reported: the INC conventional calculation of the same reference, and the result of the meson–exchange model of Oset et Hernandez (65), with only one–body annihilation taken into account. It is evident the discrepancy between experiment and calculations. In Fig. 6 the same data and the standard INC calculation are reported, together with the result of Oset and Hernandez obtained, in this case, taking explicity into account many-body annihilation. The high energy region of the distribution is fairly well reproduced. This suggests that, at qualitative level, multinucleon annihilations seem to behave as predicted by theory in fitting experimental data. However, one should be very careful before drawing definite conclusions. The calculation of the proton tail is sensitive to the interaction model for high energy pions and also to high momentum components in the momentum distribution of the target nucleons. A careful analysis of the influence of these effects has been recently performed by Cugnon and Vandermeulen (59). Their conclusion is that the status of actual calculations does not allow to take any prediction for the high energy tail of the proton spectrum more seriously than within a factor 2 or 3.

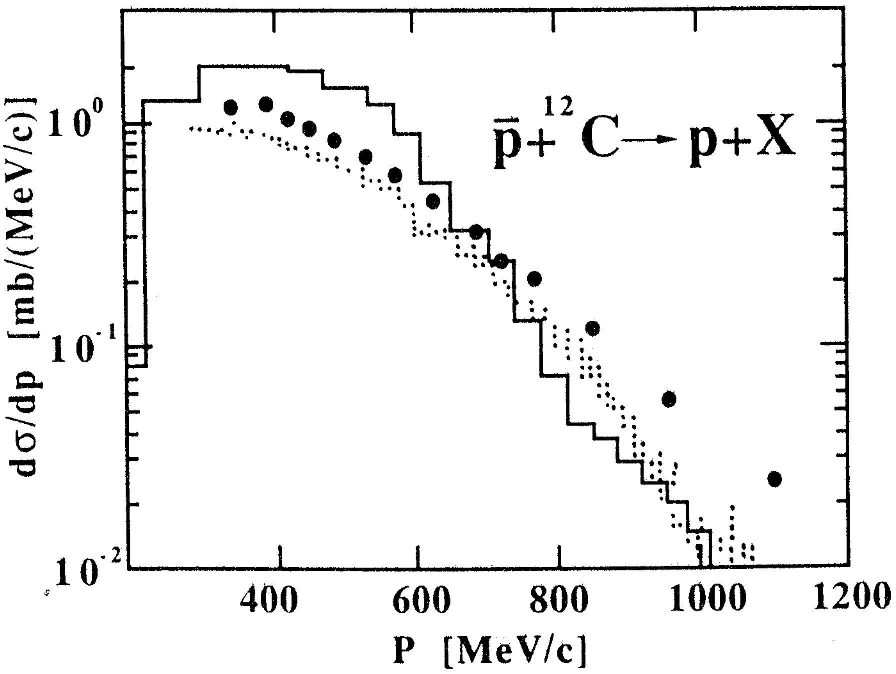

FIG. 5 - Proton momentum distribution after $\bar{p}$ annihilation at 600 MeV/c in ^{12}C. Full dots: exp. points, ref. (9); dotted line: INC calculation of ref. (9); continuous histogram: mesonic model results without taking into account many-body annihilation mechanism, ref. (65).

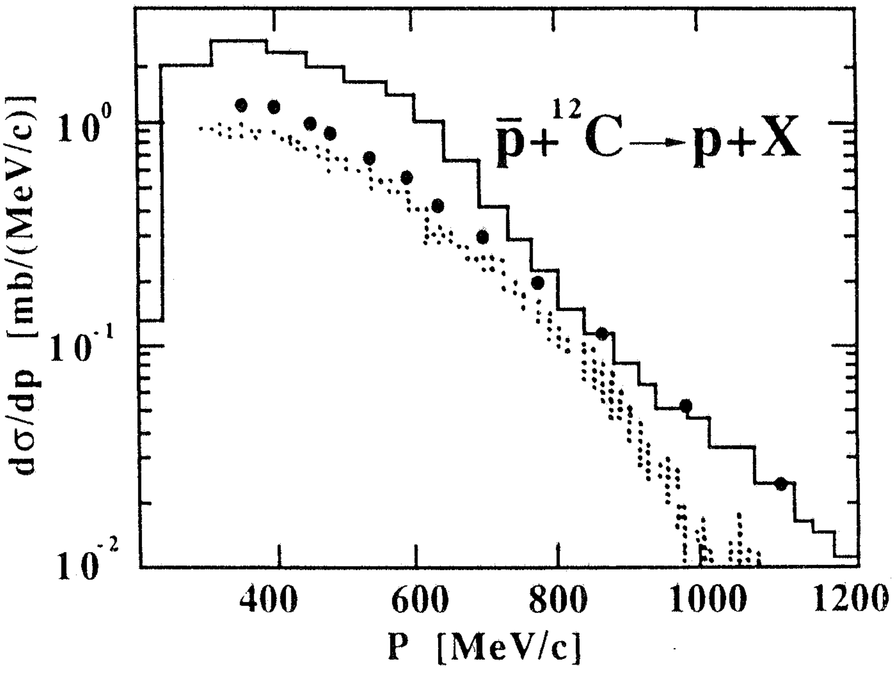

FIG. 6 - Same as Fig. 5, but the continuos histogrm contains now the contribution of many-body annihilation.

