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TRANSFER OF ENERGY FOLLOWING p̄-ANNIHILATION ON NUCLEI

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Abstract: The intranuclear cascade model is used to study the energy deposit in the nucleon system by cascading pions issued from p̄-annihilation. The emphasis is put on the correlation between the participant nucleons (number, energy, ...) and the parameters of the annihilation (location, number of pions, ...). Annihilations both at rest anc in flight (in the LEAR domain) are studied. The relation of the cascade output to the mass distribution of the residues is investigated and shown to be ambiguous. Simple procedures are used in the cases of ^{98}Mo (at rest) and ^{20}Ne and the results are compared with experimental data. It seems that not enough energy is transferred from the multipion system to the nucleon system in the cascade model. The relationship between the intranuclear cascade model and the current percolation models for nuclear fragmentation is discussed. It is suggested that p̄-annihilations on nuclei are suited to study these models and typical features like the critical percolation threshold and multifragmentation.

1. Introduction

The experimental data concerning p̄-annihilation on nuclei recently obtained at the LEAR facility [1-5]) are in general overall agreement with the simplest physical picture, namely that the antiproton annihilates on a single nucleon, generating a number of pions which then cascade through the target nucleus in a sequence of interactions with the nucleons. The inclusive measurements are consistent with such a scenario. Therefore, if unusual processes take place, as for instance the one proposed in refs. [6,7]), their identification may require that the above picture be refined; the latter is expected to give a good description of the "background" on top of which the signature of unusual processes will hopefully come into view. Turning to exclusive measurements like correlation or multiplicity distributions, we also need a theoretical landmark for the energy transfer from the multipion system to the nucleons, and from there to the fragmentation of the target nucleus.

In this perspective, the present paper exploits our intranuclear cascade (INC) model [8,9]) which has provided a good picture for the overall properties of the annihilation process [5]). More precisely we want to study the correlations between the participant nucleons (those involved in the cascade of interactions), their number, and their energy spectrum, on the one hand, and the parameters of the annihilation (location, number of produced pions, number of non-interacting pions), on the other hand. A less extensive study of this type has already been undertaken in ref. [10]). We also want to relate our approach to the now existing data and to current ideas about nuclear fragmentation.

In sect. 2, we briefly recall the main ingredients of our INC model. In sect. 3, we investigate the energy deposit and the correlations mentioned above resulting from annihilation *at rest*; we compare with the recent data for ^{98}Mo [refs. [2,11])]. In sect. 4, we discuss the evolution of the pattern for annihilation *in flight*, as a function of the incident energy. We also investigate the dependence on the target mass. In sect. 5, we discuss the relationship with nuclear fragmentation models. Sect. 6 contains our conclusion.

2. The INC model for $\bar{p}$ annihilation

Our model has been described in detail in ref. [9]) and in the papers referenced therein. We briefly recall that the nucleons are given randomly their initial position and momentum according respectively to the nuclear density distribution and the Fermi gas law. The fate of all the particles is governed by a classical scheme (they move on straight lines between interactions triggered by the minimum distance of approach) supplemented with a probabilistic ingredient to fix the final states from the set of possible ones. Besides the annihilation

$$\bar{N}N \to n\pi\,, \tag{2.1a}$$

the following reactions are introduced:

$$NN \to NN\,, \qquad NN \rightleftharpoons N\Delta\,, \qquad N\Delta \to N\Delta\,, \tag{2.1b}$$

$$\Delta \rightleftharpoons \pi N\,, \qquad \pi N \to \pi N\,, \qquad \pi N \to \pi\pi N\,, \tag{2.1c}$$

$$\pi NN \to NN\,. \tag{2.1d}$$

Details on the cross sections can be found in the references cited above. Note that pion reabsorption on two nucleons (2.1d) [see ref. [12]) for the manner this reaction is treated] was not included in our previous study of annihilations [9]); however, as we shall see, its importance is small.

3. Annihilation at rest

3.1. NUMERICAL RESULTS

It is known that nuclear absorption of the antiprotons decelerated in matter follows from the capture on a Coulomb orbit. A cascade of electromagnetic de-excitation of the $\bar{p}$-nucleus atom [13]), essentially through the $(n, l = n-1)$ states, emits X-rays, which permits us to trace the $\bar{p}$ down to the level where annihilation takes place. The product of the radial distribution of the $\bar{p}$-atom in the state of principal quantum number n and of the nuclear density can be considered as the distribution for the radial location of the annihilation site. It can be written

$$p(r) = Cr^2|\psi_{n,n-1}(r)|^2\rho(r) = Dr^{2n}\,e^{-2r/na}\rho(r)\,, \tag{3.1}$$

where ρ is the nuclear density, C and D are normalization constants, and a is given by

$$a = \frac{1}{\alpha}\frac{\hbar}{Z\mu c} \simeq \frac{1}{\alpha}\frac{\hbar c}{Zm_pc^2} \simeq \frac{28.8\text{ fm}}{Z}\,. \tag{3.2}$$

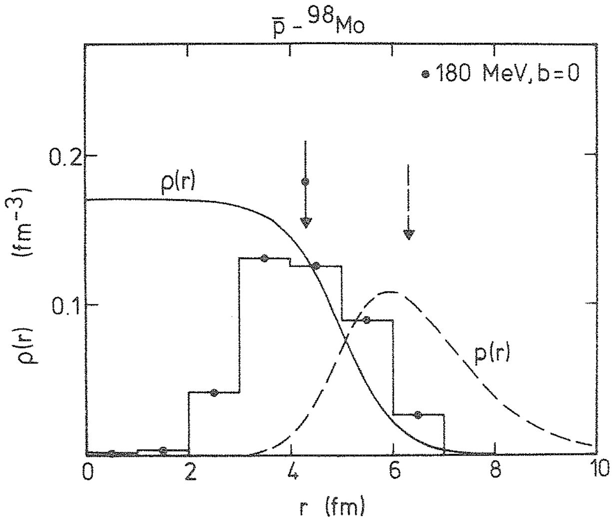

Fig. 1. The full curve is the density profile of the ^{98}Mo nucleus, as used in the text. The dashed curve gives the probability distribution $p(r)$, eq. (3.1), of having the annihilation at a distance r from the centre of the nucleus for bound antiprotons. The histogram represents the same quantity for 180 MeV antiprotons falling on the nucleus with zero impact parameter. The arrows gives the respective mean annihilation positions.

