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The Elementary Structure of Matter

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Antiproton-Nucleus Annihilation

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1. INTRODUCTION

Just before the opening of the LEAR era, annihilations of antiprotons on nuclei were considered of considerable interest [1], especially after a paper by J. RAFELSKI [2], who speculated about exotic processes triggered by the annihilation. The bulk of the experimental results obtained so far in the LEAR regime is largely consistent with the following simple scenario : the incident $\bar{p}$ annihilates on a single nucleon, mainly at the surface of the nucleus, creating a few pions which cascade through the nucleus, eject some fast nucleons and leaves the residual nucleus with a moderate excitation, which is evacuated by evaporation. (We analyse this scenario in Section 2). However, $\bar{p}$-annihilation on nuclei presents some special interest in two respects : (i) it may provide a very useful tool for studying the break-up of the nucleus under the injection of increasing excitation energy. This process could show some typical features of critical dynamics. (ii) The very presence of other nearby nucleons could alter some characteristics of the annihilation process. We successively discuss these possibilities in Sections 3 and 4. For the last case, we analyze the present indications for unusual annihilations.

2. THE DYNAMICS OF THE $\bar{p}$-NUCLEUS ANNIHILATION

2.1 The Simplest Dynamical Scheme

The simplest dynamical scheme one can think of is composed of three stages :

(1) The $\bar{p}$ annihilates on a single nucleon at the surface of the nucleus, after an electromagnetic cascade for the annihilation at rest and after some possible distortion of its motion for the annihilation in flight.

(2) The created pions cascade through the nucleus, interacting with the nucleons, ejecting a few of them as a result of two-body interactions.

(3) After this fast ejection process is over, the residual nucleus, still with some excitation energy (due to the nucleons which are involved in step (2) but which have not enough energy to escape), evaporates a few particles, mainly neutrons.

It can be furthermore assumed that the annihilation is a well-defined event in space-time (with the same properties as in free space) and that the multiple scattering process proceeds through collisions occurring successively in space-time. The whole scheme can be made quantitative by describing the complicated multiple scattering process (and even stage (1)) with the intranuclear cascade (INC) model. This has been done by at least four groups in refs. [3-6] where the model is described. In short, the cascade is viewed as a succession of binary collisions (and decays) which occur according to their free-space cross-sections (except for Pauli blocking effects). The following collisions are usually included : $\pi N \to \pi N$, $\pi N \to 2\pi N$, $\pi N \rightleftarrows \Delta$, $NN \to NN$, $NN \rightleftarrows N\Delta$, leading to a complicated propagation of the pions travelling through the nucleus and to their possible absorption.

The INC has been shown to successfully reproduce the bulk of available $\bar{p}$-nucleus data, and especially the inclusive measurements of ref. [7], as shown in Fig. 1 for one particular case.