The second example refers to an impressive experimental result obtained years ago by Oh et al.(66). In $\bar{p}d$ annihilation in the 1÷3 GeV/c region they measured the spectator proton spectrum being active a strangeness trigger on $\bar{K}K$ pairs. The proton spectrum shows (see Fig.7) 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 (61), which confirms the emission from a nuclear region particulary heated by energy deposition. The interesting feature is that this clear signal completely *disappears* in the background (67), when the $\bar{K}K$ trigger is not used (see Fig.8). In such a way a *direct connection* seems to be put in evidence between *strangeness production*, *high momentum proton tail* and *multinucleon annihilation*: just according the prediction of the statistical model of Cugnon and Vandermeulen(60). There is also a quantitative information: from the entity of the excess of events above 0.2 GeV/c one can quantify the B = 1 contribution in pd annihilation: this number turns out to be around 10%, which is in agreement with the prediction of the model(68).

6. - CORRELATION MEASUREMENTS

Measurement of correlations between emitted particles should in principle be more sensitive to the dynamics of antinucleon-nucleus interaction than inclusive measurements. Correspondingly, in the description of intranuclear cascade, observables like particle correlation need to be tackled by models which include the "full development" of the multipion cascade, taking into account specifically the non linear aspects of the multipion dynamics, such as the local reduction of nuclear density (trawling effect) and the interaction between the cascade particles. Indeed, with the inclusion of trawling, the INC code reproduces fairly well correlations between emitted particles, up to about 2 GeV/c(43). But the model gets striking discrepancies at higher energy.

A first consideration is that, at low energy, non-linear effects do not play a mayor role in particle correlations. In Fig.9 the correlation between the average number of pions and the overall multiplicity M, measured by the streamer group PS 179 on Neon at 600 MeV/c (6), is shown. The streamer chamber "sees" all charged particles and the overall multiplicity takes into account pions, protons and heavy fragments. The INC code of Iljinov et al.(57), which includes the effect of depletion of nuclear target step by step along the cascade due to fastest particles (*trawling*), reproduces well the apparently puzzling increasing of the average number of pions with the total multiplicity(6). But the same good agreement is found also by Cugnon and Vandermeulen calculation(58), in which the ejection mechanism is assumed to correspond to a clan picture where the ancestors are pions.

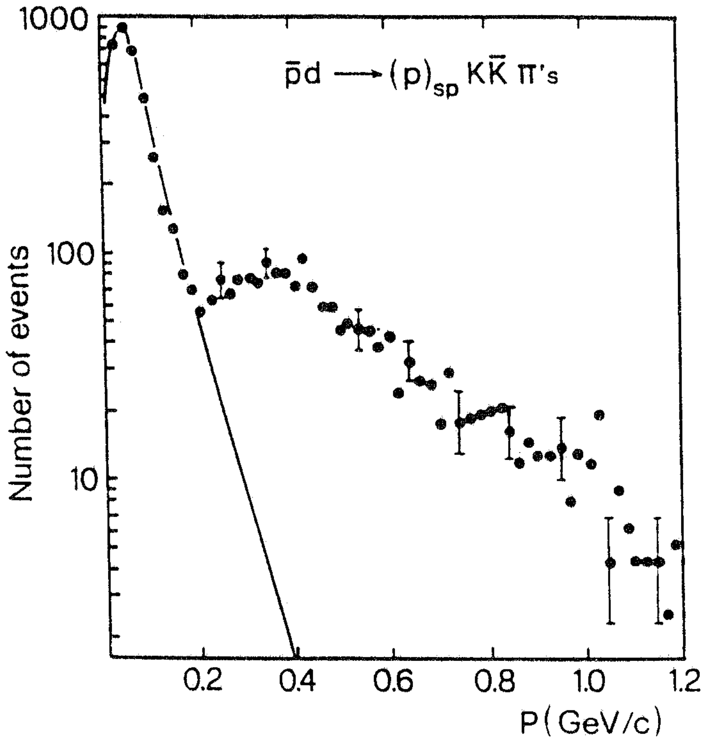

FIG. 7 - High momentum spectator proton tail in $\bar{p}$ absorption on deuterium at (1÷3) GeV/c under KK trigger. The experimental points are from ref. (66). Solid line: deuterium wave function.

