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NUCLEAR PHYSICS WITH ANTIPROTONS

Joseph CUGNON

Univ. de Liège, Institut de Physique, Sart Tilman B.5, B-4000 LIEGE 1 (Belgium)

1. INTRODUCTION

In this lecture, we will restrict ourselves to the annihilation process. This is one of the special features of the antiproton probe, compared to conventional ones, shared nevertheless with some mesonic probes (π,K,...). The conservative picture of the process is that the antiproton annihilates on a single nucleon at the nuclear surface (because of the huge annihilation cross-section at low momentum) giving birth to a few pions which rescatter through the target. The nucleus appears as a black structureless disk to the incoming antiproton and the main action comes from the energy released from the annihilation. An interesting question, not very much studied up to now,is how this energy is dissipated and how the nucleus reacts to this disturbance. This will be discussed in section 3 (after a brief theoretical description in section 2) as well as the possible multifragmentation of the target.

Although the existing data are more or less consistent with the conservative view explained above, there has been several suggestions pointing toward a more complex annihilation process. In section 4, we will discuss the possible occurence of special events, in which the $\bar{p}$-annihilation involves several nucleons at the same time. We will review the experimental information in favour of such a possibility.

2. THE INTRANUCLEAR CASCADE FOR $\bar{p}$-NUCLEUS

The conservative picture of the $\bar{p}$-annihilation on a nucleus is made more precise in the intranuclear cascade (INC) model, with the help of the following assumptions : (a) the $\bar{p}$ annihilates on a single nucleon at the surface of the nucleus, creating a few pions, with the same properties as in $\bar{p}$-nucleon annihilations ; (b) some of the pions cascade through the nucleus, interacting with the nucleons, ejecting some of them, in a process by which they can also be absorbed ; (c) after this fast ejection process, the nucleus dissipates the remaining excitation energy at a much slower rate, by evaporation and/or fission. Steps (a) and (b) are described by simulation using known experimental data.

The INC model has been used by several groups[1-4]. It reproduces successfully[3,5-7] the bulk of the existing experimental data (see ref. [8] for a recent review) : inclusive proton and pion cross-sections, pion multiplicity distributions for annihilation in flight, neutron spectrum and the mass residue distribution after annihilation at rest. The agreement is generally very good but departures at the level of 10 to 20 % may be observed. This is usually considered as satisfactory in view of the simple dynamics of the model and the complexity of the process. Whether the remaining discrepancy may be removed by improving the model with the addition of detailed but conventional aspects of the nuclear dynamics or by requiring new (exotic) features is not known yet.

3. THE NUCLEUS' RESPONSE

The 2 GeV or so released by the annihilation is not entirely used to excite the nuclear system. Some of the primordial pions (those issued from the annihilation) can escape right away from the nucleus, just because of the peripheral nature of the annihilation. Furthermore, a sizeable fraction of the interacting pions escape from the nucleus (πN interaction is strong but mainly elastic at low energy). These effects substantially reduce the energy transferred from the multipion system to the baryonic system. The energy transfer amounts to about 500 MeV for annihilation at rest (for target dependence, see refs. [1,6]) and to ~ 800 MeV for annihilation in flight in the LEAR energy regime. Th amount of excitation energy contained in the target (baryons inside the nuclea volume), as calculated in the INC model, is displayed in fig. 1, as a function of time. Roughly speaking, the energy is dissipated on two time scales. First it is removed by the ejection of rapid nucleons. During this stage, the excitation energy is concentrated close to the pion paths. In a picturesque language the whole nucleus is not "fired" by this process, as schematically shown by fig. 2

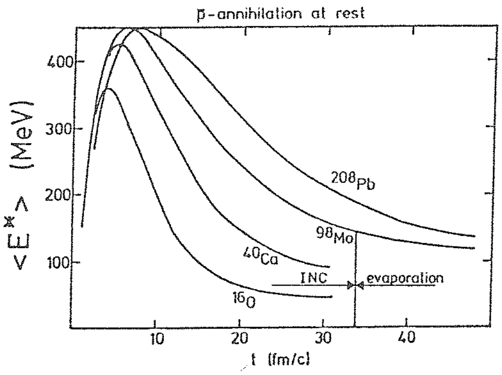


FIGURE 1

Time evolution of the target excitation energy after antiproton annihilation on various nuclei.