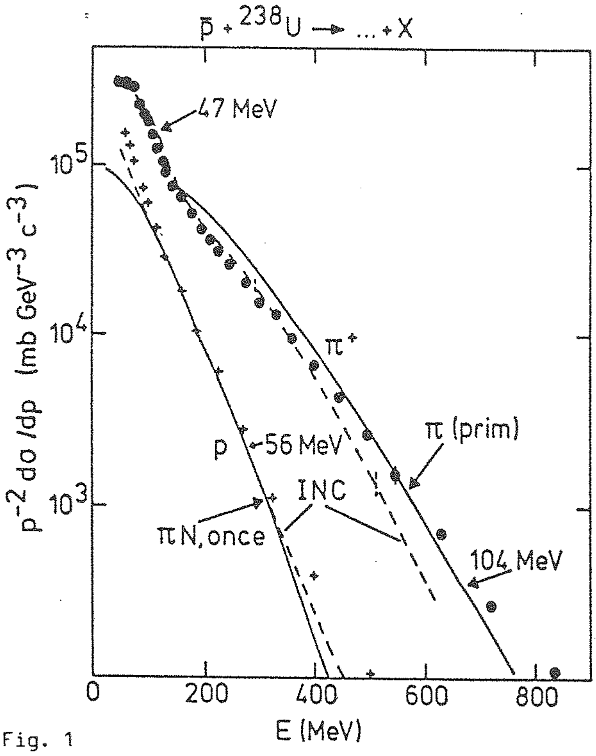

Fig. 1

π^+ and proton spectra for $\bar{p}$ + ^{238}U annihilations (E is the kinetic energy). Dots and crosses : experimental data [7]. Dashed curves : INC calculations [7]. The full curves correspond to the spectra of the primordial pions and of the nucleons which have been hit once by a pion, respectively. The "temperatures" are indicated by the numbers (see text).

2.2 The INC Dynamics

One of the striking features of Fig. 1 is the Maxwell-Boltzmann tails in the π^+ and p spectra with large corresponding temperatures. This should not be interpreted as the evidence of the heating of a piece of nuclear matter. We eludicate this point in describing the main features of the INC dynamics for the annihilation at rest. The antiproton annihilates at the edge of the nucleus, giving birth to about 5 pions according to the available phase space. These pions display a thermal-like spectrum akin to the one of the observed high energy π^+ (see Fig. 1). Therefore this part of the spectrum is due to noninteracting pions (about half of the original pions). The pions which penetrate the nucleus make a few collisions, hitting the nucleons. Since they are quite energetic a single hit is sufficient to tranfer a large amount of energy to the nucleons. This is shown also in Fig. 1 where the spectrum of the ejected nucleons which have been hit once and once only by a pion is displayed. Secondary collisions give rise to the low energy pions and protons. The average number of collisions per pion is the order of 3-4 [8,9].

While travelling through the nucleus, pions are transforming back and forth into deltas. At the most one delta is present inside the nucleus. About one sixth of the pions is ultimately absorbed. The interaction between the pions and the baryon system transfers energy to the latter. This is shown in Fig. 2, which fixes the time scale by the same token. The large amount of energy transferred to the nucleus is evacuated

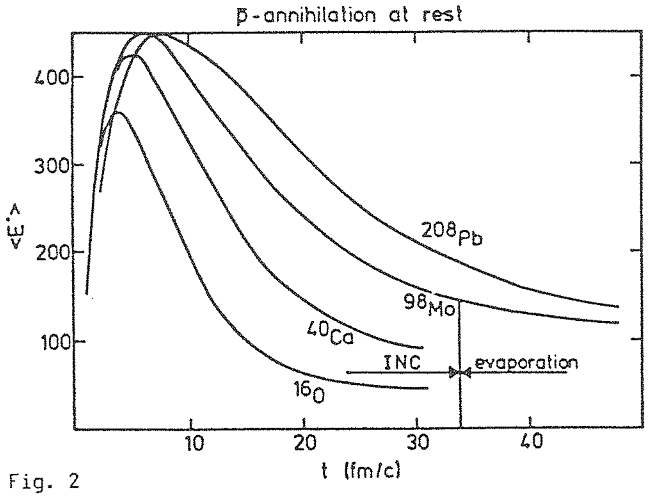

Fig. 2

Time evolution of the average excitation energy E* in the target. The separation between the INC and the evaporation phases is indicated for the ^{98}Mo nucleus. Adapted from ref. [11].

on two time scales. First, the largest part is released very quickly by the ejection of fast nucleons (about 4 for the ^{98}Mo case). After this time, one may consider that the remaining excitation energy is more or less randomized, and is released by evaporation. The separation between the standard INC cascade involving hard collisions and the evaporation is shown in Fig. 2. However this separation is admittedly loosely defined.

2.3 Residue Distribution

The shape of the residual mass distribution has recently been measured by radiochemical techniques [10] for the $\bar{p}$-Mo case. On the average, about 15 nucleons are removed from the A = 98 nucleus. This means that about 10 nucleons are evaporated. This agrees with the calculations of ref. [11] (see Fig. 3) in which an evaporation calculation is switched on at the end of the INC.