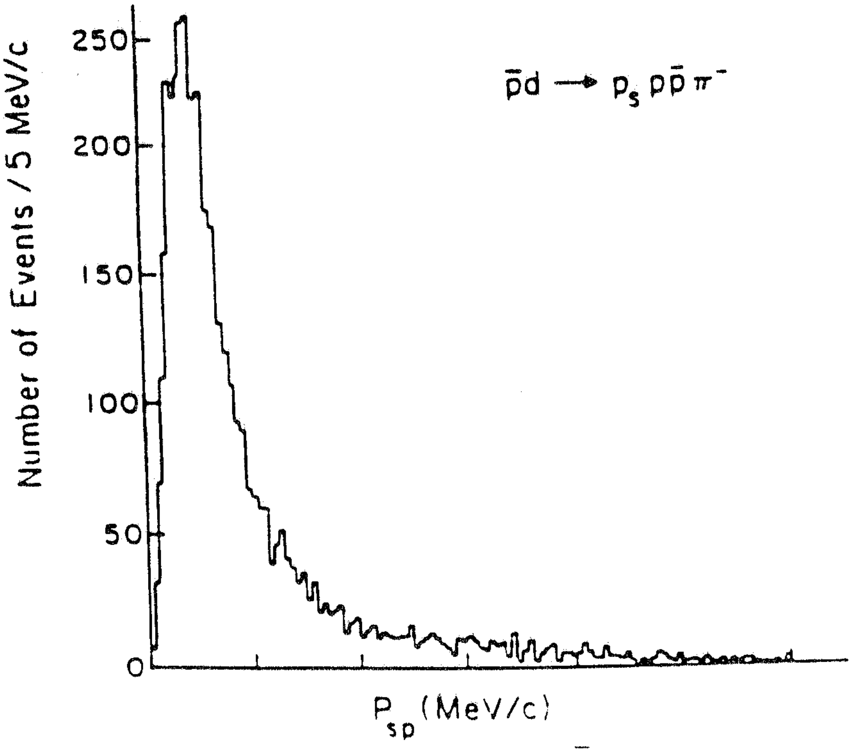

FIG 8 - Spectator proton momentum distribution in $\bar{p}$ absorption on deuterium at (1.6÷2) GeV/c, ref. (67). The clear signal at high momenta seen under strangeness trigger completely diseppears in the background.

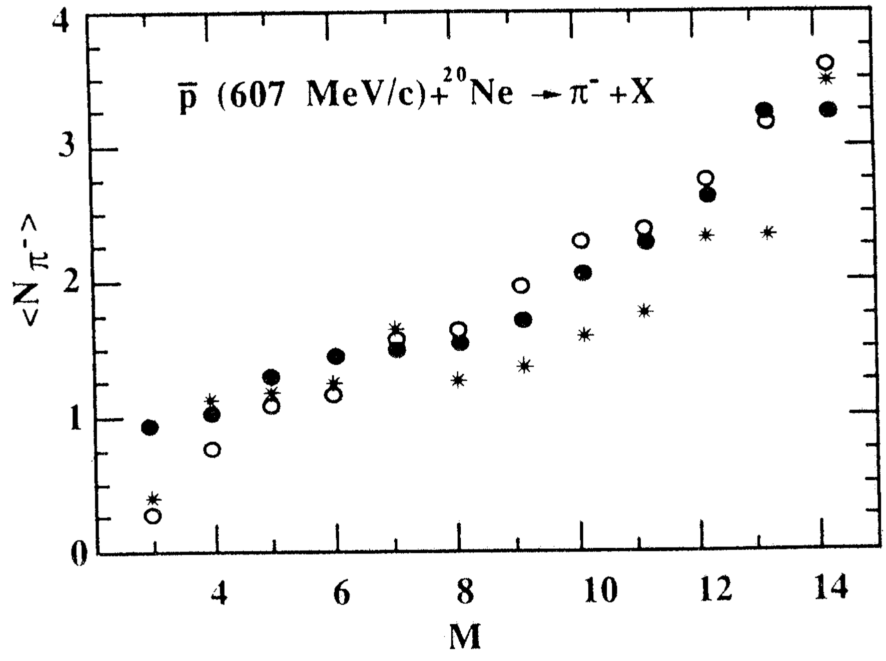

FIG. 9 - Correlation between the average number of π^- and the total multiplicity M after $\bar{p}$ annihilation in ^{20}Ne @ 607 MeV/c. Full dots: exp. points, ref. (6); open dots: Iljinov model including trawling, ref. (57); stars: Iljinov model without trawling, ref. (57).

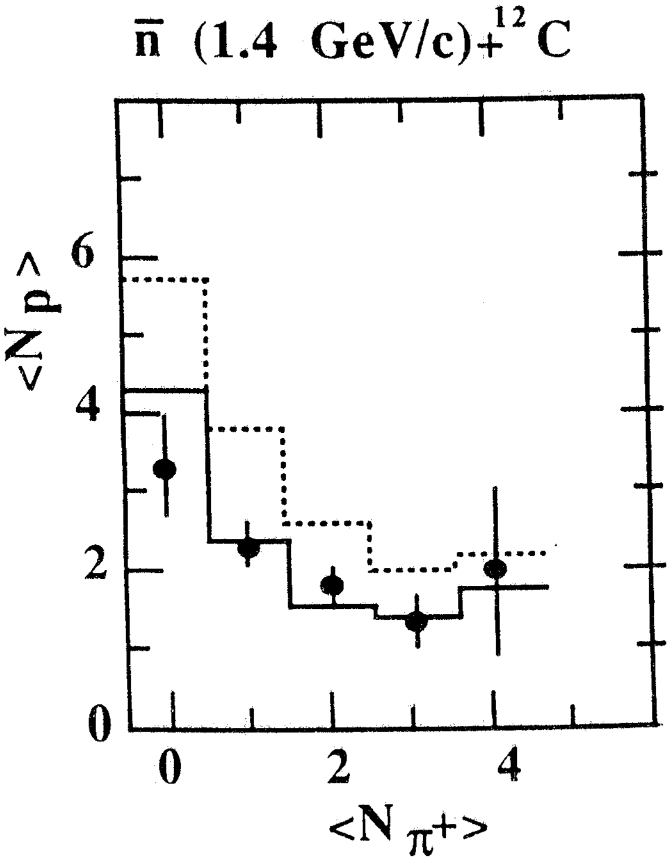

FIG. 10 - Correlation between the average number of protons and the number of pions after $\bar{n}$ annihilation on ^{12}C at 1.4 GeV/c. Full dots: exp. points, ref. (71); continuous histogram : Iljinov model including trawling, ref. (57); dashed line: Iljinov model without trawling, ref. (57).