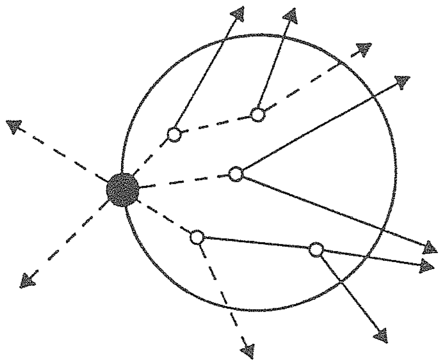


FIGURE 2

Schematic representation of the interaction between the annihilation pions (dotted lines) and the nucleus (see text for detail)

The latter suggests that the interacting pions are producing ejectiles more or less independently from each other. This emission pattern is sometimes named as a clan picture, each interacting pion being the initiator of a "clan" of ejectiles. This pattern could leave some trace in the ejectile multiplicity distribution[9]. In particular the charged particle multiplicity shows a negative binomial shape[10], typical of a clan structure (an aspect well documented in high energy collisions[11,12]).

After this fast process is over, the remaining energy is much more evenly distributed in the whole nuclear volume. The energy is then dissipated by evaporation. For a nucleus like ^{98}Mo, the remaining (randomized) energy is around 150 MeV, i.e. about 1.5 MeV per nucleon. An INC calculation for the fast process supplemented by a standard evaporation calculation reproduces reasonably well the observed residual mass spectrum for several nuclei[3,6]. On the average, a nucleus like ^{98}Mo loses about 15 nucleons, but fluctuations are large and it may loose as much as 30 nucleons.

Here, one encounters a well debated question among nuclear physicists[12] : what happens to a nucleus when one tries to inject in it more and more (randomized) excitation energy E^* ? The current ideas can be summarized[13] as follows : (a) if $E^*/A \lesssim$ 2-3 MeV the nucleus loses nucleons by evaporation but a big residue subsides ; (b) if E^*/A is larger, the nucleus may fragment in many pieces of intermediate size : this is the so-called multifragmentation. The issues of this study, also conducted with heavy ions, are : (i) how does the nucleus lose its cohesion, its stability ? ; (ii) what is the basic mechanism for the transition from evaporation to multifragmentation ? ; (iii) is the transition sharp or not ? does it display phase transition features ?

Obviously, the experiment PS186 does show[14] that in $\bar{p}$-annihilation at rest the nucleus responds in the subcritical regime. The question is then : how can one get overcritical ? The simplest (but not necessarily the only one) answer is to increase the energy. In order to make some predictions, we studied the problem by supplementing the INC with a percolation model. The idea is to observe the voids created inside the nucleus by the multipion cascade and to assume that fragments appear as in percolation : two nucleons belong to the same cluster if the relative distance is small enough. Results of this study are contained in figs. 3-5. One can see that the excitation energy is increasing with the incident energy until the latter reaches ~ 2 GeV, above which it saturates. The mass yield is shown for two values of the incident energy in figs. 4 and 5. Clearly, at 180 MeV the regime is still subcritical, but at 4 GeV, the overcritical regime has set in. One of the important quantities is the exponent σ characteristic of the mass yield $Y \sim A^{-\sigma}$ for the lightest clusters ($A \lesssim 20$).

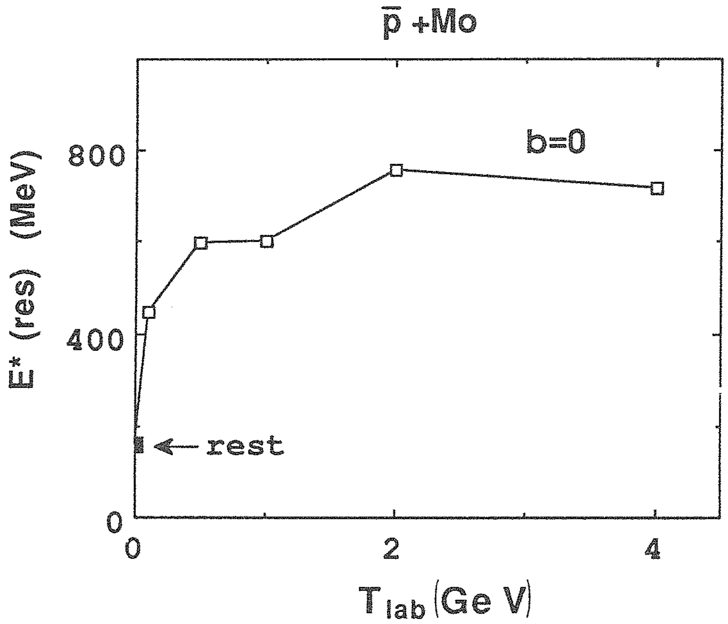
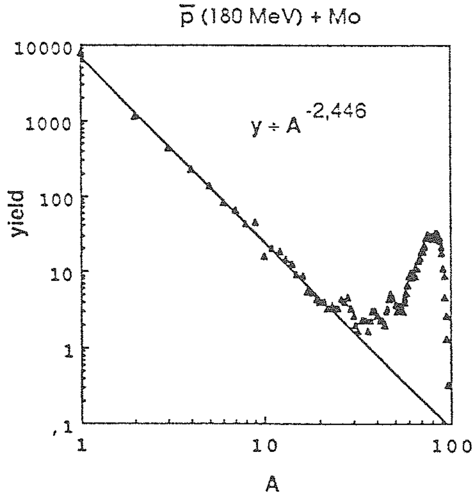