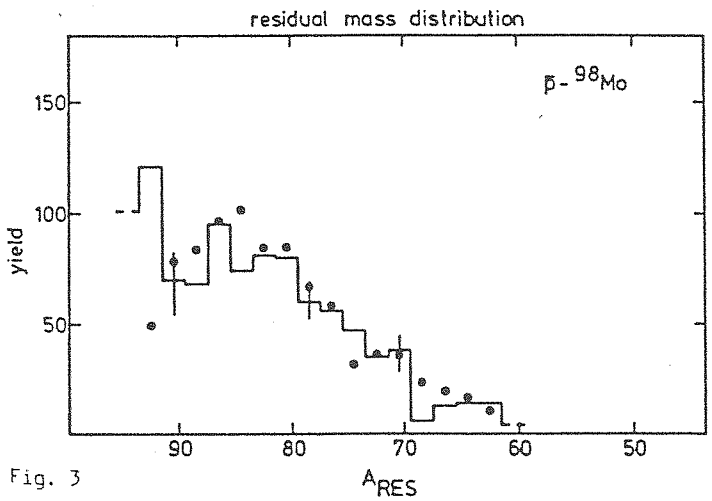

Fig. 3

Residual mass distribution for $\bar{p}$-Mo annihilation. Data (dots) from ref. [10], INC results [histograms]. Adapted from ref. [11]

In conclusion, the following picture seems to emerge at low energy : the annihilation produces an extremely localized thermalised system which decays into pions. These pions produce some streaks in the nucleons, ejecting a few fast nucleons. The nucleus does not undergo a very strong disturbance (except for the very small ones). It keeps its cohesion and de-excites by evaporating a few nucleons.

3. NUCLEAR FRAGMENTATION

3.1 Introduction

There is currently a great interest among nuclear physicists in the way the nucleus of mass A behaves after it receives excitation energy E^*. The answer to this question depends, of course, on the way the excitation energy is injected. If the excitation energy is rapidly thermalized, the answer is known in at least two limiting regimes. If $E^*/A \lesssim 2$-3 MeV, the nucleus loses its energy by evaporating particles, a few neutrons essentially. If $E^*/A \simeq 20$-100 MeV, the nucleus basically disintegrates into its constituents [12] : p,n plus a few created pions. For the intermediate regime, it is believed (and there are already experimental indications of this phenomena) that as E^*/A increases, the nucleus first loses more and more nucleons, then fragments into many large pieces (of the order of C or O nuclei), a feature referred to as the multifragmentation, and for still larger E^*/A, fragments in many more smaller fragments (see ref. [13] for a review). There are some speculations on the fact that the onset of multifragmentation could be rapid, showing some features of a phase transition : the condensation transition, studied by Fisher [14], which corresponds to the transition from a liquid phase to an assembly of droplets. The properties of this transition should bear some relationship with the saturating properties of nuclear forces and the nuclear surface tension.

3.2 Percolation Models

As we have seen, in a $\bar{p}$-nucleus system, the excitation energy is, very likely, not rapidly randomized. Rather, most of the excitation energy is used to eject rapidly fast particles. For such a case, the current ideas are that the evolution of the nucleus will depend very much on the geometrical properties of the "damage" caused to the nucleus by this fast process. More precisely, some authors think that the evolution is very much akin to cluster formation in percolation models [15,16]. The latter tell that, if the percentage p of voids created in a medium is small, a few small clusters will break loose from a very large one (of size comparable with the size of the original system). If p is larger than a critical value p_c, the system breaks into many clusters of small size. The behaviour close to p_c is very similar to a phase transition : it is referred to as the percolation transition and can be characterized by critical exponent entering in several observables like the distribution of the largest cluster (see Fig. 4), of the multiplicity... This figure is just for illustrative purpose, since it is believed that p_c is larger for the nuclear percolation phenomena.

