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RESIDUAL MASS DISTRIBUTION FOLLOWING p̄-NUCLEUS ANNIHILATION

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Abstract: The antiproton-nucleus annihilation at rest is studied with an intranuclear cascade (INC) model plus an evaporation-fission competition model. The relevance of the distribution of annihilation sites is discussed. The mass yield is calculated and compared with experiment. The relatively high probability of soft events leading to a residue differing from the target by one unit is stressed. The average mass loss for ^{98}Mo and ^{165}Ho is well reproduced. For the ^{238}U, the fission probability, the average number of evaporated neutrons before fission and the neutron energy spectrum are calculated. The latter is compared with a recent measurement.

1. Introduction

The p̄-annihilation on nuclei has retained attention in the past years, mainly because it is an easy way to deliver to the nucleus a large amount of energy, at least for deep annihilation events. Furthermore, as suggested in ref. [1]), the rearrangement of the quark structure might involve a large part of the nucleus. However, the first, mainly inclusive, experiments at LEAR did not show any exceptional feature. The proton and pion cross sections are roughly consistent with a conventional picture of the mechanism [2-4]): the antiproton annihilates on a single nucleon, freeing about five pions, which cascade through the nucleus, ejecting nucleons and light nuclides to a lesser extent. Recently, new experiments, more exclusive, are producing more and more data, mainly on charged-particle multiplicity [5-7]), on the masses of the residues [8,9]) and also on neutron spectra [10]). Most of these experiments are dealing with annihilation at rest.

In this paper, we apply our intranuclear cascade (INC) model, which embodies basically the above-mentioned physical picture, to reproduce these observations. We will particularly concentrate on the mass of the residues. In a previous work [11]), we already reported on the particular case of the ^{98}Mo target. Here, we study several other cases, including fissile targets. We also examine the importance of the characteristics of the Coulomb state from which annihilation at rest takes place (the annihilation state) and try to relate them to the inelasticity (i.e. the energy transferred from the pion system to the nucleon system) and to the average mass loss.

† Deceased.

The paper is organized as follows. In sect. 2, we sketch the main features of the model. Sect. 3 presents the calculated mass yield for several targets, discusses the importance of the annihilation site and studies the possibility of fission for heavy targets. Finally, sect. 4 contains our conclusion.

2. The model

The p̄-annihilation process at rest is pictured as follows. (1) The antiproton cascades down on Coulomb orbits; (2) From one of these orbits determined mainly by the size of the nucleus, it annihilates with a nucleon, giving birth to pions. Some of them travel through the nucleus, initiate a cascade process by which some nucleons can be ejected with large velocity; (3) The target is further deexcited by evaporation.

In our model, the annihilation state is assumed. Step (2) is described by our INC model, whose description can be found in refs. [4,11,12]). Finally step (3) is described by a simple evaporation process. The separation of step (2) and step (3) may not be as sharp as presented here. This is extensively discussed in ref. [11]). Consequently, the time after which the cascade is turned off is somewhat arbitrary, but, as explained in ref. [11]), changing this time within reasonable values may change the average mass loss by two units at the most. This may be considered as more or less the uncertainty of the calculation (at least for steps (2) and (3)).

Compared to our previous work [11]), we also introduce the possibility for a fission–evaporation competition for heavy targets. It has been realized in heavy-ion experiments that fission takes a rather long time compared to neutron evaporation when the excitation energy is large enough [13,14]). Therefore, the final fission probability is not given by phase space alone and evaporation takes place along the path of fission [15-17]). To account for this possibility, we simply design the following model. We consider that the relative neutron emission to fission probability at a given excitation energy E^* is given by a function $\Gamma_n/\Gamma_f(E^*)$ defined below. We decide stochastically which path is followed. If fission is chosen, the process terminates. If a neutron is emitted, the procedure is resumed with the new (lower) excitation energy and followed until E^* drops below the neutron or the fission barrier. This simple model basically produces the same physics as the transport equations used in refs. [15,17]), except for fine details of the fission path in the deformation parameter space. To keep the procedure as simple as possible, we chose the following simple form

$$\frac{\Gamma_f}{\Gamma_n} = A_{fn} \exp\,[2\sqrt{a_f(E^*-B_f)} - 2\sqrt{a_n(E^*-B_n)}]\,, \qquad (2.1)$$

where the values for the fission barrier B_f and the neutron barrier B_n are taken from ref. [18]). The values of a_n, a_f and A_{fn} are fixed by requiring to have the same neutron width and the same intrinsic fission width (in the 50–150 MeV range), as in ref. [17]). In fact we interpolate linearly between $A = 194$ and $A = 242$ nuclei. For the ^{238}U case, studied below, the numerical values are $A_{fn} = 0.22$, $B_f = 6$ MeV, $B_n = 6.5$ MeV, $a_n = 0.058$ MeV^{-1}, $a_f = 0.026$ MeV^{-1}.