Experimental study of the p̄–Mo system, in particular for the ^{98}Mo isotope, has determined that annihilation occurs practically entirely in the $n=6$ state [11,14]). For $\rho(r)$ we have taken a Woods–Saxon shape with a half-density radius 4.98 fm and diffuseness 0.55 fm. Eq. (3.1) then gives for $p(r)$ the shape shown in fig. 1. The product of the rising atomic density (which has its maximum for $r = n^2a \simeq 25$ fm) with falling nuclear density gives the bell-shaped distribution which is used as input for the random choice of the site of annihilation with a bound nucleon. Each annihilation generates a random pion star with $\langle N_\pi \rangle = 4.85$, the momenta being chosen according to phase space, as explained in ref. [9]).

We report on the result of a run of 1000 cascades. Of the 4.85 primordial pions generated on average, 2.21 interact with the nucleus, i.e. they interact at least once with a nucleon. The number of final pions, i.e. those emerging after the cascade has subsided, is 4.41; this average number is the sum of 2.62 pions which do not interact and 1.79 pions which emerge from the nuclear cascade. Thus, from the number of primordial pions which interact with the nucleus, 81% emerge from the cascade of interactions; 91% of the number of primordial pions are found in the final state.

Let us now assess the importance of the perturbation brought about by the pions to the nucleus. In the cascade, energy is transferred from the pion system to the system of nucleons. We call participants all those nucleons which take part in an interaction, be it directly with a pion, another recoiling nucleon or a Δ. On average, about 18 nucleons are participating and received around 356 MeV energy from the cascading pions. We have looked carefully into correlations between several quantities to see whether there exist events with particular features of the interaction between the multipion system and the remaining nucleus. The main results are collected in fig. 2. Part (a) shows the correlation between the number N_π of primordial pions, i.e. those issued from the annihilation, and the number n_π of final pions. It reflects the overall absorption and also shows that some events are creating pions. Part (b) displays the correlation yield between the number of primordial pions N_π and the number of participants N_p. The degree of correlation is rather weak, which is surprising (see below, however). Part (c) implies the number of participants N_p and the energy carried by the final pions W_π. The latter is simply connected to the energy transfer W_{tr} to the nucleon system by

$$W_\pi + W_{tr} = W_{ann}\,, \tag{3.3}$$

where W_{ann} is the energy liberated by the annihilation (here essentially twice the mass of the nucleon). One sees that the energy transferred increases as the number of participants increases. Part (d) of the figure shows that the deeper the annihilation occurs (z_a is the distance separating the centre of the nucleus from the annihilation site), the larger the number of participants is. Part (e) of the figure is revealing: it shows that the number $\tilde{n}_\pi$ of interacting pions and the number of participants are rather strongly correlated. Thus, part (b) of the figure is somewhat misleading. The apparent absence of correlation between N_p and N_π results from a strong correlation between N_p and $\tilde{n}_\pi$ and some anticorrelation between N_π and $\tilde{n}_\pi$. If the number of interacting pions is small, the number of non-interacting pions is large and vice versa. Part (f) of fig. 2 indicates a strong correlation between the number of interacting pions $\tilde{n}_\pi$ and the final pion energy W_π. To sum up, no really unexpected feature shows up. The number of participants, the number of interacting pions, the energy transfer and the annihilation depth are correlated, but not in a spectacular fashion. As shown by fig. 2, a non-negligible fraction of the events correspond to annihilations *inside* the nucleus, involving many nucleons and transferring as much as 1 GeV to the nucleon system.

The fact that the annihilation mostly takes place in the outer shell of the nuclear matter entails configurational properties for the pion system. Let us consider the direction, defined event by event, specified by the nuclear radius passing through