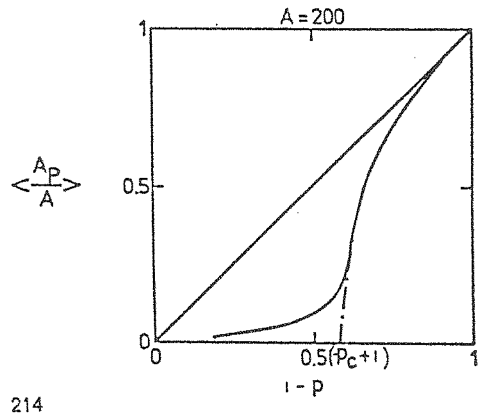

Fig. 4

Ratio of the largest cluster size to the remaining size after removal of p % sites of an infinite 2D lattice (dot-and-dashed line). The full line is the result of a percolation model for a A = 200 nucleus [34].

3.3 Specific Features of the $\bar{p}$-Nucleus System

The $\bar{p}$ annihilation appears as an alternative way to study the break-up of a nucleus, campared to the most common tools, namely high energy proton-induced reactions and intermediate energy heavy ion reactions. High energy protons and antiprotons are very similar in the sense that they first induce a rapid knock-out (spallation) of nucleons, whereas intermediate heavy ions give rise apparently to a more complicated dynamical path [8]. Furthermore, both high energy protons and heavy ions are subject to another difficulty, namely the fact that many impact parameters, pertaining to different values of p in the analysis above, are mixed up in the observation. This is definitely not the case for $\bar{p}$-annihilation at rest, where the initial system is always "prepared" in the same way.

From Section 3.2, it seems however that $\bar{p}$-annihilations at rest are subcritical in the sense of the current nuclear percolation models (see Section 3.2), although, according to some models [16] the energy deposited seems close to the required value for the onset of multifragmentation. Thence, the important question is how to make $\bar{p}$-nucleus overcritical ? Two answers at least are possible : (1) Study $\bar{p}$-annihilation in flight. Rough estimates indicate that $\bar{p}$-nucleus will become overcritical for energies above 1 GeV to 5 GeV, depending upon the models [17]. As we mentioned, one would thus lose the simplicity of the analysis, typical of at-rest annihilation. (2) Go to antideuterium (or heavier antiparticle) annihilations.

4. UNUSUAL ANNIHILATIONS

4.1 Introduction

Are there "unusual" annihilations, whose properties are different from those implied by the scenario of Section 2.1 ? The minimal departure would be a $\bar{p}$-annihilation on two nucleons. This possibility, first proposed by S. KAHANA [18], seems plausible in the light of the arguments of ref. [19], which tell that the ($\bar{p}$p) fireball lives long enough to interact with another nucleon before decaying inside a nucleus.

In ref. [19], the properties of these annihilations are studied using the simplest assumption, namely that the decay of B = 1 ($\bar{p}$NN) system is governed by phase space. In other words, the decay is described in the frame of a microcanonical ensemble. The rate for a given multiplicity n is

$$f_n(\sqrt{s}\ ;\ m_1,\ldots,m_n) = C^n\, R_n(\sqrt{s}\ ;\ m_1,\ldots,m_n) \quad , \qquad (1)$$

where R_n is the invariant phase space integral [20]. The only free parameter C is fitted to reproduce the pion multiplicity distribution in $\bar{p}$p. The most important prediction of ref. [19] is a considerable enhancement of strange particle production in B = 1 annihilations, compared to B = 0. This is a pure consequence of phase space, since the threshold for the ΛK channel in B = 1 is well below the $\bar{K}$K channel in B = 0. This conclusion is illustrated in Table 1, which gives relative yields for several channels. Comparison is also done (for the quark content) with quark-gluon predictions. It has been stressed in refs. [21,22] that strangeness producing reactions are very fast inside the plasma. However, it is rather unprobable that $\bar{p}$-annihilation leads to plasma formation. In ref. [23], it is shown that if $\bar{p}$p annihilation generates a plasma, the strangeness saturation degree of the latter should be only of 10 % at most, to have sensible results. Therefore, if strangeness enhancement production is observed in $\bar{p}$-nucleus, it could be due to either unsaturated plasma, although not probable, or to B ≠ 0 annihilations, saturating phase space in the hadronic phase.