3. Numerical results

3.1. THE ANNIHILATION STATE

We consider several targets ranging from O to U. If the annihilation Coulomb ($l = n - 1$) state is rather well known for light targets, it is not the case for heavy ones. For ^{98}Mo, the annihilation state corresponds to $n = 6$ according to ref. [19]). But for heavier targets, there should presumably be a contribution from several (at least two) states. We consider $n = 7$ and 8 for ^{165}Ho, $n = 9$, 10 for ^{208}Pb and $n = 11$, 12 for ^{238}U. In this latter case, we also consider a lower value ($n = 9$), sometimes mentioned in the literature for Th [ref. [20])], in order to study the sensitivity of the results to the annihilation state. The annihilation distance probability distributions, as defined in ref. [12]), are shown in fig. 1 for all these cases. From this figure and from table 1, it seems that, on the average, the annihilation takes place farther from the nuclear surface when the target mass A_T increases. This basically comes from the fact that the Coulomb wavefunction is more and more spread out when n is

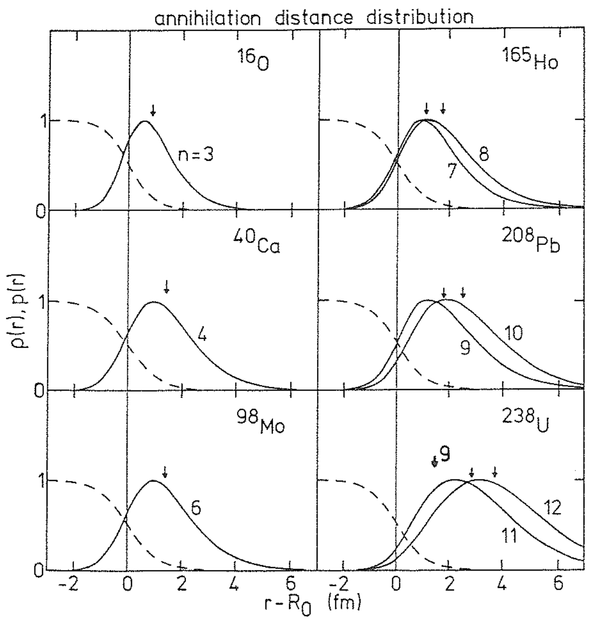

Fig. 1. Distribution $p(r)$ (eq. (3.2)) of the annihilation site in different nuclides, for the (n, $l = n - 1$) Coulomb states (full curves). The nuclear density $\rho(r)$ is shown by a dashed curve. All the curves are normalized to their maximum. The arrows indicate the mean location of annihilation. For U, $n = 9$, only this location is indicated, to keep the figure legible.

TABLE 1

Value of the quantity I (eq. (3.1)) (in 10^{-3} fm^{-3})

State	O $n=3$	Ca $n=4$	Mo $n=6$	Ho $n=7$	Ho $n=8$	Pb $n=9$	Pb $n=10$	U $n=9$	U $n=11$	U $n=12$
I	0.14	4.20	2.90	40	0.76	0.45	0.64×10^{-3}	4.09	0.11×10^{-2}	0.11×10^{-4}

increasing. For a given overlap between the square of wavefunction $\psi_{n,n-1}(r)$ and the nuclear density $\rho(r)$, the wavefunction is pushed further and further outside as n increases. This is also indicated by table 1, which gathers the values of the integral

$$I=\int_0^\infty p(r)\,\mathrm{d}r\,, \tag{3.1}$$

where

$$p(r)=r^2\rho(r)|\psi_{n,n-1}(r)|^2 \tag{3.2}$$

represents the annihilation probability density. The quantity I can be taken as the width of the Coulomb state, except for a constant factor. Going from one state to the next changes I by at least two orders of magnitude. The values for O to Mo suggest that I lies between 10^{-4} and 10^{-2}. Therefore the $n=8$ state is the probable annihilation state for Ho and $n=9$ for Pb. For U, $n=11$ or 12 is very likely too large, the most probable value being, in our opinion, $n=10$ or perhaps $n=9$.

The use of a Coulomb state (which is commonly done [26]) is a simplification since one thus neglects strong interaction effects on the shape of the initial state. However, we will show that the validity of our main results is not really affected by uncertainty. We shall come back to this point in our conclusion.

3.2. THE RESIDUAL MASS SPECTRUM

Our main results are contained in fig. 2, which show the calculated mass yield for various cases. For the Mo, Ho and Pb targets, the spectra have a characteristic shape. After a peak at $A_{\mathrm{res}}=A_{\mathrm{T}}-1$ (first bin in fig. 2), there is a vague plateau (for $A_{\mathrm{T}}\gtrsim A_{\mathrm{res}}\gtrsim A_{\mathrm{T}}-20$), followed by a regular decrease. The fluctuations in the spectra are probably statistical, since there is no real source, in our model, for narrow structures. The U case, in which we have averaged over the $n=11$ and 12 annihilation state distributions, displays a strong fission peak around $A_{\mathrm{res}}\approx110$. The average mass loss for all cases of fig. 2 is given in table 2.