The model, devised to account for the charged track pattern, retains the basic premises of the INC, but handles charge conservation exactly at each step. The calculation reproduces beautifully the behaviour of $< n_\pi - >$ vs M. Being the clan model intrinsically *linear* (the limits of the picture - and the possible explanation for discrepancies from experimental results - lay just in the problem of the interaction between different clans and between particles within the same clan)(69,70), while trawling is a *non-linear* effect, this fairly good greement between data and *opposite* models confirms the deduction that, at least at 600 MeV/c, non linear aspects of the cascade do not appear relevant: the constraints due to charge and baryon number conservation seem to predominate towards dynamical effects.

At momenta around 2 GeV/c the situation looks differently. Indeed, in this energy region, the INC picture predicts quite radical changements(64). First, virtually, all pions of high energy produced by the annihilation travel in the forward beam direction. Secondly, which is relevant for our aim, the total cross section of $\overline{p}p$ interaction has decreased sufficiently that the annihilation takes place at some distance ($\approx$ 1 fm) within the nucleus. Therefore, it is natural to expect that depletion of target plays a more specific role.This is confirmed by the correlation measurement between the average number of protons and the average number of $\pi^\pm$ performed by Besh et al (71) using an antineutron beam of 1.4 GeV/c on ^{12}C (Fig.10). The experimental results are fairly well reproduced by a cascade calculation including trawling, while disregarding the effect the model systematically overstimates the number of protons(43). In other words, the measured number of protons is lower essentially due to the already ejected high energy nucleons and to the consequently fewer collisions suffered by target nucleons. The refined version of INC model(57) appears therefore able to fully understand the experimental features up to 2 GeV/c.

Where situation seems to escape drastically to INC control is at higher energy (<10 GeV/c). Fig. 11 shows a correlation measurement between proton and pions emitted in a cascade initiated by a high energy *proton*(72). Here the incident particle has not to deal with the annihilation fate and hadronic cascade is dictated by strong interactions in nuclear matter. If the version of the INC code which takes into account the depletion of the target is used, the data continue, as at lower energy, to be fairly well reproduced(43). In particular is reproduced, also in absolute value, the trend according to which the average number of emitted pions increases with the average number of emitted protons per event. On the contrary, if the model does not include trawling, the prediction misses also the trend of the distribution. In conclusion, if a very special event like annihilation matter-antimatter does not take place, an ordinary hadronic cascade, based on two-body established processes of which cross sections are known (and which takes into account also non linear effects), is still working very well. But, if the fate of the particle is to annihilate in an energetic "meson factory" at microscopic level, the scenario changes abruptly at high energy and INC seems to fail its job. Let's consider, in fact, Fig. 12, in which the results of the cascade fired by a 6 GeV/c antineutron beam on Tantalum are shown. The correlated emission of proton and pions has been measured by Andreev et al. with the bubble chamber LYUDMILA at Serpukhov(42,43). The antineutron beam was obtained by stripping on hydrogen nuclei of the chamber a 12 GeV/c antideuteron beam. The data present these features: the production of a high number of protons (≈ 8) is associated to the *absence* of pions in the final state. Absorption of protons seems to produce pions. Taking into account the produced number of protons for $< n_\pi >\ = 0$ and the number of neutrons of tantalum (N≈ 2.5 Z), it seems that at this energy a cluster of about 20 nucleons is produced, a cluster which subsequently disintegrates with absorption of nucleons and production of pions.