4.2 Analysis of Various Systems

(a) $\bar{p}$ + d. This system has been studied in ref. [24] for the $\bar{p}d \to p + \pi^-$ channel, in ref. [25] for the $\bar{p}d \to \bar{K}Kp$ channel and recently by another group (see ref. [26]). The very observation of the exclusive $p\pi^-$ channel [25] is already an evidence for

B = 1 annihilation. In the $\bar{p}d \rightarrow \bar{K}Kp$ reaction, the protons are observed with a very high momentum tail, totally unconsistent with a "spectator" proton, which would have only the average momentum inside the deuteron. The importance of this tail indicates that B = 1 annihilations occur about 10 % of the time [19]. With this frequency and using ref. [19], one can make definite predictions for the branching ratios for $\bar{p}d \rightarrow p\pi^-$ and $\bar{p}d \rightarrow \Lambda + x$: they turn out to be 3×10^{-5} and 4.7×10^{-3} respectively. They compare rather well with experiment, which yields 0.9×10^{-5} and 3.6×10^{-3} respectively.

(b) p̄-nucleus. The theoretical problem here is to determine the frequency of B = 1 annihilations. Only crude estimates are made in ref. [19], based on geometrical considerations only. Anyway, we can look whether pure B = 0 annihilations are sufficient to reproduce some observables involving strangeness. The latter can be :

(1) K^+ yield : the K^+ abundance is practically unchanged by the cascade process since K^+ scatters only elastically with the nucleons. At rest, the K^+ abundance in $\bar{p}p$ is 0.025 per annihilation. An enhancement in $\bar{p}$ nucleus would indicate the presence of B = 1 annihilation. Unfortunately, there is no measurement available up to now.

(2) K^+/π^- ratio : this ratio may be easier to measure since it does not require a measurement over a large angular range. However, the situation is a little bit complicated here since pions can be absorbed and since large nuclei (N > Z) favour π^-'s. This could perhaps explain the observations of ref. [26]. The last problem can be minimized by using N = Z nuclei and/or considering the $K^+/(\pi^- + \pi^+)$ ratio.

(3) Λ^o production : this has been measured by Condo et al. [27] with a poor statistics. On the average, they observe $\sim (1.9 \pm 0.4) \times 10^{-2}$ Λ^o per annihilation. This figure could be obtained with B = 0 annihilations only if all the $\bar{K}$'s transform into Λ by scattering through the nucleus. This obviously is not plausible in view of the small $\bar{K}N \rightarrow \Lambda\pi$ cross-section (see below).

(4) Hypernuclei formation : in a remarkable experiment [28], a group at LEAR has observed delayed fissions (with lifetime $\sim 10^{-10}$ sec) following $\bar{p}$ annihilation in flight on ^{235}U and on ^{209}Bi nuclei. The lifetime is so long that, according to the authors, the only possible explanation is the formation of a Λ-hypernucleus. When the Λ decays, the released energy leads to fission. The mechanisms which produce the hypernucleus can be either (a) $\bar{p}N \rightarrow K\bar{K}$, $\bar{K}N \rightarrow \Lambda\pi^-$, followed by the fixation of the hyperon on the nucleus or (b) $\bar{p}NN \rightarrow \Lambda K$, followed by the fixation of the Λ. The first mechanism is plausible, since the $\bar{K}$ issued from the annihilation has just the momentum (~ 700 MeV/c), which favours the substitutional fixation of the Λ created by $\bar{K}N \rightarrow \Lambda\pi^-$ [29]. Let P_o and P_1 be the relative probability of the B = 0 and B = 1 annihilation, P_r the probability for a $\bar{K}$ to make a $\bar{K}N \rightarrow \Lambda\pi^-$ reaction inside the nucleus, and $P_f^{(o)}$, $P_f^{(1)}$ the fixation probability of the Λ in B = 0 and B = 1 cases. The yield of hypernuclei per annihilation is then given by