The experimental data for the ^{98}Mo and ^{165}Ho targets are displayed along with our numerical results. Only radioactive residual nuclei are detected and therefore a correction procedure is used to obtain the mass yield for all nuclides [8]. This correction is less reliable for small mass loss and therefore is not applied close to the target mass ($A_{\mathrm{res}}\gtrsim95$ for ^{98}Mo and $A_{\mathrm{res}}=164$ for ^{165}Ho). The corrected points

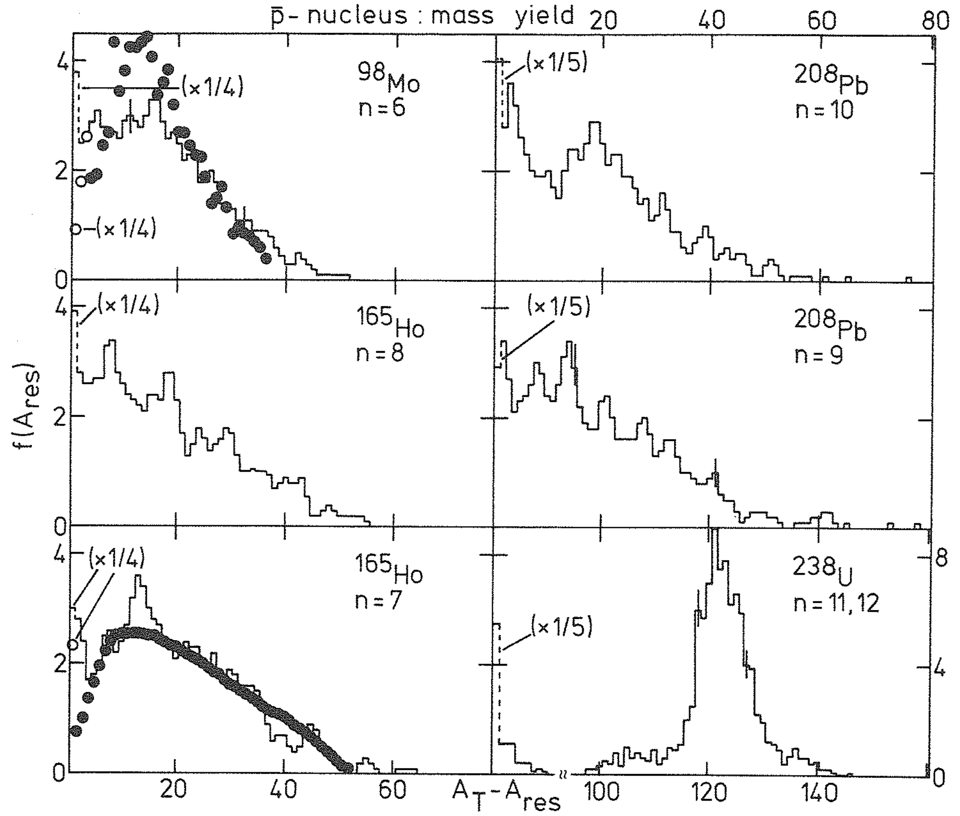

Fig. 2. Probability distribution (in percent) for the residual mass A_{res}. The histograms are the results of our model. The dots and the open circles are the experimental data of ref. [8]) (^{98}Mo) and ref. [9]) (^{165}Ho). See text for detail. The first bin corresponds to $A_{res} = A_T - 1$, for which both the theoretical and the experimental yields are multiplied by the indicated factor. Note the broken horizontal scale and the different vertical scale for the ^{238}U case. The error bars indicate the (statistical) uncertainty of the calculation.

are indicated by full points in fig. 2 and the uncorrected ones by open circles. The striking feature is the rather large yield for $A_{res} = A_T - 1$. Actually, for ^{98}Mo, only ^{97}Nb is radioactive and is detected. About the same situation occurs for the ^{165}Ho target. Therefore, the $A_{res} = A_T - 1$ yield is expected to be twice the value indicated in fig. 2. We stress that, in fig. 2, this ($A_{res} = A_T - 1$) yield is multiplied by some reduction factor in order to make the presentation more convenient. In the $A_{res} = A_T - 1$ events, the pions issued from the annihilation are actually only slightly disturbing the nucleus, transferring enough energy to make γ-transitions possible, but not enough to eject a nucleon. The common belief is that this kind of event should be very rare. But, their nonnegligible rate is confirmed at least qualitatively by the INC model. Actually, we observe within the model two types of events: those where the pions are completely missing the nucleus (the "void" or "noninteracting"