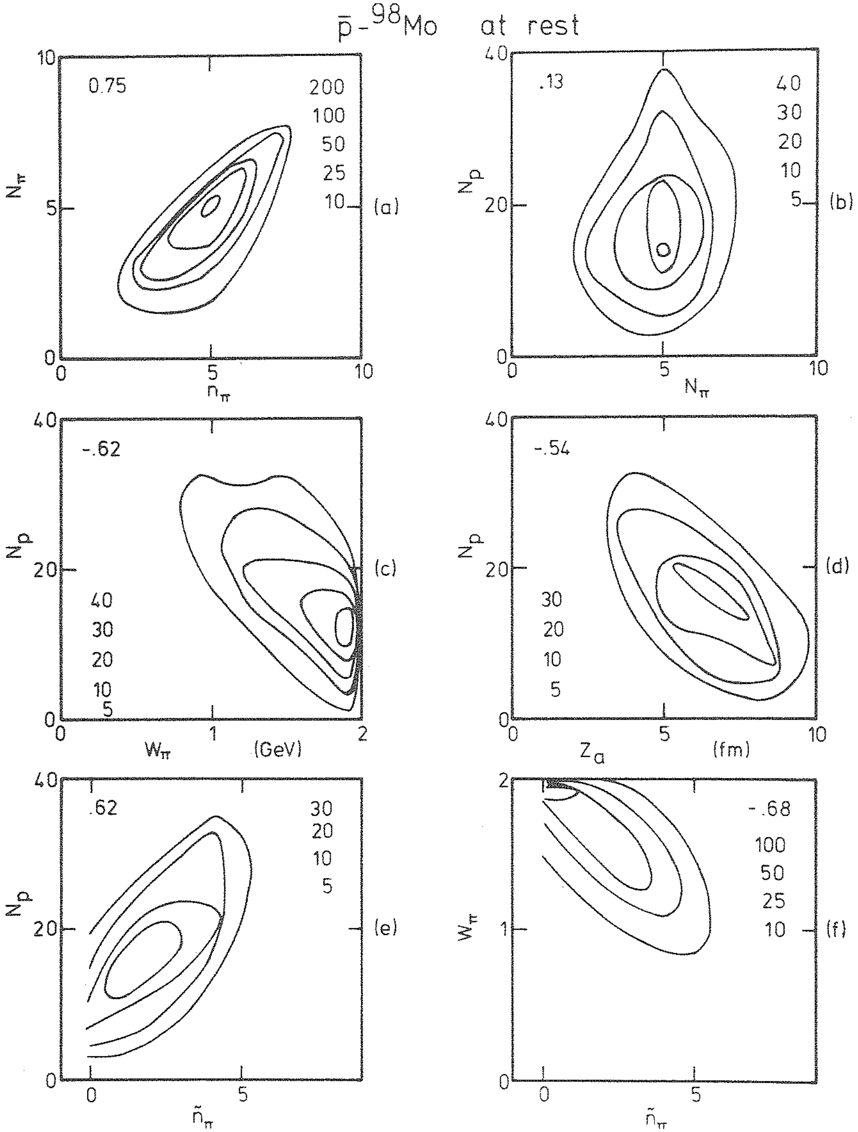

Fig. 2. Calculated correlation yields between various quantities involved in p̄-annihilation at rest on ^{98}Mo nuclei. The number in the upper-left corner in each square is the correlation coefficient. The other numbers give the relative yield for the curves shown, starting from inside the curves. See text for details.

the annihilation point. Although this direction cannot be defined experimentally it is interesting to consider the cascade properties with respect to it. The distribution of the pions is quite assymetric. This appears in the rapidity distribution (fig. 3) which shows a drastic damping in the forward direction (i.e. towards the inside of the nucleus). This feature is also revealed by comparing the pion spectra in different directions (fig. 4). Both figures illustrate the splashing of the pionic fire on the

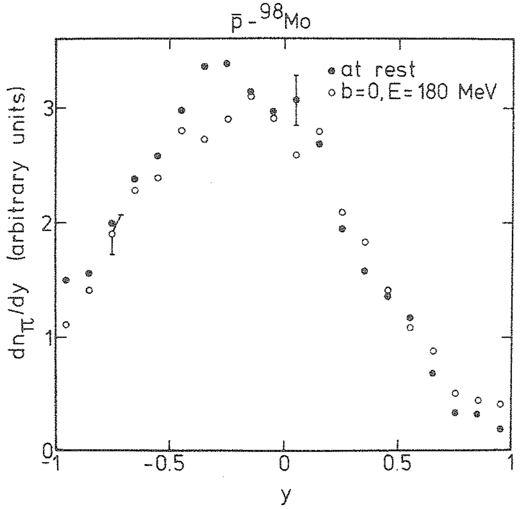

Fig. 3. Rapidity spectrum of the pions emitted after p̄-annihilation on ^{98}Mo nuclei. The error bars indicate the typical uncertainty of the calculation.

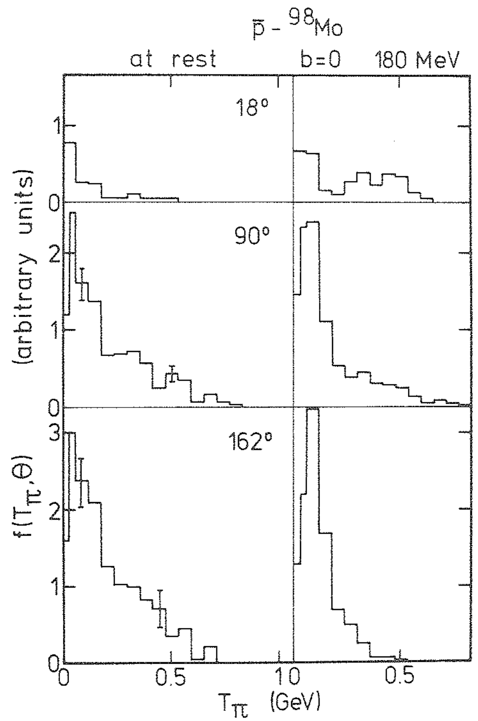

Fig. 4. Pion spectrum at different angles for p̄-annihilation both at rest (left) and in flight (right) on ^{98}Mo nuclei. The relative magnitude of the spectra is preserved. The error bars indicate the typical uncertainty of the calculation.

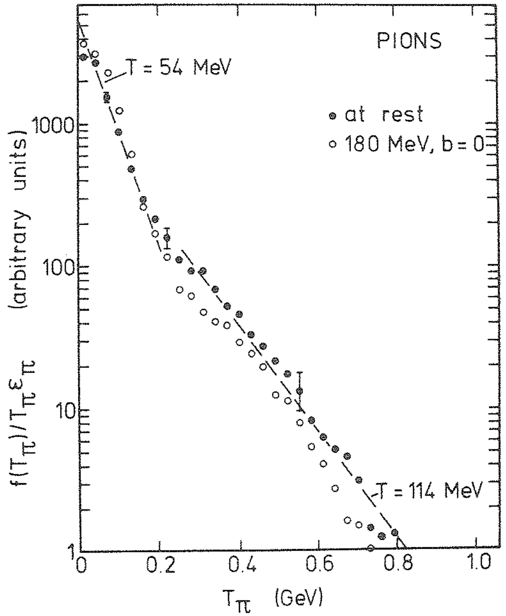

Fig. 5. Pion spectrum for annihilation at rest and in flight on ^{98}Mo nuclei. The quantities T_π and ε_π are the kinetic and total pion energies, respectively. The error bars indicate the typical uncertainty of the calculation.

nuclear "wall". The participant nucleons, on the other hand, do not show any significant anisotropy.