FIGURE 3
Residual excitation energy delivered to Mo target after $\bar{p}$-annihilation as a function of the kinetic energy of the antiproton



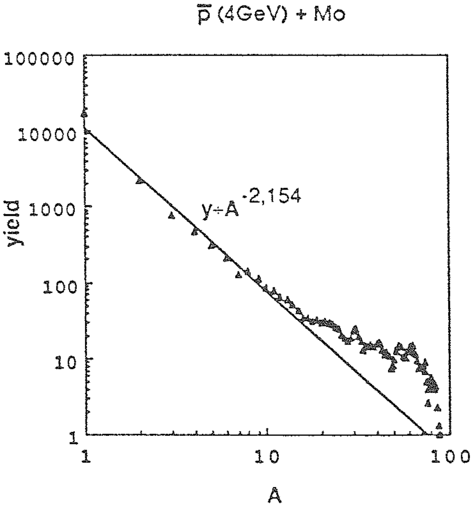


FIGURE 4
Mass yield for $\bar{p}$ (180 MeV) - Mo system. See text for detail

FIGURE 5
Same as fig. 4 for 4 GeV antiprotons

We observed a sudden decrease of the exponent σ with the incident energy, which suggests that the transition occurs around 0.8 GeV. This calculation is exploratory however and other effects have to be included : impact parameter dependence, cluster deexcitation, etc. The situation is very promising however, and we think that the $\bar{p}$-nucleus is well suited to the study of multifragmentation. In particular, we listed (Table I) in acomparison with the heavy ion case the advantages of the $\bar{p}$-nucleus system. The most important of these is the possibility of depositing enough excitation energy without very much momentum and angular momentum.

TABLE I
Comparison between $\bar{p}$ and heavy ion beams for the study of multifragmentation

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

4. ANNIHILATION ON SEVERAL NUCLEONS

The annihilation process may be more complex than a point-like event in space-time involving one target nucleon only. One may imagine that the underlying rearrangement of quarks lasts for some time. Consequently, the annihilating system can move a little bit and then another nucleon (or more) can participate to the annihilating system.

The frequency of such "unusual" events has been estimated on simple geometrical grounds to be of the order of 10-20 % for annihilation in flight[15]. An important point is the possible detection of such events. They do not leave very important changes on the particle spectra[16]. The most promising signal, beside direct observation of two-body processes like $\bar{p}d \to p\pi^-$, seems to be the enhancement of the strangeness production, according to ref. [17]. This suggestion is based on a purely statistical model for the decay of the annihilating system. The model which contains a couple of parameters (see refs. [17,18] for detail) is fitted to the $\bar{N}N$ system and then used to make predictions on $\bar{N}NN$ (B=1) annihilations (on B > 0 in general). The total strange yield is more than doubled compared to B=0 annihilation. For annihilation on nuclei, the question is more complicated. The yield for some strange particle species can be written as :

$$Y = P_0 \, BR(0) D_0 + P_1 \, BR(1) D_1 + \dots \qquad (1)$$

where P_i is the relative probability for having B=i annihilation, the BR(i)'s are the branching ratios for this particular species, and where the quantities D_i account for the possible distortion (destruction or creation) in the rescattering process following the annihilation itself. The latter quantities have not yet been calculated reliably. It is quite hard a task especially for $i \geq 1$. What has been done up to now is to estimate or calculate the first term in eq. (1) and compare it to the experimental data. Several cases have been so discussed in ref. [19]. All point toward a need of having $B \geq 1$ annihilations. Here, we will focus on the case of Λ, $\bar{\Lambda}$ and K_S^0 production in $\bar{p}$ (4 GeV/c) + Ta.[20]