TABLE 2

Average mass loss $\langle \Delta M \rangle$, average mass loss $\langle \Delta M' \rangle$ (calculated on $(A_{res} < A_T - 2)$ events), fraction of void events N_V (in percent), average number $\langle N_{ej} \rangle$ of the ejected nucleons (before evaporation) and average kinetic energy of the latter $\langle K \rangle$ for various targets

target	$\langle \Delta M \rangle$	$\langle \Delta M' \rangle$	N_V	$\langle K \rangle$(MeV)	$\langle N_{ej} \rangle$
O			19.6	75	2.86
Ca			19.7	73	3.78
Mo	15.46	18.36	13.9	72	4.11
Ho, $n=7$	18.06	19.56	7.2	64	5.92
Ho, $n=8$	13.13	17.46	14.6	66	4.94
Pb, $n=9$	15.49	18.24	13.2	65	4.81
Pb, $n=10$	13.78	17.68	20.0	62	4.56
U $(n=9)$	(17.93)	(19.95)	9.2	59	6.15
U $(n=11, 12)$	(11.17)	(15.84)	23.6	58	4.73
Ho, $Z=6.71$*	19.64	20.11	2.0	62	6.42
Ho, $Z=7.06$*	15.62	16.31	3.4	63	5.19
Ho, $Z=7.71$*	13.03	14.66	8.8	63	4.23

The asterisk refers to calculations with a fixed annihilation site, for which the distance Z from the centre of the nucleus is indicated in fm. The figures in parentheses refer to a calculation neglecting fission. See text for detail.

events) and those where some pions are interacting and transferring a small amount of energy ("soft" events). This separation occurs because of the sharp distinction in INC dynamics between a collision and a nocollision occurrence, and because of the neglect of any coherent (generally soft) process. Any modification of the model to account for these aspects will invitably transform void events into soft events.

Although the agreement between experiment and theory is very good for the average mass loss, there is some discrepancy for small mass losses. The data show some depletion for small mass losses, whereas such a feature is not clearly present in the calculation, except for the $n=7$ case of ^{165}Ho. We tried to understand this feature by analyzing carefully our numerical results. For this, we looked at the distribution of the number of ejectiles, which is directly related to the mass yield, prior to the evaporation process. For the two cases of ^{165}Ho, this is shown in fig. 3. Clearly a dip is present in the small mass-loss region, indicating that the dip in the final mass yield is not attributable to some features of the evaporation process. The existence of a dip indicates that once a nucleon has been ejected, there is a very good chance for further ejection. This may just be secondary ejection, as was suggested by a previous analysis [21]) using the concept of contagion. But the problem needs more investigation. Within the INC model, the dip seems to be stronger if the annihilation takes place further inside the nucleus. This observation is supported by fig. 4, where we have forced the antiproton to annihilate at a fixed point, whose distance from the center is indicated in the figure. The discrepancy between our results and experimental data may indicate either a lack of energy transfer efficiency

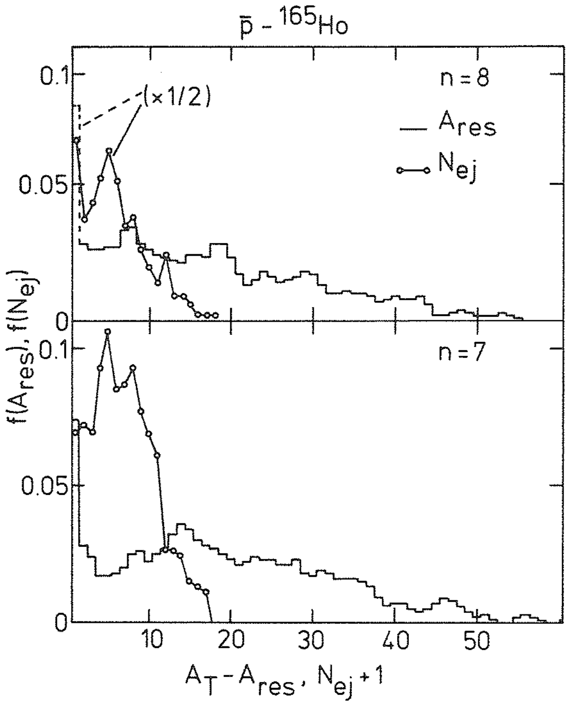

Fig. 3. Shape of the residual mass A_{res} distribution and of the ejectile number N_{ej} distribution from our model, for two annihilation states in ^{165}Ho. The quantity A_T is the target mass number.

in the model or a wrong choice for the properties of the annihilation state. For the particular case of ^{165}Ho, it may well mean that $n=6$ state is contributing. Also, the distortion of the Coulomb state due to strong interaction, which is not included in our study, may play some role. The latter, which is attractive, may drive the average annihilation site by 0.5 fm towards the nucleus, but on the other hand, the annihilation range (taken as zero in our approach) may just compensate this effect (see fig. 1, ref. [22])). This issue is not completely settled and certainly deserves further study.