We also considered the energy spectrum integrated over all directions (which is relevant to the observations). It is shown in fig. 5 for the pions and in fig. 6 for the participant nucleons. Both spectra show a low-energy component and a high-energy tail. The concept of temperature is not strictly relevant here since we deal with a total system (all the nucleons, potentially, plus all the pions) which is not at all equilibrated; we have, however, extracted from the low-energy and high-energy parts of the spectra, "temperatures" which can serve as a guide. We find for the pions $T = 54$ MeV and 114 MeV, and for the participants $T = 26$ MeV and $T =$ 53 MeV. The highest pion temperature pertains to the primordial pions which have not interacted [15]); the lower one to the system of interacting pions. It is also the temperature of the nucleons which result directly from a pion-induced interaction (essentially $\pi N \to \Delta \to \pi N$), without further interaction. The lower participant temperature presumably characterizes the system of nucleons which take part in NN rescattering.

3.2. RESIDUAL NUCLEUS: COMPARISON WITH EXPERIMENT

Recently, experimental information has been obtained on the residue of the target left by the annihilation at rest [11]). The method is based on measurements of the

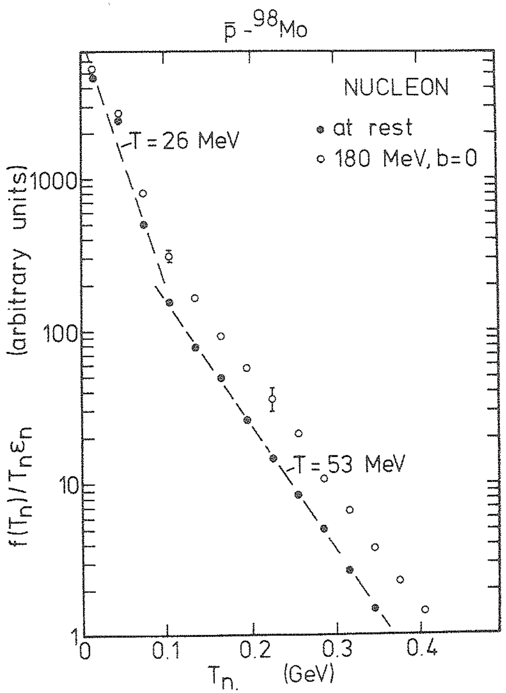

Fig. 6. Nucleon spectrum for annihilation at rest and in flight on ^{98}Mo nuclei. The quantities T_n and ε_n are the kinetic and total nucleon energies, respectively. The error bars indicate the typical uncertainty of the calculation.

residual activity. The results, quite detailed for the radioactive residues, do not bring any information on the stable residues. Nevertheless, the authors of ref. [11]) state that, in the case of ^{98}Mo, up to 30 nucleons can be emitted, with an average of about 15 nucleons. These data are not directly comparable with the number of participants, as evaluated by our model, since some of the nucleons struck in the cascade acquire too little energy to escape the nuclear mean field. The latter is neglected in our calculation, although we progress in that direction. But, even with a mean field, one needs a detailed description of the evaporation process, which may involve other particles than nucleons. In order to attempt a comparison, however, we have looked at the distribution of the number of participants whose final energy is larger than a given threshold. The results are summarized in fig. 7. If we consider the distribution of the residues, after participant nucleons with an energy larger than 40 MeV have moved away and correct by transforming the energy left in the residue into evaporated nucleons [assuming that about 10 MeV are necessary to evaporate a nucleon [16])], we obtain a curve schematically described by the full line. Changing the threshold down to 30 MeV for the escaping fast nucleons gives again approximately the same curve. One can thus roughly consider this curve as our prediction. It seems that it qualitatively agrees with experiment, although we

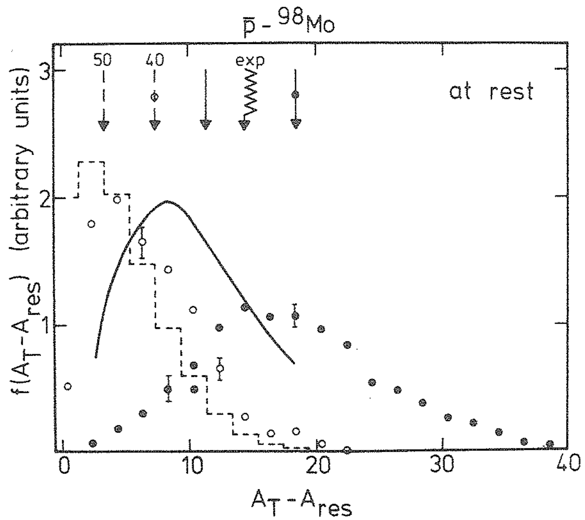

Fig. 7. Distribution of the difference between the target mass A_T and the residual mass A_{res} for p̄-annihilation at rest on ^{98}Mo nuclei. The histogram is obtained by discarding the participant nucleons with an energy smaller than 50 MeV. The open circles correspond to a threshold of 40 MeV. The full curve is obtained from the open circles by applying a correction for evaporation of the residue (see text). The distribution for all the participants (heavy dots) is shown for comparison. The arrows give the average values for the respective distributions.

obtain too heavy residues. We will come back to the problem of the residues in sect. 5.

4. Annihilation in flight

4.1. CENTRAL COLLISIONS

We particularly study the collisions at zero impact parameter, even though they cannot be isolated easily by experiment, because this makes the comparison easier with annihilation at rest. In table 1, we present such a comparison for two incident energies at the ends of the energy domain currently covered at LEAR. The most important difference pertains to the non-interacting pions, whose number decreases with the incident energy as a result of a deeper penetration of the p̄ inside the nucleus (see fig. 1) and also of the motion of the pionic fireball. As a somewhat trivial consequence, the number of participants increases, as well as the energy transfer. We will come back on this point later on.