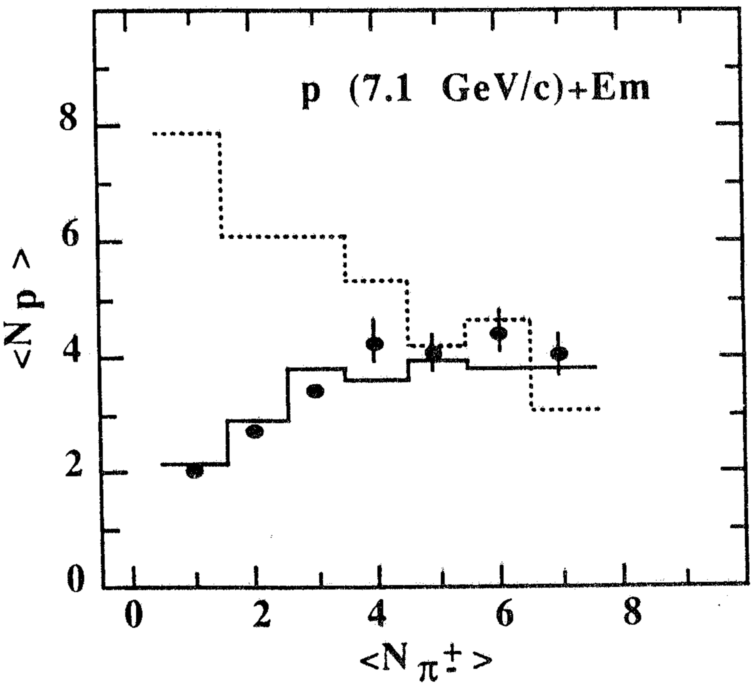

FIG. 11 - Correlation between the average number of protons and the number of pions for the interaction of 7.1 GeV/c proton in nuclear emulsion. Full dots: exp. points, ref. (72); continuous histogram: Iljinov model including trawling, ref. (57); dotted line: Iljinov model without trawling, ref. (57).

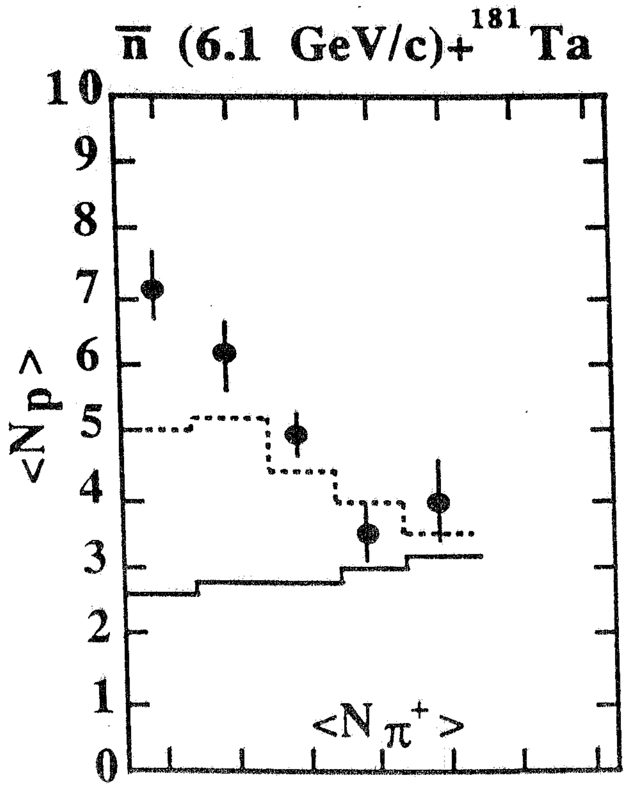

FIG. 12 - Correlation between the average number of protons and the number of π^+ in $\bar{n}$ annihilation at 6.1 GeV/c on Ta. Full dots: exp. points, ref. (43); continuous histogram: Iljinov model including trawling, ref. (57); dotted line: Iljinov model without trawling, ref. (57).

The refined version of the Iljinov model (57) which, as we have seen, was working very well in describing the cascade of a *nucleon* at high energy, fails completely in giving the picture of MPNI following the cascade of an *antinucleon*, both in absolute values and in trend. The discrepancies from experimental points appear, seemingly, more strong in the *mesonless* and *single-meson channels*: namely, just in processes which present a typical two-(or more-) body nature(56).

As we stressed already in ref.(56), it does not seem reasonable to draw any definite conclusions until more accurate experiments in this energy region of the correlations between nucleons and $\pi^{\pm}$ and π^{0} are performed. In particular, the relevant role of π^{0} in the intranuclear cascade has been recently investigated (16) (see Fig. 13). However, this is the *most striking direct evidence* of a strong discrepancy of experimental results from the cascade mechanism, as depicted by the more refined versions of the model. A cluster of many nucleons seems to have been aggregated in the annihilation of an high energy antinucleon. There are all the premises for a multinucleon (unusual) annihilation (60). Possibily, also, for the formation of a quark-gluon blob(61,62). Indeed, the calculations of Strottman and Gibbs (64) performed under two different approaches, the INC approach and the relativistic hydrodynamic model(73) (similar to that used to study heavy ion collisions), give consistent results with a precise indication: namely, that the phase transition from ordinary hadronic matter to quark-gluon plasma, predicted from QCD lattice calculations around a nuclear temperature $T \approx 180$ MeV, can be reached using an antiproton beam of energy ≈ 6 GeV/c. It is important to stress that the prediction is based on the application of two conventional models which do *not* taken into account unusual annihilations and therefore should be considered as a "lower limit" example. The above described experiment fulfills the boundary conditions on energy.