3.3. GENERAL TRENDS

From a naive point of view it could be advanced that, since the pions are freed at the fringe of the nucleus, the solid angle open for their interaction is, in rough approximation, close to 2π. In fact, the effective solid angle depends on the target size and on the annihilation site. We introduce the parameter ζ defined as

$$\zeta = 1 - \frac{\Omega}{2\pi}, \tag{3.3}$$

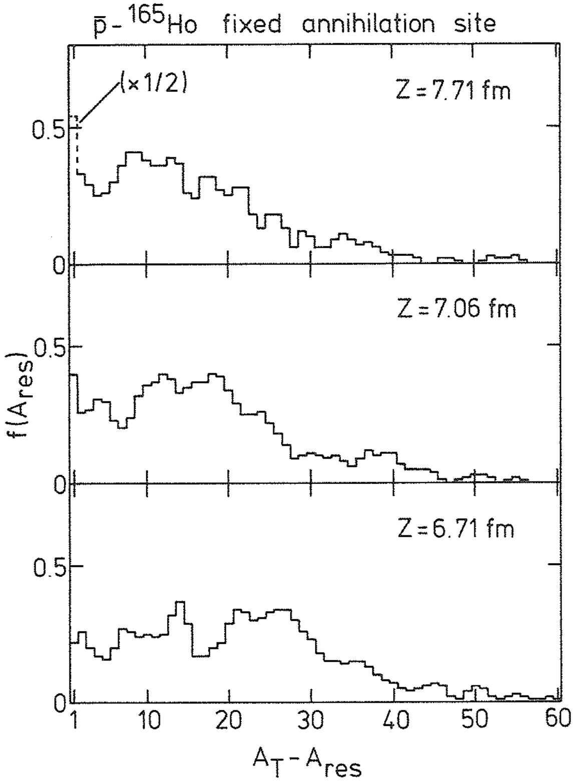

Fig. 4. Distribution of the residual masses A_{res} for ^{165}Ho target from the INC calculation when a fixed annihilation site is chosen (Z is its distance from the centre of the target).

where Ω is the solid angle under which the sphere of radius R_0 is seen from the average annihilation point. We examine how the *average* values of some quantities characterizing the annihilation process depend on ζ. In fig. 5, we give the general trends of the relationship. The number of interacting pions $\langle N_\pi^{\rm int}\rangle$ decreases when ζ increases. This is a trivial geometrical effect. Notice the (surprisingly) small values of Ω for the cases under study. The average energy transferred from the pion to the nucleon system $\langle W_{\rm tr}\rangle$ decreases when ζ increases while the number of void events (not shown) increases. The low value of $\langle W_{\rm tr}\rangle$ for oxygen is an effect of the small size of the target. We have drawn straight lines across the points to extrapolate to $\zeta=0$. We obtain $\langle N_\pi^{\rm int}\rangle=4.4$ and $\langle W_{\rm tr}\rangle=910$ MeV. This shows that most of the pions, when emitted at the nuclear radius, do interact but that the energy they transfer to the nucleus is, on the average, hardly larger than half their total energy: one has to realize that a large fraction of the interacting pions survive, thus their mass is not available for transfer. The average mass loss of the target $\langle \Delta M\rangle$ is also a linearly decreasing function of ζ.

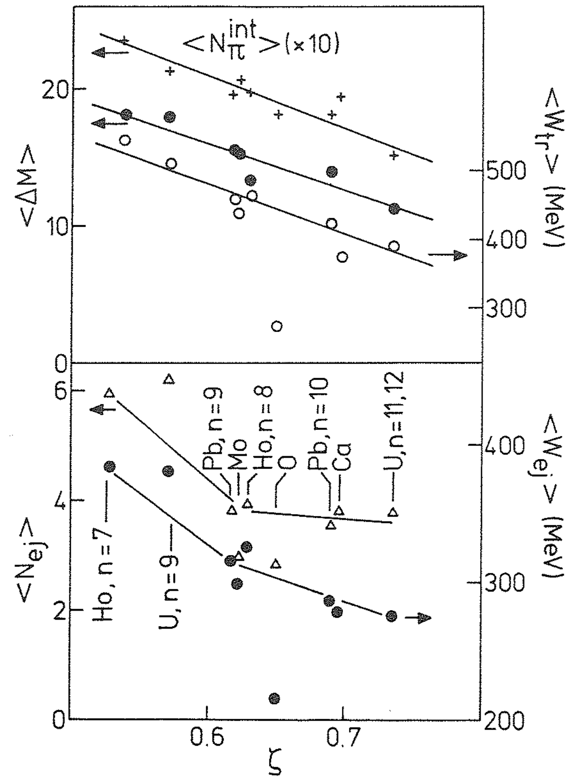

Fig. 5. General behaviour of various average quantities calculated for the indicated targets, as functions of the parameter ζ (see text). In the upper part, a linear fit is shown for the mass loss (ΔM, full circles), the number of interacting pions (N_{π}^{int}, crosses) and the energy transfer (W_{tr}, open circles). The lower part refers to the number of ejectiles (N_{ej}, triangles) and their energy (W_{ej}, dots). The lines are to guide the eye. The quantity ΔM for the U-case comes from a calculation neglecting fission.