The pattern of the interaction between the multipion system and the nucleon system is changing qualitatively, as revealed by fig. 4. In the forward direction, the pion spectrum gets a high-energy component, whereas in the backward direction, the pions are getting less energetic. This comes from the fact that the matter is relatively transparent to pions with kinetic energy above the (3, 3) resonance region. When the annihilation occurs at rest, a large fraction of the pions have their energy

TABLE 1

Comparison between annihilations at rest and in flight

		Rest	$b=0$	
			21 MeV	180 MeV
average interaction number per cascade	NN → NN	9.19	8.56	10.99
	NN → NΔ	0.03	0.02	0.08
	NΔ → NΔ	0.78	0.54	1.42
	NΔ → NN	0.47	0.38	0.88
	ΔΔ → ΔΔ	0.02	0.01	0.05
	πN → Δ	5.47	4.73	8.15
	πN → πN	0.66	1.01	1.92
	Δ → πN	4.89	3.99	7.01
	πN → ππN	0.11	0.15	0.34
	πNN → NN	0.10	0.10	0.20
	all interactions	21.72	19.48	31.04
pion numbers	primordial	4.85	4.83	5.08
	non-interacting	2.62	2.06	1.25
	final	4.41	4.53	4.42
W_{tr} [MeV] [a]		356	389	740
$\langle N_p \rangle$ [b]		18.14	17.84	23.09

[a]) Energy transfer.

[b]) Average number of participant nucleons.

about the resonance region and are therefore strongly absorbed. When the annihilation proceeds in flight, due to the c.m. motion, pions produced in the forward direction tend to be above the resonance. On the other hand, the pions produced in the backward direction are less energetic and are slowed down by strong interaction with the outer fringes of the nucleus. This pattern, already pointed out in ref. [9]), and in qualitative agreement with the measurements of ref. [5]), is enhanced when going to larger impact parameters and to smaller targets. This is dramatically illustrated in fig. 8, which exhibits the inclusive (i.e. summed over all impact parameters) pion-production cross section in ^{20}Ne.

4.2. ENERGY DEPOSIT AND PARTICIPANT NUMBER

The deeper annihilation inside the nucleus (see fig. 1) has the effect of increasing the number of participants (see table 1) and of increasing spectacularly the energy deposit in the nuclear system, as shown by fig. 9. A somewhat surprising result is the narrowing of the number of participants distribution. Presumably, this is linked to the properties of the high-energy pions we have discussed in subsect. 4.1.

We want to investigate how the energy is deposited. As we noted in subsect. 3.1 [which fact was known from previous works [9,10])], the energy is transferred to the

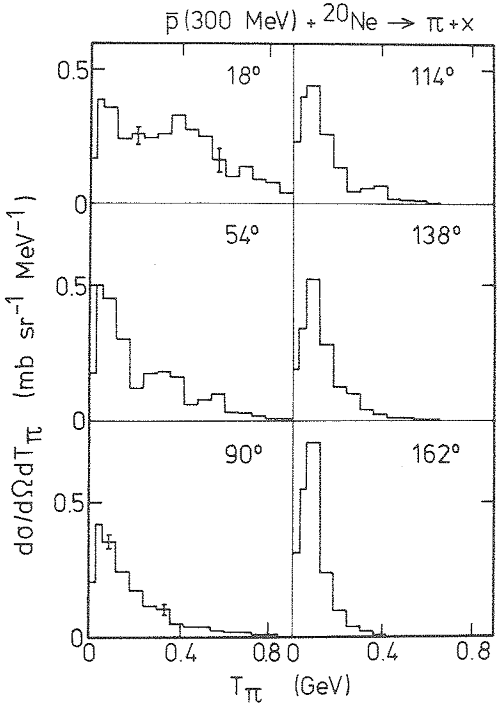

Fig. 8. Calculated double-differential cross section for pion production in annihilation of 300 MeV antiprotons on ^{20}Ne nuclei. The error bars indicate the typical uncertainty of the calculation.

nucleons through $N\pi \rightarrow \Delta \rightarrow \pi N$ reactions, which provide the nucleons concerned with a kind of thermal spectrum. The fact that the spectrum appears thermal is not really, according to us, indicative of the formation of a thermal source. It results from the fact that the original spectrum of the pions is already thermal-like and the property that reactions with mass-energy exchange like the ones referred to above are very efficient to transfer energy. One may, however, ask whether this multiple interaction between pions and nucleons can involve a large part of the nucleus. Therefore we turn to the multiplicity distribution. For the ^{98}Mo system, fig. 9 shows that up to 40 nucleons can be involved.

Fig. 10 displays the same distribution for the $\bar{p}$-annihilation on ^{20}Ne at two different energies, investigated by the streamer chamber group [4]). A larger part of the nucleus is contributing, but still not all of the nucleus.

5. Connection with fragmentation models

5.1. GENERAL CONSIDERATIONS

When a nucleus experiences some energy transfer, it eventually breaks into pieces. Many models have been devised. All of these models contain an assumption on the

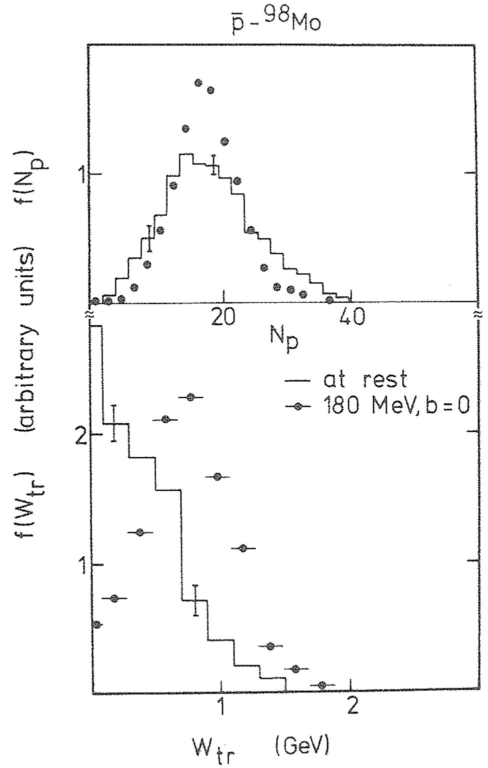

Fig. 9. Number of participants (top) and energy deposit (bottom) distributions for p̄-annihilation at rest and in flight on ^{98}Mo nuclei. The error bars indicate the typical uncertainty of the calculation.