Experimentally, the respective cross-sections are 193 ± 10, 3.8 ± 2 and 82 ± 6 mb, while the total annihilation cross-section is 1628 mb. In Table II, we report on our estimate of various contributions. The primary contribution comes from known $\bar{p}N$ processes. The rescattering contribution is due to interaction of particles issued from the annihilation with the nucleus. The secondary contribution has the same physical origin, but we single it out because it corresponds to real strangeness production whereas the previous one is merely due to strangeness exchange. One can see that assuming B=0 annihilation only underpredicts the Λ production yield, whereas there seems to be no problem for K_S^0 and $\bar{\Lambda}$. We also made an estimate of the B=1 annihilations. Assuming 20 % of those, we obtained $\sigma(\Lambda) \sim 199$ mb and $\sigma(K_S^0) \sim 125$ mb. Here the problem deals with the K_S^0 production, which is overestimated. The estimates above as well as the one of ref. [21], are rendered uncertain because of the rescattering, or more precisely, the transfer of strangeness from detected to undetected species. The theoretical estimates are much safer for strange quark production cross-sections :

TABLE II
Contributions to strange particle cross-sections (in mb) for $\overline{p}$ (4 GeV/C) + Ta

	primary	rescattering	secondary	sum
Λ	$\bar{p}p \rightarrow \Lambda X \ : \ 34$	$\bar{K}N \rightarrow \Lambda\pi \ : \ \sim 74$	$\pi N \rightarrow \Lambda K \ : \ 34^*$	~ 142
K_S^0	$\bar{p}p \rightarrow K_S^0 X \ : \ 123$	$\bar{K}N \rightarrow \Lambda\pi \ : \ \sim -32$	$\pi N \rightarrow \Lambda K \ : \ 15$	~ 115
Λ	$\bar{p}p \rightarrow \bar{\Lambda} X \ : \ 34$	$\bar{\Lambda}N \rightarrow \pi\bar{K} \ : \ \sim -32$	-	~ 2

*Estimate of ref. [21]

$$\sigma(s) = \sigma(\Lambda) + \sigma(\Sigma) + \sigma(K^-) + \tfrac{1}{2}[\sigma(K_S^0) + \sigma(K_L^0)] \qquad (2)$$

$$\sigma(\bar{s}) = \sigma(\bar{\Lambda}) + \sigma(\bar{\Sigma}) + \sigma(K^+) + \tfrac{1}{2}[\sigma(K_S^0) + \sigma(K_L^0)] \quad , \qquad (3)$$

because the strange quarks are not likely to disappear. We especially draw the attention on $\sigma(\bar{s})$, whose knowledge roughly requires measurement of K^+ and K_S^0

yields only. In the above case, the quantity $\sigma(s) = \sigma(\bar{s})$ is predicted to be ~ 198 mb for B=0 annihilations only.

The same analysis for the $\bar{p}$ Ne case[22] at 607 MeV/c leads to the same conclusions : the Λ yield can be explained with ~ 20 % of B=1 annihilations, whereas the K^0_S is largely overestimated.

5. CONCLUSION

The $\bar{p}$ annihilation on nuclei is potentially a good tool to study multifragmentation and the formation of new hadronic systems, namely the B > 0 annihilating systems. We would like to stress that the $\bar{p}$ annihilation on two nucleons is really a new process, which has nothing to do with pion annihilation on two nucleons. It indeed implies the opening of the bag of the $\bar{p}$ and the annihilation of one antiquark with a quark of one of the nucleons and at the same time the annihilation of the remaining antiquarks with the quarks of another nucleon.

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Question by O.D. Dalkarov (Lebedev Physical Institute)

Low energy $\bar{p}$ can solve in principle very old problem in nuclear physics, I mean so-called non-adiabatic effects is hadron-nucleus scattering. For these it is necessary to have a precise measurement of $\bar{p}$-nucleus scattering in diffraction minimum and an investigation of concrete inelastic channels (for instance, $\bar{p}A \rightarrow e^+e^- + A'$). For details, see my report in PANIC-87 Conference.

Answer : Thank you for the comment. I said in the beginning of my talk that I limited my discussion to the interest of the annihilation process.

Question by N.W. Tanner (Oxford)

Can you explain the meaning of the words "phase transition" which imply equilibrium and homogeneity and contradict the "cascade" description ?

Answer : You probably misunderstood my argument. I discussed the concept of the transition from evaporation to multifragmentation as possibly showing some features of a phase transition. I did not claim that the "cascade" will be able to describe these processes. Nevertheless, the cascade can be used to estimate the excitation energy of the thermalized system after the pion cascade, which may be considered as the relevant parameter for the appearance of the phase transition.

Question by T. von Egidy (T.U. München)

Your calculations seem to be in good agreement with the experimental results. Are you using for Ne the same parameters as for heavier nuclei ?

Answer : Yes, of course.