Considering the ejected (fast) nucleons, we find that their average number decreases when ζ increases. The energy they carry off behaves in a similar way. Again, we observe a transparency effect for oxygen due to the small size of the target. A linear behaviour in ζ is less obvious for the last two quantities, but there is a remarkable regularity when the average energy *per ejectile* is considered. This is shown in table 2 where $\langle K\rangle = \langle W_{\text{ej}}\rangle / \langle N_{\text{ej}}\rangle$ has a value which decreases slowly and monotonously from 75 MeV for oxygen to 58 MeV for uranium; this low and regular decrease is again an effect of geometrical type, the larger size of the target entailing a larger rescattering probability.

Two remarks are in order. The first one is that we have considered here the average values of several quantities. On an event by event basis a pair of these quantities may appear strongly or loosely correlated. When the correlation is small the two quantities may fluctuate independently. Our previous studies [12]) indicate that the energy transfer is strongly correlated to the number of interacting pions while this latter quantity is loosely correlated to the position of the annihilation point.

Let us turn to the second remark. As far as average quantities are concerned, fig. 5 can make INC predictions rid of the uncertainty of the annihilation state. Indeed, if it turns out that the value of Z (and thus of ζ) for a given nucleus should be changed (for one of the reasons we have discussed), the average value of the average mass loss f.i. can easily be read from fig. 5 with a small uncertainty.

Along the same line, we stress that the average quantities contained in fig. 5 refer to all calculated events, including the "void" events. If one wants to consider "interacting" events only (for which the INC predictions may turn out to be more reliable), one has to correct for the percentage of "void" events, which is indicated in table 2.

For some of the quantities under consideration in fig. 5, ζ seems the only relevant parameter (for annihilation at rest). Even for U, where we considered very different annihilation states, the numerical values follow the general relationship. For some other quantities, however, the target size plays a more important role. This remark applies to the energy transfer $\langle W_{tr} \rangle$, the energy carried by the ejected nucleons $\langle W_{ej} \rangle$ and the number of latter $\langle N_{ej} \rangle$, for which the representative point for the light targets, especially oxygen, deviates from the general trend.

3.4. THE U CASE

The mass yield, assuming $n = 11$ and $n = 12$ annihilation states in equal proportions (see fig. 2) shows a strong peak around $A_{res} \approx 110$ and a smaller part around the target mass. As a matter of fact, most of the events are either fission events or "noninteracting" events. The latter occur about 24% of the time, a rather high value which is due to very external annihilations (see figs. 1 and 5). We also made a calculation for $n = 9$. The peak in the mass yield around $A \approx 110$ survives. The only change is a much lower value of the noninteracting events, whose contribution is now ~9% only. Experimentally, it seems that the fission probability [23]) is close to 100%. This would suggest the actual annihilation state to be well described by the $n = 9$ Coulomb state.

We predict that "interacting" events are mostly fission events (the fraction is 0.93). This is of course due to the large Γ_f/Γ_n ratio for the ^{238}U nucleus which is about 1 at $E^* \approx 100$ MeV. The fission probability is not very sensitive to this value even if it is changed by one order of magnitude. Decreasing it by a factor 10 changes the fission probability per interacting event to ~0.81. When Γ_f/Γ_n is decreasing or increasing, the fission peak in the mass yield broadens or narrows, respectively. Also the probability of fission $P_f(n)$ as a function of the number n of evaporation neutrons displays a limited sensitivity to this parameter, as shown in fig. 6. This behaviour is reminiscent of the evolution of a heavy-fissioning compound nucleus formed in a heavy-ion reaction [17]).

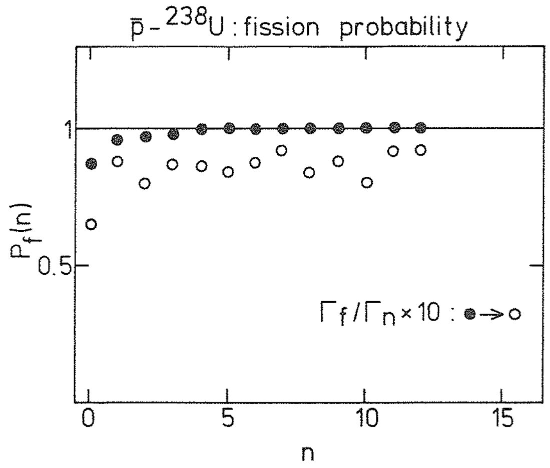

Fig. 6. Fission probability $P_f(n)$ versus the number n of evaporation neutrons, in our model (case of ^{238}U). The full dots correspond to our adopted function Γ_f/Γ_n. The open dots correspond to an enhancement of the latter by a factor 10.