way the energy is transferred, a description of the intermediate excited state of the system, still existing as a single nuclear entity, and finally a prescription linking this state to the final fragmentation state. Among possible scenarios, one can single out two limiting pictures, depending on the way the energy is transferred. In one extreme view, the energy is transferred to a generally small number of nucleons which are ejected, leaving behind a cold bound nucleus: this is the strict spallation model. At the other extreme, there is the compound nucleus model, where the transferred energy is shared by the whole nucleus. The latter, if it is not too much excited, will decay by evaporation, i.e. by a statistical emission of light particles with a thermal-like spectrum. If the excitation energy is too large, the system may break into many pieces of intermediate mass, perhaps linked with the underlying liquid–gas phase transition [17-19]).

One may, however, conceive an intermediate scenario, where most of the energy is deposited on a few energetic nucleons, which will be ejected, but which, on their way out of the nucleus, will lose energy, shared more or less collectively by the nucleons of the remnant. It is then natural to believe that the final break-up of the nucleus will strongly depend upon the geometrical properties of the remnant. Models

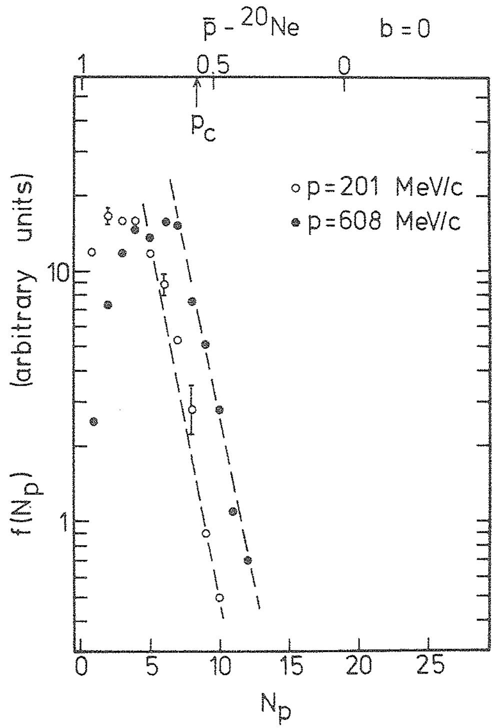

Fig. 10. Distribution of the number of participants N_p for $b=0$ annihilation in ^{20}Ne. The scale at the top gives the corresponding value of the parameter p (see text). The dotted lines exhibit the parallel fall-off of the distributions. The error bars indicate the typical uncertainty of the calculation.

based on this idea are exploiting results borrowed from percolation theory [for a review, see ref. [20])].

5.2. CASCADE MODEL AND SPALLATION

Strictly speaking, our INC model fits the first limiting picture since it gives the momenta of the struck nucleons (participants) and the outgoing pions. Let us stick for a while with this description and look at the ejectile multiplicity M_ν. Fig. 11 shows the inclusive distributions in the ^{20}Ne case at the three energies where data have been obtained by the streamer chamber group at LEAR [4]). These distributions having the same shape for high multiplicities; we have renormalized them to superpose the high multiplicity part, as already done by the experimentalists. These distributions have a striking resemblance in shape with the experimental charge distributions. There are, however, two discrepancies. First, when the estimated correction is made to eliminate the neutrals, our prediction is smaller than the experimental result: about 6 charged particles instead of 6.7 ± 0.2 for 608 MeV/c p̄'s. Second, the kind of break in the curve at $M_\nu=15$ appears only at 808 MeV/c in the model whereas it is already present in the experiment at 608 MeV/c.

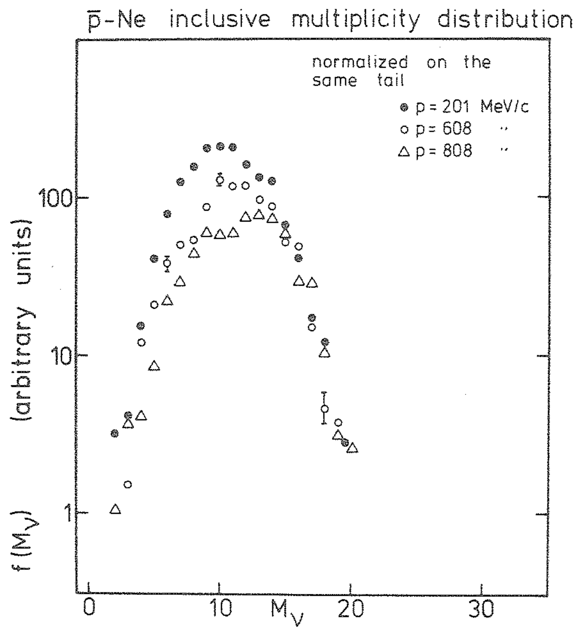

Fig. 11. Inclusive multiplicity M_ν distribution for p̄-annihilation in flight on ^{20}Ne at three different energies. The quantity M_ν is the sum of the number of participants and of the number of final pions. The distributions have been normalized to have approximately the same value at $M_\nu = 15$. The error bars indicate the typical uncertainty of the calculation.

The fact that a common tail occurs in the experimental distributions for $p = 201$, 403 and 608 MeV/c has been suggested as an indication of a limiting property relative to annihilations deep inside the nucleus [4]). However, in our calculations, we did not observe any correlation between high multiplicities and deep annihilations. In fact, for $b = 0$ events, the correlation coefficient for the quantities M_ν and z_a is only 0.08 ($p = 608$ MeV/c). We have looked at other correlations implying M_ν and found that the largest coefficient (0.65) occurs for the correlation with the number of interacting pions. This matches up with the situation at rest.