$$Y = P_o \, B_{\bar{K}}^{(o)} \, P_r \, P_f^{(o)} + P_1 \, B_{\Lambda}^{(1)} \, P_f^{(1)} \quad , \tag{2}$$

where $B_{\bar{K}}^{(o)}$ and $B_{\Lambda}^{(1)}$ are the branching ratios for $\bar{K}$ production in B = 0 and Λ production in B = 1 respectively. Assuming $P_o = P_f^{(o)} = 1$, $B_{\bar{K}}^{(o)} = 0.06$, and evaluating P_r with $\sigma(\bar{K}N \rightarrow \Lambda\pi^-) = 1.6$ mb, one obtains $Y = 10^{-4}$ at the most [30]. The observed yields are 3×10^{-4} and 9×10^{-4} for Bi and U respectively. The latter can be explained only if the B = 1 annihilations are possible. With $P_1 \approx 0.1$, the experimental value is obtained, if $P_f^{(1)} \approx 10^{-1}$ for Bi, which seems quite reasonable.

4.3 Other Possible Signals for Unusual Annihilations

The understanding of the dynamics of the B = 1 annihilation is very difficult, since the description of the $\bar{p}p$ annihilation at the quark level is still in its infancy [31,32]. Nevertheless, it is very reasonable to believe that the proximity of other nucleons can disturb considerably the complicated rearrangement of quarks occurring in the course of annihilation. It is quite possible that the distribution of the number of emitted pions can be altered compared to free space annihilation. Therefore, the charged pions multiplicity distributions and if possible, the total pion multiplicity distributions should be considered as a possible way for looking to unusual annihilations. Of course, pion multiplicity are changed by the cascade, but this effect could in principle be handled satisfactorily by the INC model.

5. CONCLUSION

Although the bulk of the experimental data on $\bar{p}$-nucleus annihilation is consistent with a conventional view of the process, we have pointed out two important aspects of the annihilations. First, it may provide a useful tool for studying multifragmentation of nucleus. For this, measurements of the fragment mass yield is needed, as well as exclusive measurements of the fragmentation. We stress the theoretical importance of the nuclear multifragmentation. It is as important to understand how a nucleus loses its cohesion as to understand the origin of its self-boundedness. In this respect, this question is closely related to the general title of this School, since most of the matter in the Universe is organized in nuclei. From the phase transition theory, the problem is interesting since it deals with (unknown) transition from a Fermi liquid to a droplet (fog) phase.

The second important aspect is the unusual annihilations. We have indicated the available evidence for B = 1 annihilations. The mechanism for such annihilations is far from being understood, but their experimental study should be pursued. More generally, the modification of the annihilation process due to the presence of surrounding nucleons has not been investigated. Experimentally, this might be done by studying pion and charged particle multiplicity distributions in $\bar{p}$-nucleus annihilations.

Table 1. Branching ratios (in percent)

	π's only	$\langle n_\pi \rangle$	$\bar{K}K$	ΛK	ΣK	$\langle K^+ \rangle$	$\langle K^+/\pi \rangle$	$3\bar{s}/q$
$\bar{p}p$, at rest exp.	95	5.01	5	-	-	~2.5	0.5	-
$\bar{p}p$, microcan. ref. [19]	95.5	5.05	4.5	-	-	-	-	-
$\bar{p}NN$, microcan. ref. [19]	88.5	4.73	2.71	2.86	5.52	5.5	1.4	11
Φ(3N), microcan. ref. [19]	85.4	4.36	1.77	4.32	8.07	-	0.019	-
quark-gluon T = 200 MeV ref. [21]	-	-	-	-	-	-	25	-
quark-gluon, $\bar{p}p$ ref. [23]	-	4.5	-	-	-	-	0.5 if F=0.1	-
$\bar{p}A$, cannon. ref. [33]	-	-	-	-	-	-	-	10-15

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