The situation is practically the reverse for a Pb nucleus. In that case the Γ_f/Γ_n ratio is very small for all the excitation energy domain relevant to our problem. We calculated that the fission probability per "interacting" event is ≈ 0.09.

We also study the properties of the cascade (i.e. emitted in the first stage) and the evaporation neutrons, since a recent measurement of the neutron spectrum has been made for the ^{238}U case. For $n=9$, we predict that ~3.8 (fast) neutrons are emitted in the first stage (this figure is lowered to ~3.0 when restricted to the momentum range considered in ref. [10]) and ~0.9 are evaporated (this last figure is lowered to 0.4 if Γ_f/Γ_n is multiplied by 10). Their energy spectrum is shown in fig. 7, where it is split in its two contributions. It is customary to extract temperatures from such spectra. To extract a temperature, assuming that an equilibrated system exists, one has to remind that the distribution is given by

$$dN \propto p^2 \, e^{-E_t/T} \, dp \,, \tag{3.4}$$

where $E_t = \sqrt{m^2+p^2}$ is the total energy. In the nonrelativistic regime, the distribution as a function of kinetic energy $E = (E_t - m)$ is given by

$$dN \propto \sqrt{E} \, e^{-E/T} \,. \tag{3.5}$$

The factor $\sqrt{E}$ is needed in order to give T a physical meaning. This point was overlooked in refs. [10,24]). Using (3.5) for our spectrum gives a temperature of ~3.4 MeV for the evaporated neutrons. The neutrons issued from the cascade show more or less a broken curve with two temperatures, ~25 MeV and ~52 MeV. Those

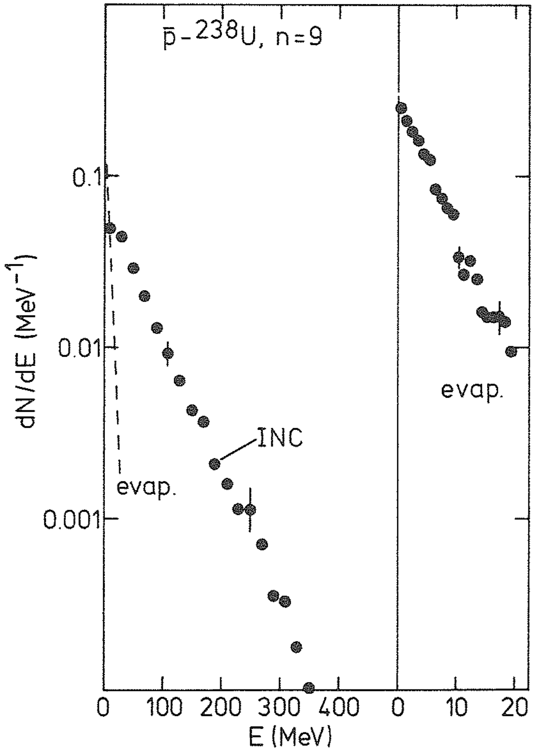

Fig. 7. Neutron energy spectrum from our model (^{238}U). The right part of the figure is a close-up of the evaporation contribution, which is crudely described by the dashed line in the left part. The error bars indicate the typical uncertainty of the calculation.

figures are remarkably close to the values that we obtained for the Mo nucleus [12]. We explained previously that this high energy exponential slope does not indicate the presence of an equilibrated piece of matter but arise from the direct knock-out from the primordial pions, which have a thermal spectrum with high temperature [25]. The low temperature arises from secondary collisions.

In fig. 8, we compare our results with the experimental data of ref. [10]). In the 200–500 MeV/c range, our results are in rather good agreement with experiment, indicating that these neutrons are essentially cascade neutrons (direct neutrons, in the terminology of ref. [10])). For lower momenta, we obviously underpredict the neutron yield. This may have several explanations. (i) The evaporation is more copious than we expect. This cannot be completely ruled out, as the neutron–fission competition for highly-excited nuclei is not precisely known. (ii) The missing yield may come from fission-neutron emission. It seems that the multiplicity of these neutrons increases quickly with excitation energy [18]); however, data for ener-