5.3. CASCADE MODEL AND PERCOLATION MODELS

Models based on percolation ideas have been devised to explain nuclear fragmentation and we shall devote this section to some brief considerations on a possible link between these models and the INC. Let us first give a short account of the state of the art. Some percolation models like that of ref. [21]) are of a pure geometrical type: they assume that, in some primary process, a number of nucleons are ejected from their site on a lattice. The remnant nucleus then decays into fragments corresponding to regions of the lattice which have remained in a compact form. The most sophisticated model of a percolation type has recently been built up by

Campi and Desbois [22]). They start from the assumption that $(1-p)A$ nucleons $(0<p<1)$ are ejected at random by some fast process and that the remaining nucleons can be characterized by a thermal momentum distribution. The temperature is fixed by the requirement that the remnant acquires an excitation energy of 8 MeV per nucleon through soft collisions. The remnant is subject to a fragmentation into many pieces whose formation is ruled by the requirement of compactness both in the real and in the momentum spaces [for technical details, see ref. [22])]. The main conclusions from this model are:

(a) for $p>p_c$, the remnant fragments into a big clump plus a few small ones, a process similar to what is usually called evaporation;

(b) for $p<p_c$, the remnant fragments into many small pieces: the so-called multifragmentation process;

(c) the value of p_c is ≈ 0.55 (i.e. close to the percolation threshold in two-dimensional space) for all nuclei, but the transition is the sharpest for the largest nuclei;

(d) the mass yield of the fragments takes the form of a power law, $A^{-\tau}$ $(\tau \approx 2\text{–}3)$, close to the percolation threshold.

Let us see how the results of an INC calculation can be exploited in the light of percolation. The cascade is likely to give a good description of the hard (quick) process. Therefore, the nucleons called above "participants" can be identified, in a first approach at least, as the $(1-p)A$ ejected nucleons. In fact, this somewhat stretches reality since a fraction of these participants have small energy, as shown in fig. 6, and can hardly be accepted as direct ejectiles, as discussed in subsect. 3.1. If we nevertheless make the identification between the total number of participants and the $A(1-p)$ ejected nucleons, in a preliminary exploration, the INC model is potentially able to answer two questions: (i) Are the participants picked up in a random way? (ii) What is the value of the parameter p in a definite case? To answer the first question we observe that the almost isotropic emission of pions, followed by energy-mass exchanges $(\pi N \rightarrow \Delta \rightarrow \pi N)$ must lead to a reasonably isotropic and homogeneous dispersion of the energy deposit, i.e. of the "damage" to the nucleus in most annihilation events. Concerning the second question, we present in figs. 10 and 12 the distribution of the participant number N_p for the Ne and Ag cases, respectively. At the top of fig. 10 and at the bottom of fig. 12, the horizontal scale is transformed for the parameter p by means of the simple law

$$1-p = N_p/(A_T-1)\,, \qquad (5.1)$$

A_T being the target mass number.

In the Ne case, the multiplicities obtained in the LEAR range bracket the percolation threshold whereas, for Ag, the threshold is always exceeded, i.e. the initial damage to the nucleus is not important enough to induce multifragmentation. It thus seems, from our INC results and from the percolation approach of ref. [22]), that light targets are well suited to study multifragmentation. It should be kept in

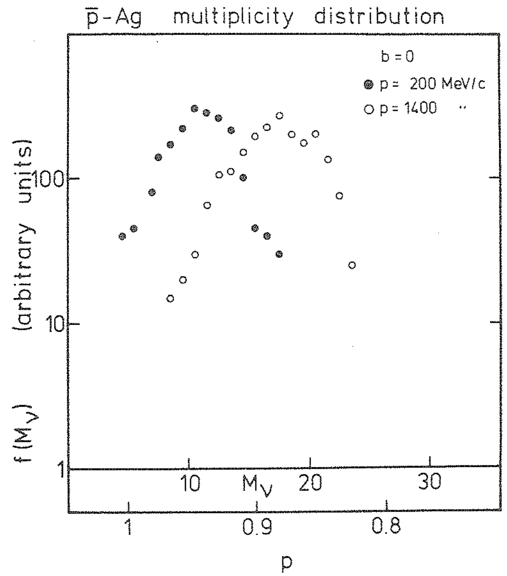

Fig. 12. Multiplicity M_ν distribution for p̄-annihilation on ^{107}Ag nuclei. The lower scale gives the corresponding value of the parameter p, through relation (5.1), after removal of the pions.

mind, however, that a fraction of our participants should probably be discarded since they are involved only in soft collisions (namely, secondary or tertiary collisions of recoiling nucleons) which should not be strictly considered to belong to the primary process consisting of quick (hard) collisions. This is somewhat compensated by the soft nucleon–nucleon collisions, which are neglected in our INC model [9]). At any rate, we want to suggest that a connection can be made between the INC model and the fragmentation of the nucleus, and that the percolation approach may be an interesting way to ensure this connection and thus a complete description of the interaction process following p̄-annihilation.

For heavy targets, the above considerations suggest that for the LEAR energies the final stage of the process is akin to evaporation following ejection of a few fast nucleons; in subsect. 3.2, we have anticipated this conclusion.

Finally, we have made a calculation for the annihilation of 5 GeV antiprotons on silver, to show that an alternative way of increasing the fraction of participants is to use larger beam energies. The multiplicity distribution is shown in fig. 13 and we see that the parameter p, again obtained from (5.1), is now below p_c. Note, however, that the randomness of the participant localization is weakened now since the pion fireball travels essentially in a forward cone.