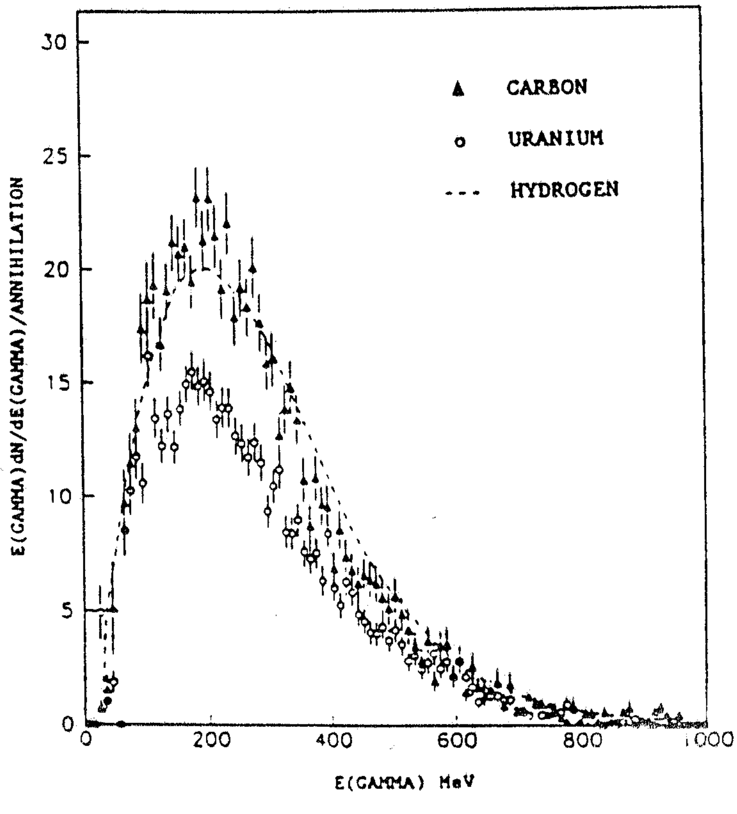

FIG. 13 - Energy-weighted spectra of gamma-rays from carbon, ref. (16); uranium, ref. (16) and liquid hydrogen, ref. (92).

As programme for a future investigation, but also as possibility using the *existing* data, in order to check if this correlation measurement represents or not a clear hint of new phenomena, one should:

a) to analyze the spectrum of emitted protons'in order to determine, from the Maxwelliam slope, the temperature of the emitted nucleons and hence the level of excitation of at least a region of nuclear matter;

b) to determine the size of the source, in such a case the many-nucleon cluster, with the pion interferometry technique (GGLP-effect⁽⁷⁴⁾) measuring the correlations between $(\pi,^{+}\pi^{+})$ or (π^{-},π^{-}). The size of the annihilation spot usually is constant, indipendent on energy and mass number and with a value around 1÷2 fm. An abrupt increasing in dimension could be the signal of the phase transition to the dehadronized phase;

c) to measure the distribution of particle over transverse momentum and then the rapidity of emitted particles, in order to identify the effective target involved;

d) to measure the eventual yields of associated strange particles, looking for a strangeness enhancement, which is a signature both of multinucleon annihilations and of quark-gluon plasma formation, according to the statistical model of Cugnon and Vandermeulen (60) and the Rafelski model for the quark-gluon plasma(75).

7. - HEAVY MESONS NUCLEAR INTERACTION

As mentioned in Sect. 4, the copious production of meson resonances in antiproton annihilation open a branch of hadronic physics scarcely explored up to now. As a rule, at least one pionic resonance is produced in each annihilation event(76). As for η- and ω-mesons, their decay lenght is larger than the internucleon distance and therefore such a resonance state interacts with a nucleus as a whole but, in general, it appears rather difficult to extract the result of interaction from the background due to incoherent MPNI. It is, however, possible to select particular processes free of such difficulties and also to obtain evidence of the role of meson resonances in many aspects of annihilation dynamics. Iljinov et al(48) firstly suggested the investigation of interaction of pionic resonances with nuclei after creation in $\bar{p}$-annihilation. An analysis of the role of mesonic resonances in antiproton-nuclei annihilation has been performed by Cugnon et al.(77). The role of mesonic resonances in $\bar{p}$ annihilation has been reviewed by Sapozhnikov and Rozhdestvensky(78) and, more recently, studied by Iljinov and Golubeva(79). More specifically, the importance of mesonic resonances in strangeness production has been explored by Ko and Yuan (80), Dover and Koch (81) and Cugnon et al (77). The influence of resonances in determining the yield of residual nuclei has been examined by Hofmann et al.(13), and their role in justifying discrepancies found between the measured pion multiplicities and the prediction of INC model has been examined by Cughon et al.(59). The possibility of η-nucleus bound or resonant states has been investigated by Haider and Liu(83÷85) and discussed by many authors(86). We shall briefly discuss these points.

Interaction of pionic resonances with nuclei. According to Iljinov(48), a process which in principle should be relatively free from incoherent background is the two-nucleon absorption of a pionic resonance, which may proceed in a nucleus analogously to the two-nucleon absorption of pions and kaons:

$$\begin{aligned} &\eta + (NN) \rightarrow N + N \\ &\omega + (NN) \rightarrow N + N \end{aligned} \qquad (1)$$

Detection of the emission of nucleon pairs with energies near 1/2 $m_\eta \approx 300$ MeV or 1/2 $m_\omega \approx 400$ MeV and at an angle $\theta_{NN} > 120°\text{-}150°$ would be sufficiently reliable evidence that a process of the type (1) has occurred. This process may provide valuable information not only on the interaction of pionic resonances with nucleons, but also on the nuclear structure, since the momenta P_N of nucleons produced in the two-nucleon absorption of a particle p $P_N \approx \sqrt{m_p m_N}$ determine the specific distance of this process $r^p_{abs} = P^{-1}_N$. For the absorption of pions and kaons one obtains, respectively:

$$r^\pi_{abs} \approx 0.6 \text{ fm} \qquad r^K_{abs} \approx 0.5 \text{ fm} \qquad (2)$$

The specific distances for η- and ω-absorption are:

$$r^\eta_{abs} \approx 0.3 \text{ fm} \qquad r^\omega_{abs} \approx 0.2 \text{ fm} \qquad (3)$$

Therefore it is open the possibility of investigating nuclear correlations which are considerably shorted-ranged than those studied by means of the absorption of pions and kaons.