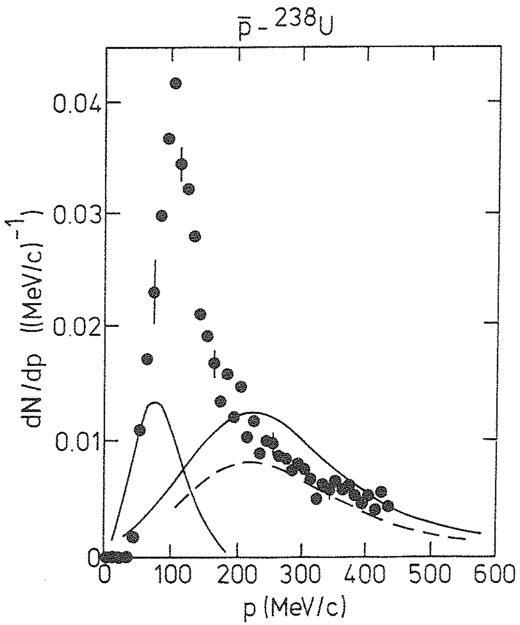

Fig. 8. Neutron momentum spectrum. The points are the experimental data of ref. [10]). The full curves are the predictions of our model, for the evaporation and the INC components, respectively. To compare to the data, the INC component is multiplied by the acceptance of the experimental apparatus of ref. [10]) (dashed curve).

gies larger than ~20 MeV are rather scarce. Furthermore, no real indication on their mean energy is available. (iii) The cascade neutrons are more frequent, but this is hardly possible since INC well describes charged-particle yields [3]).

4. Conclusion

We applied our INC model to calculate the residual mass distributions after p̄-annihilation. The predicted average mass loss agrees with experiment for the Mo and Ho cases, provided that for the latter the $n=7$ $(l=n-1)$ Coulomb state is chosen as the annihilation state. We predict a sizeable yield for events where pions are just "touching softly" the nucleus. We explain this by the rather small solid angle subtended by the bulk of the nucleus as seen from the annihilation point (see figs 1 and 5). The occurrence of these "soft" events is confirmed by experiments, with a smaller rate however. This may be connected to the details of the distribution of the annihilation site. In this respect, we show the relevance for large targets of the parameter ζ related to the solid angle mentioned above. For ^{238}U, we introduce a fission-evaporation competition model. We predict that for "interacting" events, the fission probability is close to unity. We calculate the neutron energy spectrum which compares rather well with the experimental data of ref. [10]), at least for momenta larger than 200 MeV/c.

We have chosen here a pure Coulomb annihilation state. This is of course a simplification since one so neglects the effects of the strong interactions on the shape of the initial state. The following remarks are relevant at this point.

(i) In many cases investigated here (as we already said), the quantum numbers of the annihilation state are not known.

(ii) The real part of the strong interaction potential being attractive, its effect is to drive the average annihilation site towards the centre of the nucleus. On the other hand, the imaginary part has mainly the effect of depleting the probability close the nucleus, i.e. an *opposite* effect.

(iii) It is not yet clear whether the real part is very attractive or moderately attractive.

(iv) It may be questionable to include the imaginary potential in the calculation of the density probability for the *initial* quasi-stationary state, i.e. prior to absorption, since this imaginary part is responsible for the absorption itself. This seems to be a problem, at least in a time-dependent scheme, as the one we used here.

(v) It is also not yet clear whether the primordial pions are effectively present at the annihilation point. The current ideas about hadronization may indicate that they are present as interacting particles at later time and at a slight distance from this annihilation point.

In view of all these uncertainties, we preferred to keep on with the simple hypothesis of a Coulomb state as it is usually done [26]). This is presumably not a serious limitation for our results. At any rate, as we demonstrated above, the main results of our investigation mainly depend on the average annihilation distance in a very simple way. Therefore our work has a validity which goes beyond the uncertainty of the initial state. If, in the future, initial state for a particular system is known with precision, it will suffice to look at our figures of table 2 to interpolate the result corresponding to this precise case (see in particular fig. 5). The good agreement that we obtained for Mo and Ho seems to indicate that our initial annihilation state, though simply taken as a simple Coulomb state seems to provide a satisfactory description of the annihilation site at least on the average.

For the events corresponding to a loss of a few nucleons, the INC model is overestimating the yield, missing more or less the presence of a dip. This observation, in conjunction with the fact that we predict the good average mass loss, suggests that we describe correctly the gross feature of energy transfer mechanism (since the average mass loss is directly connected with the average energy transfer), but that the detail of the dynamics of a high energy pion or of the recoiling nucleons is too crude in our model. It may also indicate the effect of some distortion of the wavefunction of the annihilation state due to strong interaction process. This certainly deserves a careful investigation. In particular, one may think to include recent calculations of antiprotonic states [27,28]) in our scheme. This however goes beyond the scope of this paper and we reserve it for future work.

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J. Cugnon and J. Vandermeulen want to dedicate this paper to the memory of their friend and collaborator Pierre Jasselette, who died recently and who was a man of great distinction and culture.

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