These considerations do not aim at supporting the foundations of percolation models, but suggest that, if these models [at least the one of ref. [22])] are relevant, the transition from subcritical to overcritical percolating fragmentation can be studied in the p̄-nucleus interaction, since the average value of p is found below

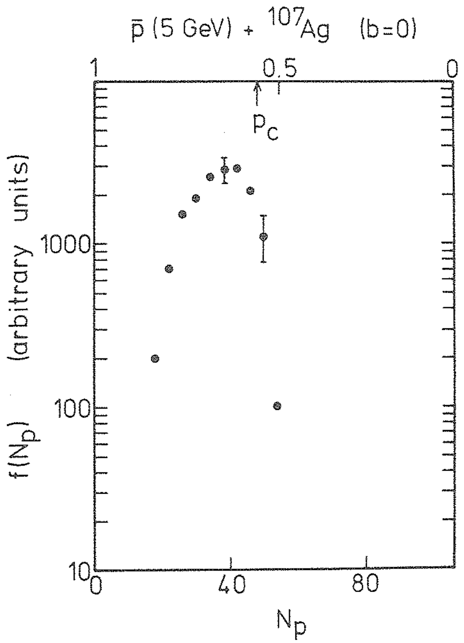

Fig. 13. Number of participants distribution for 5 GeV antiproton annihilation on ^{107}Ag nuclei. The scale at the top gives the parameter p through eq. (5.1). The error bars indicate the typical uncertainty of the calculation.

and above p_c, depending upon the size of the target and upon the antiproton incident energy.

6. Discussion and conclusion

We have studied from the INC point of view the way energy is deposited in the nucleus by the multipion cascade following p̄-annihilation, at rest and in flight.

For annihilations at rest, we have looked at correlations between various parameters in order to see whether there are specially violent events, and what determines the occurrence of such events, sometimes referred to as inside annihilations [4,5]). We indeed observe correlations between annihilation depth, energy transfer, number of interacting pions and number of participants. However, it seems that the parameter which determines the violence of the events is the number of interacting pions. The latter is increasing, on average, with the incident energy, but not on a dramatic scale, over the domain covered by the LEAR machine.

The correlation yields that we have calculated are qualitatively similar to those obtained in refs. [10,24]). This gives mutual confidence in the accuracy of the INC codes.

We have investigated the transfer of energy from the multipion system to the nuclear system. A large fraction of the transferred energy is carried by high-energy ($E \geq 50$ MeV) nucleons. The INC is well suited to the description of this first category, corresponding to hard collisions. It is less reliable for the second category: the slower nucleons which originate from a slower process, dominated by soft interactions. The cascade assumptions are more uncertain when the energies are of comparable magnitude to the binding, and more collective effects probably take place. Therefore, the link between the INC picture and the residual nucleus is rather loose. One may introduce an evaporation model to take over from the cascade in the last stage.

The case of ^{98}Mo that we have studied particularly seems to indicate that not enough energy is transferred in the classical cascade picture. This may be due to a variety of factors. Concerning the annihilation mode, we have assumed a point-like annihilation of the p̄ with a single nucleon, producing the same number of pions as observed in free-space p̄p annihilations. Annihilation in the nucleus might involve two nucleons [6,7]). This gives ~150 MeV for the nucleon system from the start; however, this is at the price of a 10% decrease in the mean number of pions as well as an increase of strangeness production, which implies reduced subsequent interaction and energy transfer. As a result, the transfer of energy due to two-nucleon annihilation should not be spectacular, unless the majority of annihilations are of that type. The propagation of Δ inside nuclear matter may be modified compared to our assumption of classical collisions and decay with the free-space lifetime; the pion propagation may be different as well [24]). Also, we have assumed that the pions are produced directly whereas we know that p̄N annihilations produce resonances. However, at least at first sight, it seems difficult to obtain an increase of the energy transfer through the inclusion of resonances for this would mean that a resonance has transfer properties superior to the sum of those of several pions; long-lived resonances should rather restrict further the exchange.

Let us notice that it is intriguing that in heavy-ion relativistic collisions the INC overestimates pion production [25,26]), i.e. transfers too much energy from the nucleon system to the pion system, whereas we seem to observe that in p̄-annihilations in nuclei the energy transfer from the pion system to the nucleon system is underestimated. It is true that the conditions are not similar since there is no density increase in annihilations, but the experimental situation suggests that both types of reactions can provide complementary information.

Let us come back to the handling of the residues. The idea that the whole fragmentation process of the target is composed of a fast process, due essentially to the ejection of fast particles through hard collisions, and a slow process, due perhaps to soft collisions, is rather old. The relative importance of the two processes is not very well known and depends upon the dynamics with first stages of the collisions. By varying this relative importance, one covers a large class of models ranging from the cold fragmentation [27-29]), or spallation (if the soft processes are neglected), to the evaporation model (if the fast process is dropped out). We have seen in the ^{20}Ne case that interpreting the INC model as a strict spallation model we obtain multiplicities slightly too small.

The occurrence in the cascade model of slow nucleons led us to think that, in the p̄-annihilation on nuclei, one should rather consider an intermediate model, managing at the same time fast and slow processes. Such models have recently been modified by the adjunction of ideas taken from percolation theory: the evolution due to slow processes is assumed to be governed by the geometric properties of the voids left in the nucleus by the fast process. Beyond a certain fraction of voids, the remnant is likely to fragment into many pieces (the so-called multifragmentation process). Below this fraction, the remnant undergoes a modification akin to particle evaporation. The fraction of voids is supposedly related to the fraction $(1-p)$ of nucleons ejected in the fast process. We have studied the values of p with the help of our INC model and found that, for light targets (or for high energies), the percentage $(1-p)$ is beyond the critical value $(1-p_c)$. Therefore, we advocate the study of p̄-annihilation to investigate these percolation models, complementarily to proton-induced and heavy-ion reactions. Actually, p̄-annihilation might be more appropriate, since the perturbation caused by the pions are rather randomly distributed, a basic premises of percolation and related models. Furthermore, in this case, it is hard to invoke the gas–liquid transition, since only a part of the nucleus is involved in the fast process, at least as suggested by the INC model. An important and desirable information for these models is the mass yield of the fragments, which has not been measured yet. Particularly interesting in view of our discussion, would be the measurement of the mass yield as a function of the size of the target and of the antiproton energy.

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