The problem of the extent to which the mesonless absorption is suppressed as compared with other channels of the strong interaction of η- and ω-mesons with nuclei is still open. Following Iljinov(48), one can look at the suppression factor for the analogous case of the absorption of pions in flight or for the nuclear absorption of stopped K^- mesons. In the simplest estimate(87), the suppression factor equals the probabality of finding two nucleons in the interaction volume

$$W(r^{\pi,K}_{abs}) = \frac{4}{3}\pi\, r^3_{abs}\, \rho_0 \approx 0.1 \qquad (4)$$

The analogous estimate for η- and ω-mesons gives

$$W(r_{abs}^{\eta,\omega}) \approx 10^{-2} \tag{5}$$

Cugnon et al. in ref.(77) made an exploratory study using a simple model for the propagation of the resonances and assuming that they can decay or disappear through the single-pion absorption reactions:

$$\begin{aligned} \eta N &\rightarrow \pi N \\ \omega N &\rightarrow \pi N \end{aligned} \tag{6}$$

They took also into account the possibility of resonance creation:

$$\begin{aligned} \pi N &\rightarrow \eta N \\ \pi N &\rightarrow \omega N \end{aligned} \tag{7}$$

From a comparison with the output of an intranuclear cascade calculation(59), which fits the inclusive proton spectra(9), they concluded that a possible back-to back signal characteristic of a pionic resonance absorption would be lost in the background of energetic protons of the tail of the distribution.

Role of pionic resonances in strangeness production. One characteristic of $\bar{p}$-nucleus annihilation is that strangeness production is enhanced due to the effects of the medium *beyond* the level expected on the basis of the production in $\bar{N}N$ annihilation. As it is well known, an enhancement of strangeness would be a typical indicator of a striking phenomenon like a phase transition to a quark-gluon plasma, according to Rafelski(75), or of a less spectaculur, although still unusual one, such as a "true" multinucleon annihilation, following Cugnon and Vandermeulen(60). Taking into account a quantity like the ratio $R = \Lambda/K_s^0$ between inclusive productions, which is typically indicative of the relative importance of many-nucleon process, $\bar{p}$-nuclei data exhibit indeed values of R about one order of magnitude greater than the corresponding values in free space. However, apart the conclusions of Rafelski(88), who considers the possibility of formation of supercooled quark matter already @ 4 GeV/c, it is generally accepted that such increasing simply reflects the redistribution of strangeness produced in primary $\bar{p}N$ interaction through higher order reaction processes in the nuclear medium. In these multi-step processes the contribution of pionic resonances

$$\eta N \rightarrow K\Lambda \tag{8}$$

$$\omega N \rightarrow K\Lambda$$

is taken esplicitly into account. Of course, any estimation is considerably affected by the uncertainty due to limited or inexistent knowledge of the cross sections of the elementary processes (8), overcome with *ad hoc* hypoteses by the various authors; and also by the scaling law applied to calculate primordial contributions before rescattering.

According to Ko and Yuan(80), @ 4 GeV/c the ω-contribution to Λ production amounts to $\approx$ 12 mb, i.e. 10% of the calculated Λ production cross section (σ_{th} (Λ) $\approx$ 122 mb, to be compared with the experimentally measured value σ_{exp} (Λ) $\approx$ 193 mb(29)). Dover and Koch(81) evaluate that the η-contribution to strangeness production is smaller in percentage: about 7 per thousand, but they take into consideration also short-lived resonances, like ρ, for which they obtain a contribution to Λ-production of the order of 18%. Cugnon, Deneye and Vandermeulen(89) have performed an intranuclear cascade type calculation for strangeness production, still in the spirit of the conventional picture, and including properly all rescattering of produced particles and secondary production. A significant result is that, at low antiproton momenta, the ω-induced Λ production dominates, being about 20% of the overall production. This is interesting since, in order to be able of explaining the experimental result of PS 179 experiment @ 600 MeV/c(25) it is necessary to take into account other phenomena beside rescattering, like multinucleon annihilations: the frequency of the B=1 fireball should be of the order of 20%(68). In other words, production by resonance appears in this model as a possible competitor with annihilation on two nucleons.

Influence of meson resonances on pion absorption. While the standard INC models reproduce fairly well the gross features of the pion spectrum, in particular the two-bump structure, this is no longer the case for the zeroth moment of the pion spectrum, i.e. the pion multiplicity, which depends on pion absorption mechanism. Pion absorption plays obviously also a direct role in determining the final yield or residual nuclei after annihilation.

As a matter of fact, the more recent version of the INC model of Cugnon and Vandermeulen(59) finds multiplicity values systematically *higher* than the experimental ones, i.e. it considerably *underestimates* the pion absorption in the case of antiproton annihilation. On the contrary, it seems to *overestimate* the pion absorption in considering the preliminary antineutron multiplicities(44), which is a rather puzzling situation. Among the possible causes examined(59) in order to explain this disagreement, which enters in the detail of the multipion dynamics (modification of the pion and delta properties inside nuclear matter; inappropriateness of the pion creation and absorption mechanisms; effect of multinucleon annihilations, etc.), Cugnon and Vandermeulen have in particular evaluated, in ref.(77) the behaviour of pions "hidden" in resonances compared to the absorption suffered by "free" pions. Their conclusion is that pions coming from η- and ω-decay should be *less* absorbed that primordial pions. In other words, creation of resonances should *decrease* the overall absorption and therefore this effect could not help to correct the lack of absorption observed in comparison with experimental results.

The same conclusions essentially reach the authors of ref.(38) discussing the residual nuclei distribution after antiproton annihilation at rest on ^{165}Ho target. According to the experiment, some nuclides with $\Delta A = 1$ have large yields. Such events correspond to the annihilation of antiprotons with weakly bounds nucleons in the far periphery of the nucleus. The yields calculated using the refined version of the Iljinov model(57), including trawling effect, are one order of magnitude smaller than the experimental results. Better knowledge of $\bar{p}$-nucleus optical potential and of the nuclear density at the nuclear periphery can help to solve the discrepancies. But it is reasonable also to take into account the production of heavy mesons (ρ,η,ω) which decay into pions. In fact *uncorrelated* emission, as in the case of primordial pions, leads in some cases to more pions interacting with the nucleus, and therefore absorbed, resulting in the subsequent emission of many nucleons. If meson resonances are directly produced in the primary process, *correlated* emission of pions following their decay may result in a less relevant absorption and, consequently, favour residual nuclei which have lost only a few nucleons.

η-nuclear states. No meson has been observed to bind with an atomic nucleus to form a nuclear bound state. Both π^- and K^- mesons are observed to be captured in atomic orbits via the Coulomb attraction, but have not been observed to bind to the nucleus through the nuclear force.

Bhalerao and Liu(82) have shown that the low-energy η-nuclear interaction is attractive. Later, the possibility of η-nucleus bound states has been investigated by Q. Haider and L.C. Liu(83÷85) and other authors(86). For nuclei with A>10 the η meson should be bound to the nucleus. The binding energy should be a few MeV and the FWHM decay width about 10 MeV. Haider and Liu suggested to observe the η bound states through the (π^+ p) reaction with a π^+ momentum around 800 MeV/c. The experiment has been performed using the Brookhaven AGS hypernuclear spectrometer system: no narrow η-nuclear bound states were observed using ^{7}Li, ^{12}C, ^{16}O and ^{27}Al targets(92).

Beside the consideration if the ηN interaction is sufficiently strong and attractive to guarantee the existence of bound states formed by an η-meson and a nucleus, the first problem is to produce an η with momentum low enough to stick to a nucleus and then to identify a clear signature of the formation of the bound states. In the Brookhaven experiment the η momentum was identically zero with about 900 MeV/c incident pion momentum and a zero degree recoil proton.

As it is known, search for *antiproton-nuclear* bound states has been so far unsuccessful(12), despite the availability of an intense, pure, high-resolution antiproton beam such as the LEAR beam. The technique used was the knock out ($\bar{p}$, p) reaction on quasi-free proton of the target, detecting the outgoing proton at 0° in order to leave the probe almost recoilless in the target, thus favoring the formation of $\bar{p}$-nucleus states. It was observed the quasi-free backward elastic scattering on individual protons of the target nucleus but the absence of any narrow (≈ a few MeV) structure due to bound or resonant $\bar{p}$-nucleus states. The upper limits put by the work were more than one order of magnitude lower than the theoretical prediction(91).

The same technique can hardly be applied in searching η-nuclear states, due to lack of a monochromatic intense η-beam. It is also questionable the signature of such bound states. To look for single-meson or mesonless absorption of η-meson

$$\eta N \rightarrow N \qquad \eta NN \rightarrow NN \tag{9}$$

gives *not* an indication of a possible bound state, but simply of the production of a meson resonance with a subsequent nuclear absorption, as discussed above. At the moment, even if there are encouraging theoretical hypoteses, from an experimental point of view the problem appears totally open.

8. - OTHER PERSPECTIVES

In this paper we have overviewed the present status of antinucleon-nucleus physics, touching some of the problems not yet solved by the experiments or open for the first time by the results. Looking for other perspectives, both at LEAR and at KAON energies, the field is extremely rich. We want only to mention the practically unexplored field of rare reactions (Pontecorvo reactions); the study of mechanisms of deexcitation of nuclei (multifragmentation); the (problematic) research for a phase transition to a quark-gluon plasma measuring, as a function of energy and of A, the effective overall content of strangeness, together with a possible break up of the dimensions of the pion source; the search for multiquark bound states (in particular the H-particle). At higher energy, the new field of the physics of charm degrees of freedom is open to an antiproton probe. The direct access to all charmonium states is an unique opportunity. The study of formation of J/Ψ in nuclei as a function of A (*color transparency*) allow to enter into the mechanisms of hadronization, which is one of the unsolved problem of QCD.

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